Government Office for Science

INNOVATION: MANAGING RISK, NOT AVOIDING IT

Evidence and Case Studies

Annual Report of the Government Chief Scientific Adviser 2014.

INNOVATION: MANAGING RISK, NOT AVOIDING IT

Evidence and Case Studies

This volume comprises chapters which form the evidence for the Government Chief Scientific Advisor's Annual Report 2014, together with illustrative case studies. It should be cited as:
Annual Report of the Government Chief Scientific Adviser 2014. Innovation: Managing Risk, Not Avoiding It. Evidence and Case Studies.

The Government Office for Science would like to thank the authors who contributed chapters, case studies and their time towards this report and gave it freely. A full list of authors can be found on pages 6-8.

This report is intended for:
Policy-makers, legislators, and a wide range of business people, professionals, researchers and other individuals whose interests relate to the link between risk and innovation.

The report project team was David Bennett, Graeme Collinson, Mike Edbury, Elizabeth Surkovic and Jack Wardle.

This report consists of contributions received from academia and industry and others outside of government. The views expressed do not represent policy of any government or organisation.

FOREWORD

Advances in science and technology can yield significant societal benefits and drive economic growth. The challenge for society is to channel evidence about innovative technologies and their risks to improve decision making in the area of regulation and policy making.

My annual report sets out my response as Chief Scientific Adviser to the challenges faced by decision makers when determining policy. It considers the different perspectives through which risk is viewed by members of the public, business and policy-makers. The report also seeks to understand the bases for individual and collective decisions on when and how to innovate.

To produce my report I have drawn on the expertise of a broad range of experts and academics, who have set out the evidence about the challenges faced by policy makers and regulators. I have also sought and included notable case studies which illustrate the perspectives in the core of the report. This volume comprises that body of evidence and associated case studies.

I am indebted to the authors of this volume for their contribution. The chapters and case studies represent the authors' personal views rather than those of the Government Office for Science but their wide ranging perspectives have provided important evidence for this project, and so have helped me develop the themes and conclusions of my own report.

Mark Walport
Government Chief Scientific Adviser
November 2014

CONTENTS

EDITOR AND CHAPTER AUTHORS

Editor Mark Peplow

Chapter 1 Nicholas Stern
I.G Patel Professor of Economics and Government, London School of Economics, President of the British Academy and Director of the Grantham Research Institute on Climate Change and the Environment

Rodney Boyd
Policy Analyst and Research Advisor to Professor Stern
Grantham Research Institute on Climate Change and the Environment and ESRC Centre for Climate Change Economics and Policy at the London School of Economics and Political Science

Fergus Green
Policy Analyst and Research Advisor to Professor Stern
Grantham Research Institute on Climate Change and the Environment and ESRC Centre for Climate Change Economics and Policy at the London School of Economics and Political Science

Reuben Finighan
Independent Consultant, Melbourne, Australia

Chapter 2 Ian Goldin
Professor of Globalisation and Development at the University of Oxford, and Director of the Oxford Martin School, University of Oxford.

Chapter 3 Simon Pollard
Pro-Vice-Chancellor, School of Energy, Environment and Agrifood, Cranfield University
Professor of Environmental Risk Management

Sophie Rocks
Lecturer in Emerging Risks, Cranfield University Institute for Environment, Health, Risks and Futures

Chapter 4 Andy Stirling
Professor of Science and Technology Policy, Science Policy Research Unit (SPRU) and Co-Director of the ESRC STEPS Centre, University of Sussex

Chapter 5 Tim O'Riordan
Emeritus Professor of Environmental Sciences, University of East Anglia, Norwich

Chapter 6 David Spiegelhalter
Winton Professor for the Public Understanding of Risk University of Cambridge

Chapter 7 David Halpern
Chief Executive, The Behavioural Insights Team

Owain Service
Managing Director, The Behavioural Insights Team

Chapter 8 Nick Pidgeon
Professor of Environmental Psychology at Cardiff University, and Director of the Understanding Risk Research Group

Karen Henwood
Professor of Social Sciences at Cardiff University

Chapter 9 Judith Petts
Professor of Environmental Risk Management and Pro-Vice-Chancellor, University of Southampton

Chapter 10 Toby Ord
Research Fellow in the Oxford Martin School at the University of Oxford

Nick Beckstead
Research Fellow at the Future of Humanity Institute and the Department of Philosophy at the University of Oxford

Chapter 11 Joyce Tait
Professor, University of Edinburgh and Director of the Innogen Institute

Chapter 12 Lisa Jardine
Professor of Renaissance Studies at UCL
Former Chair of the Human Fertilisation and Embryology Authority

CASE STUDY AUTHORS

High Level Case Studies

Synthetic Biology
Lionel Clarke
co-Chairman UK Synthetic Biology Leadership Council

Richard Kitney
Professor of BioMedical Systems Engineering at Imperial College, and Co-Director of The EPSRC National Centre for Synthetic Biology and Innovation and National Industrial Translation Centre for Synthetic Biology (SynBICITE) at Imperial College

Roland Jackson
Executive Chair of Sciencewise

Hydraulic Fracturing
Stephen Elliott
Chief Executive, Chemical Industries Association

Harry Huyton
Head of Climate Change, RSPB

Robert Mair
Sir Kirby Laing Professor of Civil Engineering, Cambridge University

Flooding
Edmund Penning-Rowsell
Professor of Geography at the Flood Hazard Research Centre, Middlesex University and Distinguished Research Associate at the University of Oxford

Paul B Sayers
Partner, Sayers and Partners LLP, UK and Senior Fellow, Environmental Change Institute, University of Oxford

Andrew Watkinson
Professor of Environmental Sciences at the University of East Anglia

Natural Disasters and the Insurance Industry
Rowan Douglas
CEO Capital Science & Policy Practice, Willis Group & Chairman, Willis Research Network

Julia Slingo
Met Office Chief Scientist

Trevor Maynard
Head of Exposure Management and Reinsurance, Lloyd's of London

Innovation and Risk

Fukushima
Anthony Carrigan
Lecturer in Postcolonial Literatures and Cultures at University of Leeds

The High Value Manufacturing Catapult
Dick Elsy
Chief Executive, High Value Manufacturing Catapult

L'Aquila
Chris Whitty
Chief Scientific Adviser, Department for International Development

Marcus Besley
Government Office for Science

Communicating the risk of climate change
James Lyons
Senior Lecturer, University of Exeter

Risk and Innovation in Developing Countries: A New Approach to Governing GM Crops
Phil Macnaghten
Professor of Geography at Durham University, and Visiting Professor at University of Campinas – UNICAMP, Brazil

Susana Carro-Ripalda
Senior Research Fellow at Durham University

Consistency and transparency in evidence-based regulation: risk and precaution in regulation of bisphenol A
Patrick Miller
Head of Science Strategy and Governance at the Food Standards Agency

Financial Crisis
Tom Sorell
Professor of Politics and Philosophy, University of Warwick

Making Choices In The Face Of Uncertainty

Neonicotinoid Insecticides and Insect Pollinators
Charles Godfray
Hope Professor at Oxford University and Director of the Oxford Martin Programme on the Future of Food

Angela McLean
All Souls Senior Research Fellow at Oxford University and Director of the Oxford Martin School Institute for Emerging Infections

Nanomaterials
Kamal Hossain
Director, Research and International at the National Physical Laboratory and Chair of the European Metrology Research Association (EURAMET)

Human Rights and Risk
Sabine Michalowski
Professor of Law, University of Essex, Director of the Essex Transitional Justice Network

Karen Hulme
Professor of Law, University of Essex, Consultant with the Essex Business and Human Rights Project

Nuclear: The Submariner's Perspective
Rear Admiral Nigel Guild
Chairman, Engineering Council

Adapting regulation to changing evidence on risks: delivering changes to pig inspection
Patrick Miller
Head of Science Strategy and Governance at the Food Standards Agency

Accurate Communication of Medical Risk
Chris Cummins
Chancellor's Fellow in Linguistics and English Language at the University of Edinburgh

CASE STUDY AUTHORS

Framing Risk – The Human Element

Social Machines: Managing Risk in a Web Enabled World
Nigel Shadbolt
Professor of Artificial Intelligence at the University of Southampton and Chairman of the Open Data Institute, London

Electronic Cigarettes: Trade-Offs and Establishing Acceptability Thresholds
Fabian Schuppert
Research Fellow, Institute for Collaborative Research in the Humanities at Queen's University Belfast

Aum Shinrikyo and the Move to Violence
Matthew Francis
Senior Research Associate at Lancaster University, and Editor of RadicalisationResearch.org

Kim Knott
Professor of Religious and Secular Studies at Lancaster University, and Global Uncertainties Leadership Fellow

Managing Risk Perception of Autonomous Technologies: the Docklands Light Railway
Mike Esbester
Senior Lecturer in History at the University of Portsmouth and Co-Principal Investigator on the Institution of Occupational Safety and Health-funded project 'The Changing Legitimacy of Health and Safety at Work, 1960-2013'

Telling the Stories of Climate Change
Esther Eidinow
Assistant Professor in Ancient Greek History, University of Nottingham

Nicky Marsh
Professor of English at the University of Southampton

Patricia Waugh
Professor in the Department of English Studies at Durham University and also Principal Investigator on the 'Tipping Points' project located in the Institute of Hazard, Risk and Resilience, Durham University

Context and Futures

MMR, Bowel Disease, Autism and Measles
David Salisbury
Former Director of Immunisation, Department of Health, and Visiting Professor, Imperial College, London

Policy, Decision-Making and Existential Risk
Huw Price
Bertrand Russell Professor of Philosophy and Academic Director of the Centre for the Study of Existential Risk at the University of Cambridge

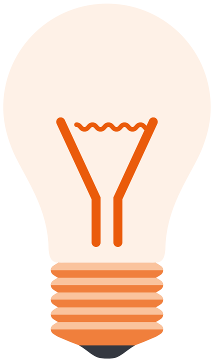
Seán Ó hÉigeartaigh
Executive Director of the Centre for the Study of Existential Risk at the University of Cambridge

Moving Things Forward – Governance and Decision-making

A Case History on GM Crops
David Baulcombe
Royal Society Edward Penley Abraham Research Professor and Regius Professor of Botany at University of Cambridge

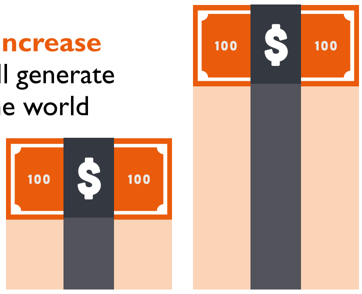
Standards: Supporting emerging technologies as an accelerator of innovation
Scott Steedman
Director of Standards, BSI

SECTION 1: INNOVATION AND RISK

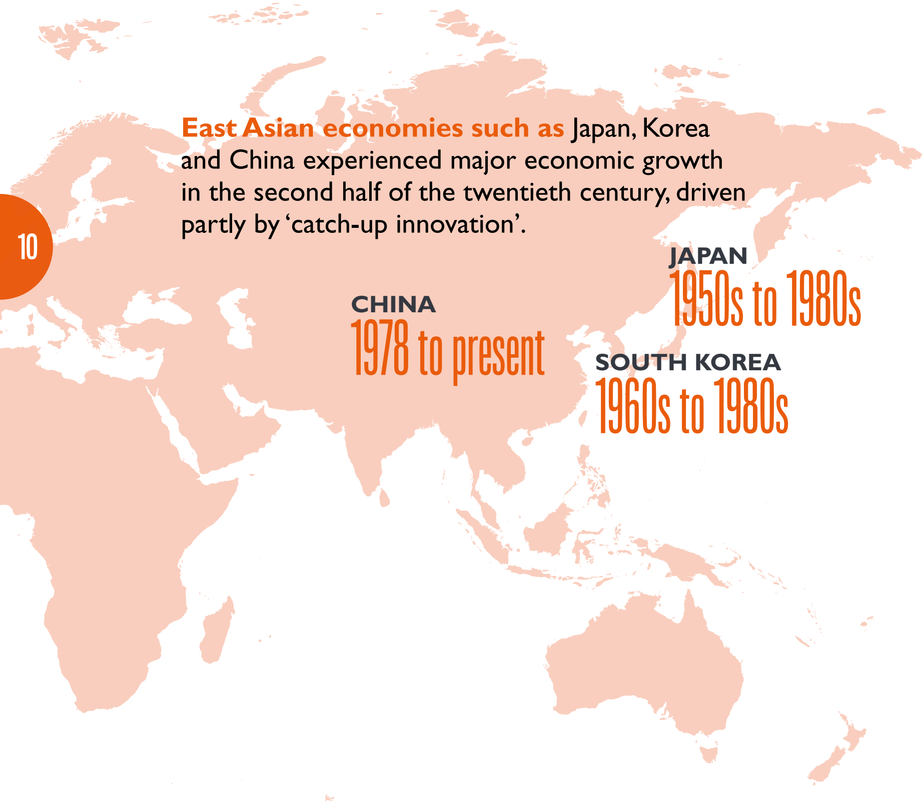


Innovation involves more than just physical products. Some 78% of the UK economy is in services, where innovation plays a key role.

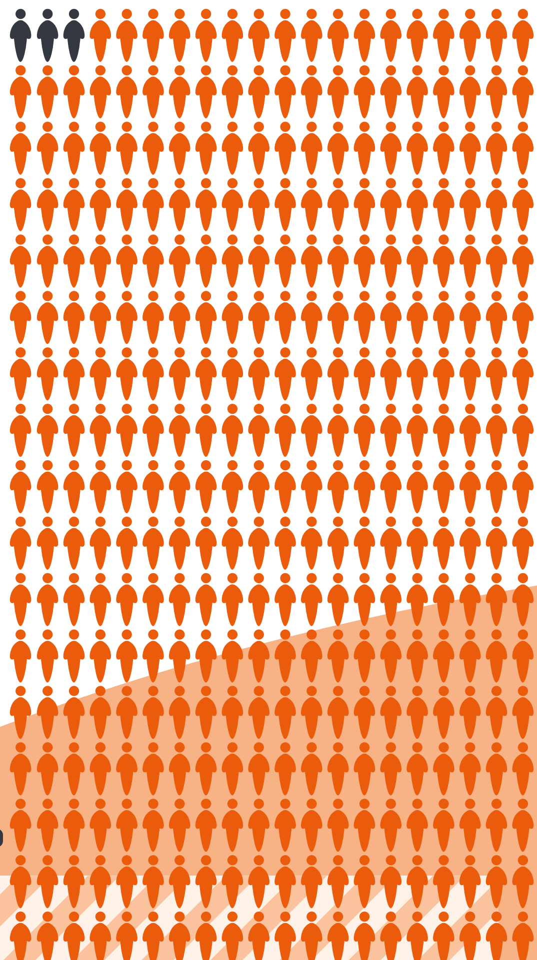
Technological improvements will increase productivity by as much as 25% and will generate a predicted \$3.7 to \$10.8 trillion for the world economy by 2025.



East Asian economies such as Japan, Korea and China experienced major economic growth in the second half of the twentieth century, driven partly by 'catch-up innovation'.



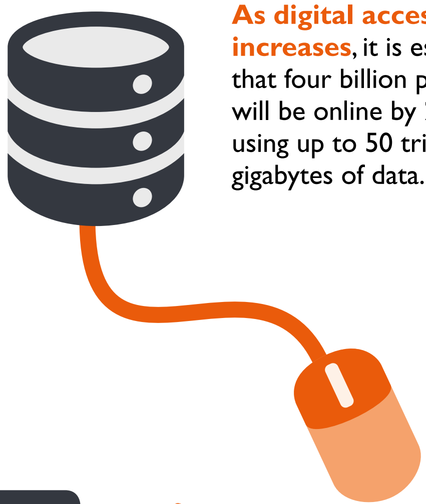
Twenty years ago, there were fewer than 3 million people with internet access; now there are nearly 2.5 billion.



The Bus Rapid Transit (BRT) system in Bogota, Colombia is a good example of (city) government-led institutional innovation.

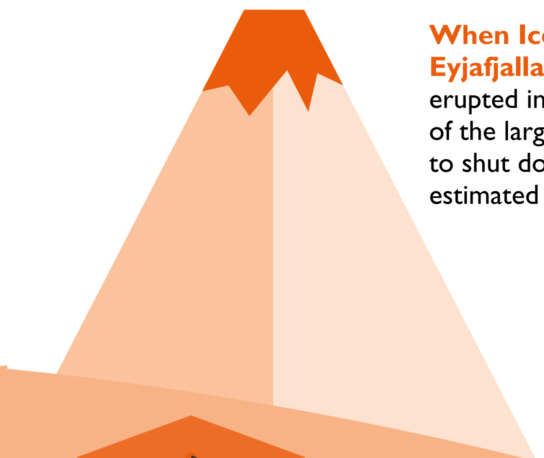
The African continent has twice as many mobile phones as the United States.

Global Alliance for Vaccines and Immunisations (GAVI) and the Global Fund have worked to prevent 5.5 million and 6.5 million deaths respectively since their inception.



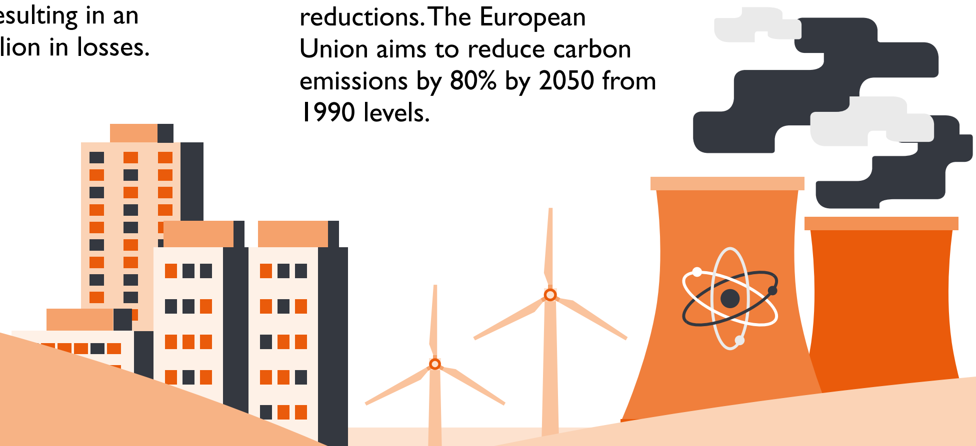
As digital access increases, it is estimated that four billion people will be online by 2020, using up to 50 trillion gigabytes of data.

There were 200 million people over the age of 60 in 1950. Today, that number has grown to nearly 800 million. By 2050, it is projected to stand at 2 billion.



When Iceland's Eyjafjallajökull volcano erupted in 2010 it caused several of the largest global airports to shut down, resulting in an estimated $5 billion in losses.

Industrial processes will need to make technological changes in order to meet domestic and regional targets on carbon emissions reductions. The European Union aims to reduce carbon emissions by 80% by 2050 from 1990 levels.



Students are not only attaining higher levels of education, they are also moving to access this education. Growing numbers of people will have access to the best academic institutions.

Rodney Boyd, Reuben Finighan, Fergus Green and Nicholas Stern (London School of Economics and Political Science)

CHAPTER 1 INNOVATION, RISK AND GOVERNMENT: PERSPECTIVES AND PRINCIPLES FROM THE SOCIAL SCIENCES

The interplay between innovation and risk, and the social interactions between public and private sectors, are critical in fostering innovation and determining its effectiveness.

INTRODUCTION

In today's globalized, rapidly-changing world, innovation is becoming ever more important as changes in technology, skills and knowledge increasingly affect countries' competitiveness externally and the well-being of their people internally. In the UK, innovation will continue to be a key source, perhaps *the* key source, of economic growth. However, competition is becoming ever more fierce, vital global resources are dwindling, and environmental problems are mounting, making innovation an ever-present challenge. Indeed, there is some evidence to suggest that the UK is falling behind many of its major trade competitors when it comes to research and development, which is closely linked to innovation (see Table 1).

In shaping growth, innovation touches on all sectors and institutions. It is sometimes portrayed as the process of going from research laboratory to physical product, but that is much too narrow a view, particularly in advanced countries where the service sector is 70-80% of the economy. We can hope to sustain economic growth, and continue improving quality of life, by changing the way we do things. But doing things differently involves embracing risk and uncertainty — risk of failure is an intrinsic aspect of innovation — and numerous market failures constrain potential innovation. Yet policies to foster innovation can be hard to get right and interpreting evidence about what works can be difficult; governments can fail, too.

Nevertheless, through good theory, rigorous analysis and rich examples, we have learnt much that can provide useful guidance. By examining some important lessons and insights from economics and other social sciences, this chapter looks at the interplay between innovation and risk, and how social interactions between public and private actors are critical in fostering innovation and determining its effectiveness.

Part A is conceptual in nature. It contains an overview of the defining characteristics of innovation, and its relationship to economic growth and to risk. In Part B, we discuss insights into innovation from the social sciences, providing real-world examples as much as possible. Finally, in Part C, we set out some broad recommendations for UK government policy that draw on the insights discussed. From our analysis, we identify pillars or foundations for first-class 'innovation infrastructure': a high-quality, merit-based system of education and training; substantial investment in basic research; a system of government-managed incentives that promote innovation via markets and entrepreneurship; and setting and investing in national innovation priorities. We also suggest associated policymaking guidelines.

A. INNOVATION, GROWTH AND RISK

(i) Defining Innovation

Innovation is about changing the way we do things. It is about pushing the frontier of what we know in the hope of generating new and useful ideas, and then putting them into practice. Successful innovation raises productivity and living standards, expanding the range of goods and services available for individuals and society as a whole, and allowing us to live longer, healthier lives.

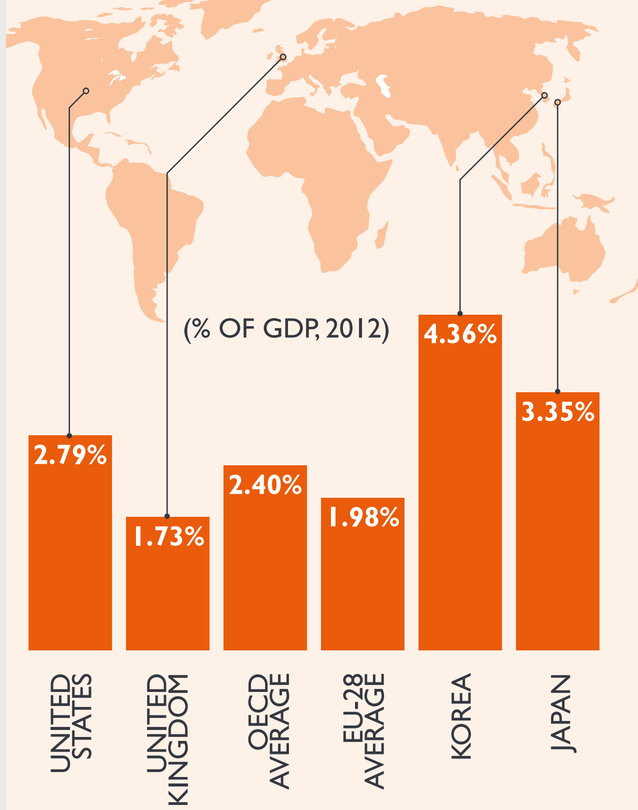
Joseph Schumpeter provides a classic definition of innovation as the development of new ideas (which he called "inventions") into products and processes, which are then spread across the market in a process he called *diffusion*[2]. Innovation, as we shall use the term, encompasses the full chain from basic research to the diffusion of ideas, goods or services across an economy. Schumpeter envisaged this occurring in a linear way, in the sense of a distinct time sequence. In reality, these different stages overlap and interweave, as parts of a complex system that feeds back to and influences future developments[3]. Nonetheless, this model provides one starting point for thinking about innovation.

Some additional features of the definition and scope of innovation, as we understand it, are as follows[4]:

- **Innovation is more than invention alone.** Some of the greatest innovators imitate, borrow or adapt new ideas from other people, firms or places. The ideas that are put

TABLE 1

GROSS DOMESTIC EXPENDITURE ON RESEARCH & DEVELOPMENT



to work may not be individually original. Innovation is about putting new ideas into practice, not just creating or inventing them.

- **Innovation is also more than just physical products, and takes place over all sectors of activity.** As an example, 78% of the UK economy is services[5], and many traditional products and associated industries are becoming turned into services (e.g. recorded music; private vehicle transport).
- **Not all innovation is about making breakthroughs.** *Incremental innovation* is the making of small improvements to existing technologies and practices. Such innovation often occurs through the process of practice, and while it is sometimes predictable in the short term it can lead to immense changes in the long term[6]. *Radical (or "breakthrough") innovation* is making breakthroughs that change the way we do things altogether. It tends to result from basic research, and tends to be much more unpredictable[7].
- **Not all innovations change market structures or displace market leaders.** From the perspective of markets, innovation can be *sustaining* — with little impact on existing market structure — or *disruptive* — where new markets are created and/or existing markets disrupted[8].
- **Innovation both creates and destroys, and the distribution of gains and losses is often uneven.** Because innovation is a key driver of growth, and usually meets some human need or desire, innovation is generally seen as socially valuable. Yet as Schumpeter noted, innovation is also a process of "creative destruction" where old ways of doing things are destroyed and replaced by new ones. While innovations (particularly disruptive ones) often bring widespread, longer-term benefits, they often also entail concentrated economic costs on some groups (for example, electric light disrupted candle-makers)[9]. If change is poorly managed, this may generate social costs, such as long-term unemployment. That said, over time innovation in general has increased living standards greatly[10].

(ii) Innovation and economic growth

Many of the greatest and longest-lasting periods of economic growth have been driven by innovation. In the 20th century, the major growth periods occurred in rich countries in the post-World War 2 period until the late 1960s, and in East Asia – most notably in Japan (1950s to 1980s) and Korea (1960s to 1980s), and more recently in China (1978 to the present). In rich countries, this was driven in part by innovations in the mass production system, automobiles and widespread electrification[11], but also by recovery from the great recession and World War 2. In East Asia much of the growth occurred through "catch-up innovation" driven in large part by a managed transition toward open economies and market-oriented institutions.

Innovation has the further distinction of being relatively limitless in its potential to generate growth[12]. As the other avenues of growth – increasing savings, capital, labour or other inputs – become exhausted in modern economies, innovation increasingly becomes the dominant driver of long-term growth[13].

> **Risk of failure is an intrinsic aspect of innovation.**

Some of the returns from innovation can be appropriated by the innovator, but new knowledge also "spills over" into the wider economy to be used by other individuals, firms and governments. There is "a consensus on the centrality of knowledge spillovers to innovation, and innovation to growth"[14]. New ideas begin to drive growth as they diffuse, become applied, and drive new innovations, throughout an economy[15].

Yet spillovers expose private innovators to risks, including being unable to appropriate much of the returns from their innovation, which in turn reduces their underlying incentives to innovate. Thus there is a tension between increasing the private appropriability of knowledge (e.g. through patent protection) and increasing its public diffusion (e.g. through promoting openness). There are various ways in which governments can manage this tension — from establishing and enforcing patent rights to offering innovation prizes — many of which are addressed in Part B. The preferred approach will depend in part upon the broader conceptual framework within which one conceives of innovation and the role of government.

In the economics literature on innovation, two main conceptual frameworks are dominant: the 'market failure' framework; and the 'innovation systems' framework.

Analysis in terms of market failures suggests innovation investment is and will remain "too low" because of several well-characterized market failures[16]:

- **Spillovers in R&D mean that private firms (and individual countries) are unable to capture the full value of their investments in a competitive market.** Indeed, innovation studies suggest that the social returns to private R&D are often much larger than the (already large) private returns[17]. This means in such cases firms will undervalue such investments — and so be motivated to underinvest relative to what might be good for society as a whole. Fostering positive spillovers is a "primary justification for government R&D-support policies"[18].
- **Key externalities, like congestion, environment and CO_2 emissions, may not be properly priced or regulated in the market.** Firms thus undervalue innovations that would address such externalities. For this reason, energy innovation has been called "a tale of two market failures" — i.e. it is undervalued due to both spillovers *and* the lack of adequate CO2 pricing[19].
- **Imperfections in risk-sharing institutions and capital markets hamper the extent to which innovation and innovative approaches can diffuse.**

Investors face additional risks when investing in a variety of new situations — e.g. new technologies, new policy environments. Some of these risks can be mitigated by policy (see Part B), but the nature of capital markets, in which lenders also have to be persuaded of the yet undemonstrated prospects, mean it is impossible to cover them all.

- **Behaviour different from that embodied in the standard "rational" representation of individuals in economic models can limit innovation.** Our tendency to focus on the short-term, to dislike risk and uncertainty, and to stick with the status quo can lead to "innovation neglect" in public and private institutions alike (see Part B).
- **The development of human capital and associated markets is restricted by its own spillovers.** The education of individuals provides *social* benefits, by providing human capital upon which public and private sectors, and society as a whole[20], can draw. These benefits are not fully captured by the educated individual, or by schools or firms that may educate that individual, so markets tend to provide less education than is socially efficient[21].
- **Sustained support for incumbent technologies.** Most energy sectors, for instance, have been historically designed for fossil fuel use, thus development of low-/zero-carbon sources of energy may be slowed and many aspects of the energy system may need to change in addition to the sources. Existing institutions, infrastructure and policies that support certain sectors, can result in sector inertia that provides "barriers to entry for new technologies"[22].

It is not just markets that fail. Governments, with good intentions or otherwise, having different competencies and facing diverse pressures, can also fail. Attempts to pick winners sometimes lead to second-guessing markets and wasted resources[23]. A poorly designed policy, or one that does not carry credibility, can present a greater threat to innovation than the market failures it was supposed to resolve[24]. Reasons for government failure include:

- asymmetric information;
- lack of experience or competence in business or science;
- rent-seeking or lobbying by private actors;
- short-term time horizons driven by electoral cycles.

The 'systems of innovation' approach focuses on how firms of different types, government actors and other economic agents, are embedded in 'systems of innovation' (sectoral, regional, national), or 'innovation ecosystems'[25]. The approach emphasizes the importance of interactions between actors in such systems (which are often non-linear, involving important feedback loops), and how knowledge is diffused throughout the economy[26]. In distinction from the 'market failures' approach, the innovation systems literature focuses on the importance of both market and non-market actors, relationships and norms in determining innovation behaviour. This expands the possible scope of useful state intervention[27], but at the same time provides further possible sources of government failure. Poor government policy may, for example, override existing norms (such as those for openness among academic researchers) and result in unexpected negative effects on innovation[28].

Both frameworks bring valuable insights to our understanding of innovation and how it can be fostered to promote growth. From here on, we focus more on the market failure framework because it has a longer-standing literature, but we draw on both.

(iii) Innovation, risks and incentives

There is significant potential for policy to boost innovation, and thereby boost economic growth. To design policy that effectively and efficiently fosters innovation, we must understand how actors along the innovation chain respond to the risks and incentives they face.

"Risk" and "uncertainty" in economic analyses are often used interchangeably but the American economist Frank Knight distinguished them along the following lines[29]:

- **"Risk" can be thought of as measurable and quantifiable in terms of probabilities,** and is most useful for describing investment in predictable advances further along the innovation chain. Intel's investments in chip technology, for example, produce incremental improvements that are predicted years in advance according to Intel's "tick-tock" model of chip improvement[30], where improvements are reliable enough that the metaphor of a clock fits.
- **"Uncertainty" can be thought of as that which is not easily measurable in terms of probabilities,** where we may even be unsure of what possibilities exist. This can be the case in complex, chaotic systems composed of many interacting elements — and along the innovation chain, "all of the actors operate under conditions of uncertainty"[31]. This applies especially in early phases of the chain, and in innovation over the long term. Policymakers could not have foreseen that studying jellyfish would found a large part of the biomedical revolution, or that military packet switching technologies intended to make military communication systems more resilient in the event of a nuclear attack would lead to the internet, social networking and the avalanche of apps spawned in Silicon Valley.

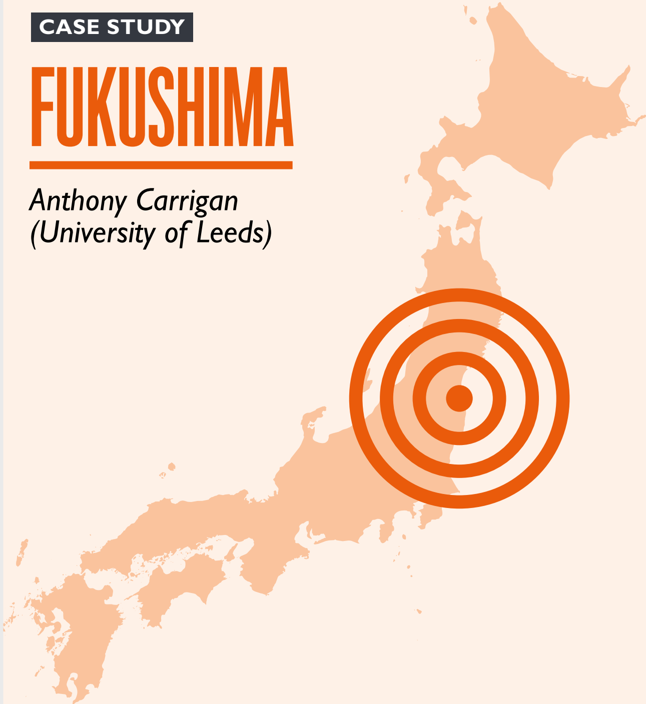
Private actors face a diversity of risks — financial risks, career risks, legal risks, and many beyond — when they choose to innovate. The balance of risks and incentives determines what choices innovators (entrepreneurs, investors, inventors, bureaucrats, etc.) will make.

Being exposed to risk is part of doing business. But some risks are appropriate guides to decision-making, while others may be unhelpfully imposed. Deciding not to proceed with an innovation investment because there is a high risk of insufficient demand is a sensible decision — the kind of decision that firms make routinely in order to maximize their value. Deciding not to proceed with a very promising innovation because of the risks imposed by regulatory unpredictability (e.g. policy risk), lack of appropriability (e.g.

CASE STUDY

FUKUSHIMA

Anthony Carrigan
(University of Leeds)



Disaster experts agree that there is no such thing as a ‘natural’ disaster. Environmental hazards become disasters as a result of the risks and vulnerabilities that people are exposed to on a daily basis. Indeed, disasters are not single events — they are compound processes that must be understood historically, and from multiple viewpoints, to effectively reduce risks in the future.

With the intensification of complex risks, including climate change, our vulnerabilities have also become more complex, arising at the intersection of technological change, environmental depletion, and economic inequality. These factors have been partly responsible for the increasing number of disasters experienced worldwide[1], and it is always the poorest who suffer most.

The 2011 Fukushima disaster — the largest nuclear catastrophe experienced in Japan since the atomic bombings of the Second World War — highlights what is at stake. The 9.0 magnitude Tohoku earthquake and tsunami, which claimed in the region of 20,000 lives, triggered the disaster. But it was the failure to meet basic safety requirements[2] at the coastal Fukushima Daiichi nuclear plant that led to a radioactive crisis whose effects continue to spread[3].

The Fukushima disaster was a compound catastrophe caused by systemic negligence over safety precautions in a highly-developed country that is prone to environmental hazards. There was a lack of minimum protection against potential accidents, with flaws identified in how private corporations ran nuclear power plants across the country, and how these facilities were regulated[4].

As a consequence, some of the biggest challenges for government and advisers responding to the Fukushima crisis relate to long-term responsibilities and ethics[5], not least in light of historical debates over nuclear power and technological risks in Japan and worldwide. Policymakers must define acceptable levels of risk in the nuclear power industry. But what is an adequate level of protection and support, and how can governments act to reduce the vulnerabilities that can lead to disasters?

There is a danger in focusing on minimum safety standards, as risk is unevenly distributed across populations and frequently outsourced from richer to poorer areas, both within nations and internationally. While uneven risk distribution is often hidden in everyday life, disasters render it visible and are therefore political proving grounds that highlight the degree of care and protection governments afford citizens in relation to risk exposure and post-disaster support. The Prime Minister of Japan, Naoto Kan, resigned just a few months after the Fukushima disaster, partly due to critiques over state accountability[6]. And similar political discontent has been expressed in the wake of disasters ranging from the Bhopal gas tragedy of 1984 to Hurricane Katrina’s devastation of New Orleans in 2005.

It may be decades before we know the full effects of the Fukushima disaster, but we can look to similar incidents to understand how distrust and anger are generated through perceived state and corporate irresponsibility. Examples like Bhopal show how ‘disaster’ may come to refer less to the original explosion in a chemical factory, and more to failures in the recovery and accountability process. In some cases, the disaster becomes synonymous with inadequate legal aid and remediation; in others, it signifies a lack of healthcare or attention to chronic trauma, grief, and depression. It can also refer to exploitative reconstruction and development initiatives, and community dispossession.

As many narratives and testimonies from Bhopal, Fukushima and New Orleans have shown, it is crucial to identify how compound vulnerabilities and structural risks build up over time, especially in poorer communities, and to support locally driven strategies for reducing these weaknesses. This not only ameliorates risk, but can establish sustained relationships of care that support long-term recovery after a disaster. Such processes are never linear, and are variegated across communities, so it is important to understand different cultural perspectives on disaster (including religious beliefs) in order to establish inclusive prevention and recovery measures.

The Fukushima disaster is a stark manifestation of risks combining human decision-making, technological design, and natural hazards. The causes of vulnerability that lead to compound disasters are more political and economic than environmental: understanding and accepting responsibility for this is essential to reducing risk.

unclear patent law), or barriers to entry (e.g. incumbent power), is a lost opportunity. It is through such risk-inducing channels that "government failure" can hamper innovative activity. The role of government is, rather, to influence the balance of risks, so that actors' decisions relate, as much as possible, to the long-term value of innovation investments.

Innovation can also create or mitigate other risks:
- some types of innovation introduce new risks (e.g. pharmaceuticals like thalidomide);
- some types can amplify existing risks (e.g. mortgage-backed securities combined with derivatives in the housing market); and
- some types of innovation (e.g. renewable energy) can reduce or mitigate existing risks (e.g. climate change and energy insecurity).

The role of governments in relation to risk and innovation is multifaceted. First, legal frameworks, government institutions and policies shape the risks and incentives faced by non-government agents with respect to innovation. Second, governments and their agencies themselves can innovate, taking on uncertainty and risk when private agents are unable or unwilling to do so. Third, governments can regulate to manage the risks that innovations bring. Yet, just as there is market failure, there is government failure: without care, governments can stifle innovation and amplify risks. These and other aspects concerning the role of government in the innovation are explored further in Part B(iv).

B. A SOCIAL SCIENCE WINDOW INTO INNOVATION

On the basis of the key ideas, definitions and issues set out above, this part of the chapter looks at innovation through the window of the social sciences. We consider insights and examples that can be grouped into four categories: (i) the structure of economies and markets; (ii) firms and other institutions; (iii) individuals and behaviour; and (iv) governments.

These categories clearly overlap, and they should not be seen as rigid. In particular, the role of government is relevant across all categories, since laws and government policies — from intellectual property rights to competition laws, and from corporate regulation to infrastructure investment — affect innovative activity by non-government agents. Accordingly, government activity will be touched on in each section, though it will be the primary focus of section (iv).

(i) The structure of economies and markets

Innovation influences the structure of modern economies and the sources of their growth. Economy-wide growth is especially influenced by so-called General Purpose Technologies (GPTs), such as computing, the automobile and electricity, which pervade many economic sectors and have many different applications and spillover effects, including spawning other types of innovation[32].

Innovation is shaped predominantly by characteristics special to each industry, and by past episodes of innovation. The level of technological opportunity (e.g. arising from engineering advances or a wealth of recent discoveries in basic research) is a major determinant of how heavily firms will invest in innovation[33]. The structure of demand is another important factor: homogenous demand is likely to favour a small number of incumbent firms, while heterogenous demand opens up a larger number of niches. For example, in industries where technological opportunity is high and patterns of demand are diverse — as in today's ICT industry — the market is likely to be characterized by a large number of small, innovation-intensive firms[34].

The market structure of an industry has differential effects on innovation, depending on the industry and the technology opportunities available. In some cases competition increases innovation, while in others, as Schumpeter predicted, competition can reduce innovation[35].

Network linkages among firms[36] and openness to trade are important drivers of innovation. Interactions across organizational (firm-firm) and geographic (national, regional) boundaries promote innovation[37]. For example, when markets open to international trade and firms start exporting, they gain access to a larger market, which brings higher returns to innovation and increased diffusion of knowledge as firms interact with more overseas customers/suppliers and learn from experience in other markets[38].

Financial markets have an important role to play in managing and sharing the risks of innovation, but tend to favour short-term investments. Assessing the value of an innovation, or of a small firm without a track record, is complex and involves substantial uncertainties. Investors tend to prefer making a smaller number of larger, and safer, investments in mature firms instead. Well-designed financial tools and institutions can unlock innovation by providing incentives for long-term investment, or by allocating capital and enabling the uncertainty and risk associated with innovation to be spread across multiple agents[39].

State development banks, including sectorally or thematically focused institutions such as green investment banks, can overcome some market failures and risks that private firms, including venture capitalist financiers, are unable or unwilling to bear[40]. Development banks can take a longer-term view, can develop a body of specialized skills that may be lacking in the private sector, and can employ a wide range of instruments (for example, instruments used by the European Bank for Reconstruction and Development include equity investments, loans, guarantees, and technical assistance). The presence of such a bank, moreover, reduces the policy risk perceived by private investors, since government policy is less likely to be volatile in relation to sectors in which the bank is involved.

(ii) Firms and other institutions

Most innovation occurs within organizations – e.g. firms, universities, government research institutes/agencies. Studying these organizations can therefore provide insights into the innovation process.

Firm size affects the quantity and type of innovation that occurs. With regard to research, the quantity of research done by firms tends to be proportional to firm size[41]. However, the type of innovation carried out does differ with firm size: larger firms tend to produce more incremental advances, while smaller firms are somewhat more likely to bring breakthroughs to market[42]. Since both types of firms have advantages in different conditions and face different kinds of constraints and market failures with different characteristics, policy should not focus on just one type or size of firm[43].

Patents are important instruments for incentivizing firms to innovate, but they also restrict the diffusion of knowledge. On the one hand, patent rights play a crucial role in incentivizing firms to innovate by providing a temporary monopoly and allowing licensing to address the 'knowledge spillover' market failure[44]. On the other hand, patents hinder innovation by raising transaction costs to the diffusion of knowledge and the transfer of technologies, deterring some other innovations that could build on these spillovers, and distorting the product market through monopoly pricing. An efficient patent system will strike a balance between the competing demands of private property rights and openness[45].

Exactly where this balance lies, and its nature, vary across industries: in the U.S., for example, patent rights block innovation in the fields of computers, electronics and medical instruments, but not in drugs, chemicals or mechanical technologies[46]. This is predominantly because in the former industries ownership of patents is highly fragmented, raising the costs and coordination challenges of innovating. This especially impacts small firms seeking patents from larger firms, because the costs of seeking licenses are disproportionately higher for small firms[47]. Good patent policy thus requires a sensitivity to specific industry conditions — as well as good data and consultation.

The same sensitivity to context is also warranted when determining what advances can be patented, since this affects basic research carried out by universities. While patents can promote basic research, it can be adversely affected where patents block access to new scientific techniques with potentially large spillover effects[48].

The linkages between different organizations within "innovation ecosystems" — particularly between universities/institutes and private firms — are a very important determinant of innovation. Whilst it is difficult to get these links right, there are lessons from experience. Basic and applied research, which typically takes place in universities and other research institutions, involves high levels of uncertainty with the potential to produce high social value over the longer term. Technology development and commercialization, which typically occurs in private firms, involves more manageable risks with the potential to produce high private value over the shorter term. Given their different institutional structures and imperatives, linking these parts of the innovation chain is challenging.

Two generic approaches for improving these linkages are (a) public-private collaborations and (b) intermediate institutions for knowledge diffusion / technology transfer. But many attempts to foster such linkages have been

Well-designed financial tools and institutions can unlock innovation.

unsuccessful. While hubs of innovation have clearly developed around the UK's major universities, attempts to recreate these success stories in other universities through co-location have generally led to disappointing results[49]. Technology transfer offices (or TTOs) established in universities across the developed world have been "found to be more at odds with both scientists and entrepreneurs, than the latter are between themselves", suggesting that they are not a trusted intermediary[50]. The UK Government's "Catapult" centres provide a different — and perhaps more promising — model for linking diverse actors within the innovation ecosystem, based on public-private collaboration (see Box 1 for an example of one such centre).

Incentive structures faced by researchers within organizations affect innovative activity. Institutional cultures that set out to experiment and learn, that give employees autonomy and that evaluate their performance over longer term cycles tend to be more innovative. The innovative activity that occurs within organizations is influenced by the institutional culture and incentive structures that researchers face, such as how much autonomy researchers are given, the structure of their employment, how performance is evaluated (shorter or longer term performance, process based or outcome based, and how these are measured, e.g. in terms of quantity of patents, types of publications etc.) and how they are rewarded[51]. Compare, for example, the Howard Hughes Medical Institute (HHMI), which tolerates failure and provides significant freedom to experiment and change course, with the National Institutes of Health (NIH), which imposes short review cycles and narrowly defined goals. Research suggests that the HHMI model results in significantly more "high-impact" papers per scientist[52].

There is a trend within the UK, the US and elsewhere to make universities and research institutes more results-oriented, commercially-focused and "entrepreneurial"; this risks emphasising shorter-term benefits at the expense of much larger, longer-term benefits to society. In the UK and US, universities are increasingly being expected to emulate private firms by patenting, and even commercialising, the discoveries of their researchers[53]. This particular approach to the public-private linkage problem (discussed above) could lead to higher volumes of innovative activity (e.g. patents) and innovation-led growth in the short-to-medium term. However, the value of this new model is unclear: spin-off companies do not appear to be driving economic growth, and patenting appears to be a minor pathway for knowledge transfer to industry, compared to traditional academic papers, conferences and relationships[54].

More problematically, system-wide rollouts of ideas like the entrepreneurial university may pose substantial risks. Innovation scholars warn that the architecture of the institutions that organize academic research is old and poorly understood. Undertaking experiments in institutional design at large scales may result in prolonged slowdowns in innovation and growth[55]. For example, the new incentives for commercialization risk crowding out the basic research that expands the boundaries of *future* innovation and economic growth, with unknown long-term effects[56]. Such pioneering basic research as the investigations into the Higgs Boson, jellyfish Green Fluorescent Protein, and mammalian gene targeting (the latter two generated new tools that now underpin modern biomedical research), each of which recently resulted in a Nobel Prize, might not have been funded in today's short-termist, risk-intolerant innovation system[57], where "results" are often measured in a narrow way such as counting the number of patents or papers.

(iii) Individuals and behaviour

Psychological factors shape the decisions people make about innovation, across all institutions — both public and private — and across all levels, from teachers, to scientists and engineers, to their managers, and to policymakers.

Individuals tend to be loss averse[58], and this may contribute to reduced innovation. When business is going smoothly, firms tend to neglect the uncertainties of innovation and favour the sure-thing of business-as-usual. The need to innovate becomes more salient once outcomes have begun deteriorating, by which point it can be difficult to innovate rapidly enough. Blackberry's failure to maintain market share is one widely cited example of innovation neglect[59].

Governments may also neglect innovation until crises arise, leading to wildly fluctuating — and therefore highly inefficient — patterns of investment. This was seen, for example, with the rise in public investment in

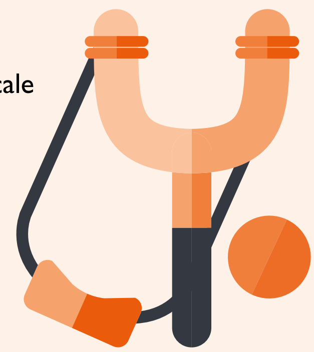
CASE STUDY

THE HIGH VALUE MANUFACTURING CATAPULT

Dick Elsy (Chief Executive, High Value Manufacturing Catapult)

The High Value Manufacturing Catapult (HVMC), the first "catapult" centre to be opened, just three years ago, helps commercialise innovative manufacturing ideas. It combines seven centres of industrial innovation across Britain, bringing together the following capabilities:

- Provides companies with access to world-class facilities and skills to help scale up and prove high-value manufacturing processes;
- Develops a network of leading suppliers who contribute to key UK industry supply chains;
- Brings industry, government and research together around a shared goal to make the UK an attractive place to invest in manufacturing.



The Catapult's financial model works on the basis of shared risk, with funding coming from three sources:

1. Government core funding;
2. Industry funding;
3. Competitively won collaborative Research and Development (e.g. Horizon 2020 projects).

Government funding helps to give industry confidence to take the kind of technological risks from which it would normally shy away. Industry can access publicly-funded manufacturing equipment and skills and has greater freedom to experiment, develop these radical concepts and learn from experience.

The uptake of the HVMC has exceeded expectations and all of the commercial targets agreed at the outset have been surpassed. Industry funding has reached 45% with collaborative R&D at 30% and government core funding representing 25% of the total. The Catapult is now examining ways to secure this funding sustainably.

In the past 12 months the HVMC has attracted:

- 1515 private sector clients;
- 1012 projects;
- 1500+ SME engagements;
- £224m total income;
- £60m of innovation income accessed by SMEs;
- £180m order book with >50% competitively won collaborative R&D;
- 1250+ staff.

As social scientists, we are interested in why institutions such as this are successful at fostering innovation, as this can help with future institutional design. The reasons behind the HVMC's apparent success are likely to include the following: it enables risks to be shared between different organizations; it reduces some of those risks; and it provides a place where specialised and complementary skills can come together and grow.

energy R&D by oil importing nations following oil price shocks in the 1970s. As oil prices fell through the late 1980s, interest in energy innovation subsided. By 2000, public spending on energy R&D had declined to 5-10% of its 1980s peak as a share of GDP[60]. Because innovation investments can take decades to deliver, and require continuity over time so knowledge and expertise can accumulate, a steady commitment to innovation is likely to produce substantially better outcomes per dollar.

Monetary rewards — a type of external incentive — may displace other motivations and norms in the innovation chain. Internal motivations, like the desire for knowledge and discovery, play a large role in some parts of the innovation chain. These intrinsic or internal motivations can be "crowded out" by the imposition of external incentives[61]. External incentives may be particularly poorly suited to creative endeavours like scientific research. In particular, they can displace the "soft" institutions that drive basic research — the bedrock of trust and institutional norms, such as academic freedom, openness and knowledge-sharing — with a more opportunistic culture[62]. This may explain why institutional incentive structures affect basic research outcomes, as discussed in the previous section.

Better understanding of psychology and behaviour can itself lead to valuable institutional innovations. Individual choices — including critically important choices around savings, insurance, healthcare and education — can be powerfully shaped by seemingly non-rational psychological factors, with often immense welfare implications[63]. Behavioural economists (like those in the UK's Behavioural Insights Team) use psychological research to design simple and low-cost interventions to spur sometimes dramatic changes in behaviour, which can provide rich and important examples of innovation:

- making organ donor programs opt-out instead of opt-in (which should have no effect in the standard economic view)[64];
- changing the wording on tax payment forms to prime social norms[65]; or
- regulating the possible structures of credit card and banking fees in order to prevent predatory practices[66].

One of the most important insights concerns the value of experimental policy design, where randomized control trials are used to identify the most effective approaches[67]. Given the importance of incentives, social norms, and other complex behavioural factors for innovation decisions, innovation policymaking should become behaviourally literate.

(iv) Governments

Governments have a critical and multifaceted role to play in innovation, especially at the medium and macro scale. Among other things, there is a strong case for governments to: shape the formation of human capital through education and training[68]; carry out and finance basic research in universities and research centres; support institutions to link universities and research institutes with industry; uphold an efficient, effective and appropriately constrained intellectual property regime[69]; and provide targeted support for innovative activity, both its supply (e.g. grants and loans for demonstration and deployment of new technologies) and demand (public procurement, fiscal policy, regulations/standards, fostering new social norms/values)[70].

> **Psychological factors shape the decisions people make about innovation.**

However, governments are ill suited to intervening in the micro-details of innovation processes, and should avoid being excessively prescriptive. For example, specifying outcomes that researchers are to achieve is usually inappropriate given the impossibility of predicting them. Similarly, constraining researchers within rigid timeframes, or within incentive systems that demand "breakthrough" outcomes or commercialization, is likely to impair researcher creativity. Once the innovation infrastructure has been provided, and, broad national priorities set, innovators should be allowed substantial leeway to pursue the questions they believe to be important in the ways they see fit[71].

Governments have an especially important role to play in carrying out and financing basic research and development. Due to the public goods aspects of basic research, and governments' high capacity to tolerate uncertainty and delayed returns on investment, governments are uniquely suited to carrying out (e.g. through government research institutes) and financing (e.g. in universities) basic research. In the UK, the foremost funders of basic research are the seven Research Councils, which draw around £4.5 billion, or approximately 0.2% of annual GDP, in annual government funding. The rate of social return to R&D is extremely challenging to calculate, but importantly, research typically finds extremely high rates across a variety of industries—e.g. from 35-100% is typical[72]. This suggests there is considerable scope to increase basic research spending and reap large rewards.

Government funding of innovation can usefully extend beyond "letting a thousand flowers bloom", and governments have actively shaped the development of many of today's most important technologies. In many areas it is sensible for governments to focus on facilitating innovation by others. This includes looking to foster outcomes rather than details of methods or technologies and avoiding "picking winners" in the form of specific firms and sectors as much as possible, and taking care to avoid government failure. Yet sometimes it is impossible to avoid making judgements about innovation support priorities (e.g. in areas of national priority where the private sector is unwilling or unable to undertake the capital expenditures and bear the uncertainties and risks). For example, research at large-scale physics experiments, such as the Large Hadron Collider at CERN[73] or developing nuclear fusion, cannot be achieved without some involvement and focus on particular technologies or methodologies. There are, moreover, numerous cases in which state institutions have proactively engaged and inspired scientists and engineers to envision and invent some of the most important breakthrough technologies of the last half-century[74]. For example, the US Defense Advanced Research Projects Agency (DARPA) played a vital role in organising and funding the development of computers, electronics and the internet in the 1960s and 1970s[75]. The US Government is currently playing a similar role — financing and coordinating a group of leading innovators — in the development of nanotechnology[76].

State institutions and policies can provide the patient, long-term finance needed for the demonstration and early commercialization stages of innovation. New technologies typically face funding gaps as they proceed from development to demonstration and commercialization, including early-stage deployment, when production costs are high, private returns are difficult to appropriate and commercial finance is difficult to obtain. State institutions and policies can help to overcome this gap by providing long-term, 'patient' capital. One area where this is especially important is in clean energy technology, largely because demonstration and commercialization is so capital-intensive. As we mentioned previously, state development banks can operate in sectors or themes that still have private sector barriers. For example, the China Development Bank, German KfW and Brazilian Development Bank (BDNES) are leading state financiers of clean technology firms[77], and the UK Green Investment Bank was recently established to play such a role in the UK[78]. The Catapult Centre example discussed earlier (see Box 1) provides a different model for government financing in the demonstration/commercialization stage.

Government policies and regulations influence the direction and volume of demand for innovative products and services. Governments can grow (and hinder) market demand for innovations by using regulation, taxes and other policies. Regulation constrains the choices that producers and consumers can make. Market instruments, such as taxation, tradable permits or market-based subsidies, change the price of certain activities/products and therefore change the quantity demanded. Both types of policy instruments provide strong incentives for firms to innovate. For example, regulated standards for phasing out lead in petrol spurred the development of unleaded petrol[79]. Meanwhile, market incentives for the supply of clean energy in the form of purchase guarantees and premium payments (e.g. feed-in-tariff schemes) have proved effective at increasing demand for renewable energy infrastructure in countries such as Germany and Denmark (especially solar PV and wind), fuelling innovation and rapid cost reductions through incremental innovation (learning-by-doing), economies of scale and industry competition[80].

Finally, governments can also shape many markets through their own procurement policies and practices (e.g. for computer hardware and software, and sustainable buildings and appliances), since they are themselves large consumers.

Governments can also innovate in the provision of public services and the design of government institutions and policies. Governments are important providers of public services that can be improved through innovation. An example is the development of a highly cost-effective Bus Rapid Transit (BRT) system in Bogota, Colombia and needed government action on the use of road space to do this[81]. Following Bogota's success, BRT systems were introduced in a number of other Latin American countries and have since spread to more than 160 cities around the world, with the aid of the C40 Cities Climate Leadership Group – itself a good example of (city) government-led institutional innovation[82].

Government (in)action can introduce policy risk that hampers desirable innovative activity. Badly designed or implemented government policy can discourage private innovation by raising the policy risk associated with investment. For example, making frequent changes to funding mechanisms for clean technologies undermines investment in this important field of innovation (especially when the changes have a retrospective effect, as with the changes to Spain's feed-in-tariff scheme)[83]. Public institutions can play an important role in mitigating policy risk in particular fields. For example, the UK's National Institute for Health and Care Excellence (NICE) provides national standards and guidance in healthcare, bringing transparent criteria and analysis, stability and consistency to national health policy.

On the other hand, antiquated regulations, and unreasonable regulatory inertia, can hold back the diffusion of innovative products and business models. An example of the latter concerns regulations associated with vehicles in many parts of the world, which have been slow to adapt to new business models associated with the sharing economy (e.g. taxi and parking regulations inappropriate for car-sharing services) and to battery-powered vehicles (e.g. zoning regulations hampering the growth of battery charging and switching infrastructure, or making it difficult to connect electric vehicles to the energy network in the first place; and energy pricing structures ill-suited to encouraging the benefits of electric battery storage of electric vehicles)[84].

Governments can influence the utilization of innovations, and thereby respond to the risks posed by innovations themselves. Not all innovations produce social value[85]. To take a recent example, the financial derivatives associated with sub-prime mortgages in the US housing market were certainly an innovation. But these took concentrated risks and made them systemic, triggering the Global Financial Crisis. Many other innovations pose significant risks to security, human health and the environment. Government therefore has a role to play in regulating the utilisation of innovation.

C. CONCLUSIONS

Innovation touches on all economies, all sectors and all institutions. It should be interpreted broadly as new ways of providing and creating services and products, as well as new services and products themselves. It is likely to continue to be the single most important source of economic growth for the UK, and a central focus of any discussions of our comparative advantage. Innovation in services — which account for nearly four-fifths of the UK economy and are experiencing high growth in productivity — will be particularly important to the UK's future economic prosperity. These facts should be reflected in government thinking — and ambition — for policies intended to foster innovation.

Innovation policy is difficult to get right. Human rationality is bounded and innovation, along with the factors determining it, can be complex: Knightian uncertainty is ubiquitous, time horizons may be long, and the evidence about what works can be difficult to interpret[86]. Learning from past experience in order to improve the innovation system is difficult, and efforts to influence the system carry their own risks. We should, therefore, be sceptical about simplistic approaches, and take a broad view of process, products and sectors. We should not insist on one theory of innovation, or disproportionately favour one kind of innovation (breakthrough vs. incremental), one phase of the

CASE STUDY

L'AQUILA

Chris Whitty (Chief Scientific Adviser, Department for International Development) and Marcus Besley (Government Office for Science)

In the early hours of 6 April 2009, an earthquake devastated the medieval city of L'Aquila in central Italy. L'Aquila's residents were used to living in an earthquake zone, and to taking precautions such as sleeping in the car during periods of seismic activity. Yet this time 309 people were killed.

Six days earlier, a meeting of earthquake experts had been held in L'Aquila. In the margins, the deputy head of Italy's civil protection department was filmed saying that the situation was favourable, and agreeing that everyone should "go and have a glass of wine". He and six scientists were later prosecuted for involuntary manslaughter, on the claim that 29 of the deaths were a direct result of them underestimating and inappropriately communicating the risks of a major earthquake. All seven were convicted and sentenced to long prison terms, although the six scientists have recently had their convictions overturned.

Those verdicts raised potentially serious questions for scientific advice in other countries. In the UK, government relies on having the best science to hand, including in emergency situations. This happens through multiple mechanisms: many scientists are employed as civil servants or serve on advisory committees, but external scientists also lend their expertise less formally, as good citizens.

As a consequence of the trial, the Government Chief Scientific Adviser asked a group of departmental Chief Scientific Advisers to look into the implications of the L'Aquila case for the UK. This resulted in specially-commissioned advice from government lawyers, an independent barrister, and an expert in Scottish law. The advice is due to be published towards the end of 2014 on the GOV.UK website. It summarises the current position in UK law, and covers all scientists providing advice to the government, whether or not they are actually employed by government.

The lawyers considered the various legal routes, both civil and criminal, by which an allegation of negligence in scientific advice could be pursued. Assuming that the contested advice was given professionally, honestly, and in good faith, they concluded that there are multiple legal tests and high bars for any such action to succeed against an individual scientist in the UK, and that the courts are alive to the need not to stifle or discourage valuable research.

For example, the infamous weather forecast before the Great Storm of 1987, in which the public were told not to worry about reports of a hurricane, did not lead to a L'Aquila-style case. It would be hard to argue that such a situation should do so.

This should provide reassurance against the scenario of scientists around the country being hit with a flood of legal claims, either civil or criminal. Nonetheless, the lawyers noted that in a case of grossly negligent scientific advice, prosecution for manslaughter (culpable homicide in Scotland) is theoretically possible. It is important that scientists communicate risk well, saying enough to be helpful while avoiding blanket statements that may come back to haunt them.

There has yet to be a test case analogous to L'Aquila in the UK. But there is a need both to encourage appropriate professional standards, and to protect scientific advisers who make a sensible best estimate that may later turn out to be wrong. The government community of Chief Scientific Advisers is continuing to develop and share good practice in this area.

innovation process, or one sector or set of activities. And we should be wary of imposing perspectives or policies that may skew innovation priorities in undesirable ways.

Yet, there are data to be studied, rich lessons to be learned, and more benefits to realize. Nevertheless, policy has to be made and the evidence we have tried to assemble is, we would argue, helpful and valuable. This chapter has sought to capture some of the most important evidence from economics and other social sciences. Understanding what has made innovation work or fail can play a valuable role in influencing what can make it work in the future.

Drawing together the conclusions of this chapter, we identify four pillars or foundations of a first-class 'innovation infrastructure':

1. **The first pillar is a high-quality, merit-based system of education and training.** Its importance is difficult to overstate. The UK possesses some advantages in top-tier institutions, but there is increasing competitiveness in universities worldwide, and these advantages require constant investment to be maintained. Further, the UK faces a serious risk of falling behind rising stars like South Korea in crucial population-wide competencies. Too many children experience low-quality schooling, which presents large economic costs for the long-term. On the national budget, education should be viewed not as an expenditure but as one of the highest-return investments available.
2. **The second pillar is substantial investment in basic research.** Governments are able to manage levels of risk and time horizons on investment, which the private sector may find more difficult. This gives governments a special and indispensable role in supporting basic research. The UK government should take great care to ensure that its comparative advantage in basic research is not overwhelmed or weakened by understandable enthusiasm for commercialization in universities. By increasing its support for basic research, the UK government can expand the horizon of future growth.
3. **The third pillar is the system of government-managed incentives that promote innovation via markets and entrepreneurship.** First is an efficient and effective, and appropriately constrained, system of intellectual property rights. The system is due for an evaluation, with sensitivity to industry-specific needs. Secondary institutions include: systems and incentives for technology transfer that promote the diffusion of knowledge; policies to assist small firms to access licensing patents; regimes of taxes, subsidies and regulations that do not arbitrarily discriminate in fostering new firms and new ideas; and state development banks to provide patient, long-term capital to innovators. The details matter, and we have tried to indicate how they should be examined.
4. **The fourth pillar is the setting of, and investing in, national innovation priorities.** One clear priority is resource management: increasing the productivity of energy, land and other natural resources, and minimising greenhouse gas emissions. The design of cities, as drivers of resource consumption as well as creativity and economic growth, is especially important. These are areas where markets and prices alone are unlikely to capture the interdependence and public nature of many of the key services and outcomes. They are also areas where benefits are likely to be fairly long-term. Other priorities should be determined through assessment of strategic advantages, engagement with leading innovators, and the generation of aspirational technology roadmaps.

Finally, we identify four guidelines for the process of innovation policymaking:

1. **Take a long-term, systems view of innovation.** This means avoiding narrow, compartmentalist views of policymaking that focus on just one sector and/or a short time horizon. An effective policy mix will take account of each part of the innovation system; will take advantage of, and be wary of, feedback between system components; and will appreciate that actions today have critical long-term implications. This type of approach will help lessen the scope for government failure that can arise from bureaucrats and politicians fiddling with processes they fail to understand. On the other hand, the potential market failures are so important, and the subject so vital for growth, competition and living standards, that government *disengagement* is not a sensible approach.
2. **Consult widely.** Innovators' needs vary widely across industries and institutions, and across parts of the innovation chain. Innovators may also recognize the potential for unwanted impacts, or detect them in practice, before policymakers are able. Ensure that important voices which may not be sufficiently prominent, such as those of small firms, teachers and of research scientists, are given weight.
3. **Adopt a learning approach to policy design and evaluation.** This means trialling different approaches, and improving the collection of data on inputs, processes and outcomes as well as feedback from key actors. A range of innovation policy problems could benefit from this approach, including the design of grant application rules for basic research, of the school system, and of institutions for fostering university-industry linkages. Accompanying this should be a sustained investment in research on innovation itself. Such research is not easy given that the subject is about learning, covers many disciplines, and the outcomes may be uncertain and long term: but it is very important.
4. **Ensure that innovation policies are transparent, consistent and stable over time and investment.** Innovation will be more likely to proceed where actors are more confident rather than more confused, and where evaluations of sovereign and policy risk favour commitment rather than withdrawal. Where future flexibility may be required, as is often the case for experimental policy, ensure that processes are specified in advance. Certainty is not on offer, but unnecessary uncertainty can be reduced. A fundamental lesson is that government-induced policy risk can be a major deterrent to both innovation and investment.

Ian Goldin (Director of the Oxford Martin School, and Professor of Globalisation and Development at the University of Oxford)

CHAPTER 2: FUTURE GLOBAL TRENDS IN INNOVATION

Innovation and the associated flow of ideas, products, services and people are likely to continue to provide significant opportunities for progress — but these same trends are also likely to be associated with increasing systemic risk, complexity and uncertainty.

1. TRENDS IN INNOVATION AND GLOBALIZATION

Globalization and innovation are transforming the way we live. The pace of change and increasingly interconnected nature of our societies makes predictions even more hazardous than in the past. Future developments are unlikely to reflect a continuation of past trends. The only certainty about where the world is headed is that it will be full of surprises. Innovation in products, services and processes will yield extraordinary benefits for humanity, not least in the areas of health and medicine. Negative shocks are also likely, with the future characterized by increased systemic risk, and a higher likelihood of potentially destabilizing and even catastrophic events.

The integration of the global economy has been associated with increased access to ideas which allow for the transformation of both economic and social systems, as well as access to the products, goods and services which enable improvements in livelihoods. Recent decades have been associated with the most rapid decline in poverty in history and remarkable improvements in health outcomes for billions of people.

Not everyone is benefitting equally from these concurrent trends of innovation and globalization: globalization is uneven, and as many as 1.5 billion people have not accessed the improvements that globalized innovation affords[1]. Within almost all societies, inequality in access and outcomes is growing, as those able to benefit from change accelerate ahead of those locked into increasingly outmoded systems. A more interconnected, mobile and educated world yields many positive benefits. However, it also places a greater premium on remaining up to date and reinvesting in health, education, infrastructure and other determinants of economic and social outcomes. The more rapid the innovation, the greater is the requirement for investment and agility in order to stay abreast. For particular individuals or communities, such as the elderly, who do not have the necessary capabilities to remain current, the pace of change may provide a threat to at least their relative place in society.

In the first section of this chapter, we consider a number of the drivers of technological innovation and identify a sample of the major trends currently transforming the global landscape, including globalization, rising levels of education, and economic and demographic change.

As our world becomes increasingly interconnected and complex, new dangers also emerge: we become increasingly vulnerable to systemic risks. To reap the benefits of our interconnected and innovative world, we must address and mitigate these risks. This will be the subject of the second part of this chapter.

1.1 Technological change

Elderly people today have seen revolutionary technological change during their lifetime. Yesterday's science fiction is today's reality. In 1980, we barely understood genes, now we can manipulate them. In 1990, a mobile phone was the size of a brick, now the nanotechnology industry is creating electronics that float on air and that you could not see without a microscope. Twenty years ago, there were fewer than 3 million people with internet access; now there are nearly 2.5 billion. Genetic modification can give rabbits an eerie green luminescence. Robots make cars. Guns can be manufactured with a 3-D printer.

Technology is a double-edged sword. It unleashes new potential and has been central to human progress. It can level the playing field, helping the emerging economies of the world to catch up more swiftly, and continues to lift more and more people out of poverty. However, technological change also can wreak havoc, as exemplified in the unchecked growth of derivatives, which Warren Buffet called 'weapons of mass destruction' in the financial sector.

Forecasting beyond the near future, however, is a foolish effort. Google was founded as recently as 1998, Facebook in 2004 and Twitter in 2006. What new technologies will define our lives in 2030 or 2050? We cannot be sure. But we can be reasonably confident that the future will be influenced by a number of current technological revolutions: nanotechnology, biotechnology, mobile networking, a faster and more accessible internet, 3-D printing, the spread of sensors, and machine learning. These will affect our daily lives, the operations of companies, and the prospects of global markets.

Gordon Moore's 1965 forecast that computing power would double about every two years has proven true, and will likely continue to do so for the next several decades[2]. Although there are many questions regarding certain dimensions of the future of processing speed, not least with respect to heat generation and energy efficiency, the continued exponential growth in processing power is likely to continue to transform all our lives, and also has fundamental implications for our economies and society.

A 2013 report by the McKinsey Global Institute estimated that technological improvements will increase productivity by as much as 25% and will generate a predicted $3.7 to $10.8 trillion for the world economy by 2025 (ref. 3) . A number of recent technological advances already have had a global impact. The number of mobile phones worldwide exceeds the total population[4]. Indeed, more people have access to mobile phones than to working toilets, illustrating the depth and breadth of saturation in the mobile phone

As our world becomes increasingly interconnected and complex, we become increasingly vulnerable to systemic risks.

market[5]. The African continent has twice as many mobile phones as the United States[6]. In some areas, such as mobile financial services, a number of African countries are global leaders, illustrating the potential of new technologies to disrupt older systems and leapfrog ahead of older fixed line phone systems or traditional banking services in rapidly growing emerging markets[7]. As digital access increases, it is estimated that four billion people will be online by 2020, using up to 50 trillion gigabytes of data[8].

Meanwhile, improvements in artificial intelligence increasingly allow robotic processes to augment or replace tasks previously undertaken by people. Apple, for example, is planning to install over a million robots in its China manufacturing plants to produce the iPhone[9]. Artificial intelligence is permeating a growing range of jobs, and has significant implications for skilled as well as unskilled workers. In medicine, for example, the New York Memorial Sloan-Kettering Cancer Center has used IBM's Watson supercomputer to survey hundreds of thousands of medical reports and millions of patient records to improve its oncology care[10].

Analysis suggests that automation may lead to as many as 47% of jobs being lost in the United States and a similar proportion in the United Kingdom as a result of computers replacing human capabilities[11]. While this raises major concerns regarding employment, these and other technological changes are likely to be associated with increased productivity and new types of employment, as with previous technological revolutions.

If knowledge is power, digital sensors are poised to become the data providers of the twenty-first century. In electrical power systems, sensors that provide real time data to processing centers and automated control systems can reduce electricity usage and waste, improve supply efficiency, and isolate electrical failures, thereby minimizing the impact of blackouts. Smart grid technology was deployed recently in London, Houston, and Singapore to streamline traffic. Control routing centers effectively decreased average commuting times by 10-20%, enhancing productivity for workers. This technology is also being deployed to farming, with real time crop moisture readings ensuring that drip irrigation is able to maximize efficiency, a critical component in feeding a substantially growing population.

In addition to infrastructure improvements from smart grids and sensors, automated driving is becoming a reality. An automated Google car has already driven 300,000 miles on American roads with no accidents. Driverless cars have multiple benefits. They free up the would-be driver to other tasks. This is a substantial improvement, given that the average American car commuter spends 750 hours per year driving, while the average European car owner spends about 300 hours per year behind the wheel. Additionally, automation with sensors will allow cars to drive far closer together, reducing wind drag (allowing lower fuel consumption per mile traveled) while also diminishing congestion without the need for additional infrastructure. Finally, given that 1 million people die in traffic accidents per year — with 70-90% of those caused by avoidable human error — automation could also improve safety on the roads substantially.

Artificial intelligence is permeating a growing range of jobs.

3-D printers are machines that print out physical objects rather than words on a page. Using design blueprints, they print out a substance — currently most often a plastic —with layers upon layers that eventually form a tangible object. The scale of these items is no longer small. A Dutch firm is currently in the process of creating an entire house from specialized 3-D printers. 3-D printing is also being used to produce a car, the Urbee 2.

3-D technology is transforming a variety of processes in product design, development, and manufacturing. It rapidly is becoming easier for both established companies and start-ups to produce prototypes for new items, reducing design costs and allowing better testing and design tweaking before products come to market. Moreover, products can easily become customizable to the specifications of individual consumers at low-cost. UPS, for example, is introducing 3-D printers to several of its stores in the United States, allowing consumers the option of creating their own objects easily.

Technology is also emerging that gives scientists the ability to 3-D print living tissue, with printers emitting cells rather than ink. The possibilities of this nascent technology are wide-ranging; already, custom-made cartilage has been printed that might be used to repair damaged knees, and there is the possibility that eventually doctors will be able to 3-D print customized organs.

This technology, while impressive, also presents perilous new frontiers. With production passed onto consumers easily, there is substantial opportunity for counterfeit products, lack of quality control, and safety issues. For example, a 3-D printed gun has already been produced and successfully fired. Piracy is also a major concern.

Nanotechnology refers to products and properties that exist and emerge at scales of less than 100 nanometers. For comparison, the average human hair is 100,000 nanometers wide. In nanotechnology, the basic building blocks are individual molecules and atoms. The potential economic impact of this is far reaching.

Nanotechnology could be used to create disposable or digestible wireless devices, for example, with applications including the fabrication of digestible transmitters attached to tablets to monitor the use of prescription medicines.

In health care, nanotechnology is being applied in a variety of ways. Researchers have developed ways to use gold nanoparticles as cancer "sniffers" that are not only able to detect cancer before visible symptoms or tumors exist, but also can pinpoint exactly which kind of cancer is present in the body. Nanoparticles generated by IBM are able to kill antibiotic-resistant bacteria, attaching to the bacteria and poking tiny holes in it — potentially a critical breakthrough in the fight against global disease.

Recently discovered properties of absorption at the nano-scale also offer substantial applied value. The low-cost nanocarbon graphene can be used as a filter to remove salt from saltwater, sifting out the salt ions while letting the water molecules pass through. This method could be used to desalinate seawater, and improve the prospects for recycling, a key to overcoming global water shortages in an era where already 780 million people do not have access to clean, safe drinking water.

In addition to these technologies, there are new frontiers in nanotechnology that have not yet been realized but are both plausible and revolutionary. For example, Eric Drexler of the Oxford Martin School argues that molecular-level manufacturing could dramatically transform global production. The economic possibilities associated with nanotechnology are hard to calculate because the technology is advancing so rapidly. Nanotechnology may well have a revolutionary impact, ranging from cancer treatments to everyday use. However, as in so many other revolutionary areas of progress, the potential negative and harmful applications are inadequately understood, and these, together with the consequent regulatory implications, need urgent attention.

The human genome was successfully mapped and declared complete in 2003. The implications have been impressive. Scientists can now use genetic screening to determine whether an individual patient is prone to a wide range of genetic diseases. Such screening is becoming increasingly affordable

Genetic material can also be used to treat patients. Gene therapy has already effectively cured patients with hemophilia, a debilitating blood disorder. The ability to manipulate the genetic code will open new frontiers in research and ethics. It will soon be technologically possible for parents to choose desirable traits using genetic screening in combination with in vitro fertilization. This is a particularly stark reminder that as we enter the Age of Mastery, we must tread carefully. Even when the economic incentives and technological breakthroughs allow advancement, they may be ill advised. In addition, as we highlight in our discussion on systemic risks, the potential abuse of these technologies to create new biological pathogens reminds us that all technologies are potentially dual use.

As economic growth continues around the world, our energy needs are also expanding. New technologies are under development to make previously uneconomical resources fit for extraction, reduce the carbon emissions of current extraction methods, and enable renewable sources of energy. The combination of horizontal drilling and hydraulic fracturing makes it possible to reach oil and gas deposits that were known to exist in the United States and other places but that were not economically accessible by conventional drilling methods. Citi estimate that the cumulative impact of new production, reduced consumption and associated activity may increase real GDP in the United States by 2% to 3.3%, or $370-$624 billion (in 2005 $) respectively[12]. The growth in this energy source has spillover effects on the petrochemical industry, improving the viability of Gas to Liquid plants (GTL) currently under consideration. With large payoffs at stake there are further new types of reserves, including coalbed methane, tight sandstones, and methane clathrates that could potentially usher in another energy revolution.

Industrial processes will need to make technological changes in order to meet domestic and regional targets on carbon emissions reductions. The European Union aims to reduce carbon emissions by 80% by 2050 from 1990 levels. Each industry is called upon to develop techniques that will aid in achieving this target. The steel production industry is one of the industries that is likely to pilot and experiment with new carbon capture technology (CCS). The technical and economic feasibility of achieving these efficiency gains rests on incentives for further research and funding for these types of technologies. Already it is clear that price incentives alone from the EU carbon-trading scheme will not be enough to prompt such investment.

Renewable energy presents a way for society to move from being driven by processes that strip the earth of its natural resources — which potentially creates political conflicts and pollutes the atmosphere — to a self-sufficient endless supply of energy. Such promise holds great economic benefits if it can be unlocked, but the cost of energy generation from these methods is still much higher than oil, coal and gas. As a result, the development of the sector is highly dependent on subsidies and high carbon taxes on polluting sources of energy. Despite mixed global policies over renewables, the investment costs for solar photovoltaics and onshore wind have fallen rapidly. Beneath these gains lies an uncomfortable truth: the carbon intensity of the global energy supply has barely changed in 20 years, despite successful efforts in deploying renewable energy. Investment in this sector is likely to increase in order to facilitate the transition to a more sustainable future.

The rate of global change is accelerating, largely due to the breakneck pace of technological innovation. The economy will be transformed in many ways, from expanded existing technology, innovative new methods such as 3-D printing, and the no-longer-science-fiction frontiers of

> **Many of our greatest inventions have come through partnerships between states and corporations.**

nanotechnology and biotechnology. Developing economies — and their billions of people — will enter the digital age, lowering barriers to growth and unlocking an enormous amount of creative potential. Developed economies will continue to drive innovation and begin competing with developing economies to harness the fruits of that innovation. Companies and countries that are successfully able to invest in and harness emerging technologies will be better suited to thrive in this new era.

Policy makers and societies need to prepare for the inventions that will emerge and disrupt the global economy. Not every invention will change the way society functions nor even work at all. Technological progress at times rises out of the ashes of dead-end research programs, useless inventions and failed commercial ventures. Many of our greatest inventions have come through partnerships between states and corporations. The American railroad network and the underlying infrastructure of the Internet were initially funded by federal initiatives. Investors and entrepreneurs joined these initiatives and have made them into what they are today, huge communication and transportation networks. In order to provide these for future generations, policymakers need to decide how to partner with business to invest in new forms of infrastructure and education. In particular, lawmakers and regulators are faced with a particularly difficult challenge of new moral dilemmas relating to the human condition and the protection of citizen's rights in new domains, where technological progress is leaping ahead of our knowledge of its potential applications and consequences.

1.2 A more global world is a more innovative world

The contemporary period of economic integration was inaugurated with the General Agreement on Tariffs and Trade (GATT) in the aftermath of the Second World War. From 1950 to 2007, global trade grew at an average pace of 6.2% per year[13], and GATT's successor organization, the World Trade Organization (WTO), now has 159 country members. The 2012 accession of Russia brought all of the major global economies into the WTO fold. India, not usually thought of as a particularly strong proponent of open borders, reduced its peak tariffs on industrial products from over 200% in 1990 to less than 10% in 2009 (ref.14), and China has seen a similarly radical reduction in its restrictions on trade. The flows of products, services and people across borders have been further facilitated by regional agreements and groupings such as NAFTA, APEC and European Union's Single Market Programme.

Meanwhile, international agreements such as the 1989 Montreal Protocol and the 2003 Framework Convention on Tobacco Control have yielded significant results in mitigating ozone emissions and improving public health. International coalitions and partnerships have brought stakeholders together to find creative new solutions to major global problems[15]. The Intergovernmental Panel on Climate Change (IPCC), for example, collates inter-disciplinary research on climate change (see case study). The IPCC's major 'assessment' reports are collaborative

Policy makers and societies need to prepare for the inventions that will emerge and disrupt the global economy.

projects and include researchers from across the scientific community as well as policymakers. In the sphere of public health, the Global Alliance for Vaccines and Immunisations (GAVI) and the Global Fund to Fight AIDS, Tuberculosis and Malaria bring together representatives from government ministries, donor organizations, civil society, the private sector, and the academic community. According to their own estimates, GAVI and the Global Fund have worked to prevent 5.5 million and 6.5 million deaths respectively since their inception[16].

Along with goods and ideas, people are becoming increasingly mobile both within and across countries, creating networks of collaboration and 'brain circulation'. International migration increased 42% in the first decade of the twenty-first century[17], and by 2010 well over 200 million people resided outside of their country of origin[18]. People are moving within countries as well, notably from rural to urban areas. 2008 marked the first year that the number of urban dwellers surpassed the number of people living in rural areas worldwide[19].

A mobile population leads to increases in productivity, wealth and innovation. Because of their heightened mobility, migrants help to stabilize economies through their willingness to move in response to labour market fluctuations[20]. Moreover, flows of people facilitate innovation by connecting people with opportunities. Evidence from OECD countries suggests a strong connection between migration and GDP growth and total employment in recipient countries[21]. In the United States, United Kingdom and the European Union, up to a third of economic growth has been attributed to migration by some[22]. In addition to filling jobs in low-wage sectors, migrants are a key component of innovation in research and technology sphere. In the United States, migrants are only 12% of the population, but they file more than 40% of patent applications annually every year[23]. Evidence from the US also suggests that a higher concentration of migrant employees in a particular sector correlate with increased patent filings by natives[24]. It is not surprising, then, that high concentrations of migrants can be found in the most dynamic US industries.

1.3 Education and growth

The future prospects for continued innovation also look positive in the context of the improvements in quality and access to education that are occurring worldwide.

The number of children not attending school has dropped from 108 million to approximately 60 million over the past two decades[25]. Globally, 91% of primary-school-age students and 62.5% of secondary-school-age students were enrolled in school in 2010 (ref.26). Global tertiary enrolment has also risen, from 19% in 2000 to 29% in 2010 (178 million students worldwide). Though the percentage of students enrolled in tertiary education continues to vary significantly between countries and regions[27], it is predicted that global enrolment in higher education will increase by almost 50% to 262 million students by 2025, driven primarily by increases in educational attainment in China and India[28].

Students are not only attaining higher levels of education, but they are also moving to access this education. The number of university students studying abroad doubled during the first decade of this century and stood at almost 4.3 million in 2013 (ref.29). With new innovations like Massive Open Online Courses (MOOCs) altering the educational landscape, growing numbers of people around the world will have access to the best academic institutions.

With these increases across all levels of educational attainment, growing numbers of young people will develop the foundational, technical and transferable skills that can make the global population more flexible, adaptable and innovative.

1.4 Addressing demographics through innovation

Our demographic future is remarkably uncertain. The UN population forecasts for 2050 range from a high of around 11 billion people to a low of less than 9 billion. Nevertheless, one thing is clear: the global population is becoming dramatically older. Changing demographics alter the global economy and will have a powerful influence over markets and investment opportunities.

The combination of rising demands on state and private

CASE STUDY

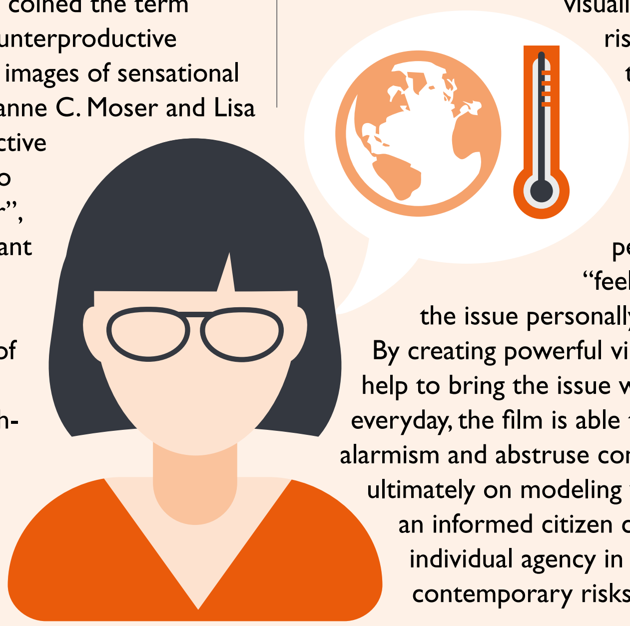
COMMUNICATING THE RISK OF CLIMATE CHANGE

James Lyons (University of Exeter)

Environmental scientists have long acknowledged that global climate change is a "highly complex and global elusive hazard", characterized by "system lags and lack of immediacy"[1], which makes it particularly difficult to convey to lay people. Investigating public perceptions of climate change, Thomas Lowe and colleagues found that this challenge is compounded by the fact that "people feel overwhelmed by shocking images and, although it heightens their concern, it also reduces their self-efficacy to take action and lessen these events through personal action"[2].

Gill Ereaut and Nat Segnit have coined the term 'climate porn' to describe the counterproductive impact of unintentionally thrilling images of sensational environmental disaster[3]. If, as Susanne C. Moser and Lisa Dilling propose[1], "the goal of effective risk communication is precisely to support proper adaptive behavior", then it seems particularly important to use strategies cognizant of the role played by images and visual metaphors in the understanding of climate change risk.

An instructive instance of a high-profile communication campaign around climate change is the award-winning documentary An Inconvenient Truth, presented by former US Vice President Al Gore. Its approach to risk communication is highly visual, employing numerous graphics, graphs, video clips and charts as part of the slideshow that forms the backbone of the film. But just as important to its approach is the way that it utilizes what psychologists Amos Tversky and Daniel Kahneman have termed the "availability heuristic" in employing imaginatively vivid and personalized examples of everyday risk arising from Gore's family life, from automobile accidents to smoking-related lung cancer[4]. In the face of an issue that can seem remote and abstract, this emphasis on visually compelling everyday risk seeks to recalibrate the audience's own risk perception, embodying what Paul Slovic, in his work on the affective dimensions of risk perception, terms the "feeling of risk" — making the issue personally and palpably graspable[5].



By creating powerful visual metaphors that help to bring the issue within the ambit of the everyday, the film is able to sidestep paralyzing alarmism and abstruse complexity, concentrating ultimately on modeling what it means to be an informed citizen capable of exercising individual agency in relation to an array of contemporary risks[6].

pensions, a surge in health care costs, and a smaller labour force to pay for these needs creates what may be called "a perfect storm" of demographic change. The impact of the storm will be uneven. It will hit some places hard while missing others completely, before returning with a vengeance in decades to come. Everywhere, the demographic storm can be weathered, even harnessed by businesses and governments alike with the right preparations and policy adjustments. Governments and investors ignore demographic trends at their own peril. While demography is not destiny, demographic transitions offer tremendous opportunities for shrewd planners in business and government.

While globalization links us all together, the advanced economies of the world are becoming the silver economies as birth rates plummet, Baby Boomers mature, and people live longer. There were 200 million people over the age of 60 in 1950. Today, that number has grown to nearly 800 million. By 2050, it is projected to stand at 2 billion. Age pyramids are becoming age funnels, and they are siphoning off economic power from the dominant economies of the late twentieth century.

In emerging markets, the storyline is inverted. Many countries are just cracking open the 'demographic window', a period when a solid base of labour will support a much smaller population of dependents. This window is projected to remain open until 2020 in China, 2025 in Brazil, 2030 in Turkey, 2035 in Indonesia, 2040 in Malaysia, and 2045 in India[30]. When the window is open, the country is primed for growth — though it will take more than good demographics to ignite this engine of growth.

Like all of these trends, new opportunities exist side-by-side with new challenges. If ageing, advanced economies do not adapt to face demographic realities, they will stagnate. Pension structures must be reformed, health care costs need to be reigned in, retirement ages need to be extended, and workplaces will need to find innovate ways to keep their employees working productively for longer. Finally, advanced economies that are open to migration to plug labour gaps will be better equipped to thrive in the twenty-first century than those that are closed off and exclude new workers. As a result of the lagged effects of demographic change, we can be reasonably certain about the contours of demographic shifts; what we do not know is how well the new silver economies will adapt or how well the young emerging markets will harness their demographic potential.

Global enrolment in higher education will increase by almost 50%.

Many countries are just cracking open the 'demographic window'.

With a dearth of people, the economic impact of the demographic problems facing developed nations can be partially mitigated through innovation and the creation of new labour-saving technologies to promote productivity growth. BMW, for example, has developed robotic technology adapted to older workers to compensate for their diminished strength relative to younger workers[31].

1.5 Economic Prospects

It is projected that the world will see steady economic growth of 3–4% until 2050 on the global scale. However, this growth will not be evenly distributed and will be concentrated in the developing economies. China and India are the obvious examples, and are set to become the first and third largest economies in the world over the next three decades. Some predict that by 2020, the Emerging 7 (China, India, Brazil, Russia, Indonesia, Mexico and Turkey) will have acquired a greater share of the world's GDP than the current G7 (Canada, France, Germany, Italy, United Kingdom and the United States)[32]. As these economies grow, they will transition from export to consumer markets. Expectations of growth in the advanced economies, particularly in Europe, should be modest at best.

There are a few safe bets and a few wild cards in the economic game of the twenty-first century. The safe bet is that low- and middle-income countries will drive global growth, while unfavorable demographics and macroeconomic weaknesses drag down the prospects of the major developed economies. Everything else is less certain. Even though developing countries are primed for a major economic expansion, countries that create the necessary institutional infrastructure for growth will be far more successful than those that do not implement overdue reforms. Likewise, while Europe, the United States, and particularly Japan will find themselves facing daunting demographic hurdles, the advanced economies could use innovation and more liberal migration policy to dampen the impending economic slowdown. Among the major wildcards are uncertainties regarding which emerging markets will put in place the right policies to take advantage of favorable demographics and create a market ripe for investment, and which advanced economies will be savvy enough to overcome the inevitable barriers to robust growth. Either way, the overall picture is certain: growth will happen much more in the developing world, and firms and investors operating in developed economies would be wise to seek opportunities for more substantial returns in newly emerging markets, the powerhouses of the twenty-first century economy.

2. Systemic risk

A more globalized and networked world has many benefits, particularly for the prospect of information sharing and innovation. However, complexity is also positively correlated with uncertainty and risk, and increased complexity can heighten vulnerability within global systems. Increasingly complex global networks diminish individuals' and governments' abilities to accurately predict the intended and unintended outcomes of their decisions[33].

Geographic concentration has resulted in efficiency gains, but has also made the global system less resilient to single shock events. Urbanization and increasing population density in metropolitan regions facilitates the transmission of diseases, while concentration of capital and production in a few geographic regions creates the possibility of massive market disruptions.

Systemic risk can be understood as the potential for holistic systemic break down, as opposed to a more partial breakdown of individual system components. This complete collapse occurs when an adverse systemic shock cannot be

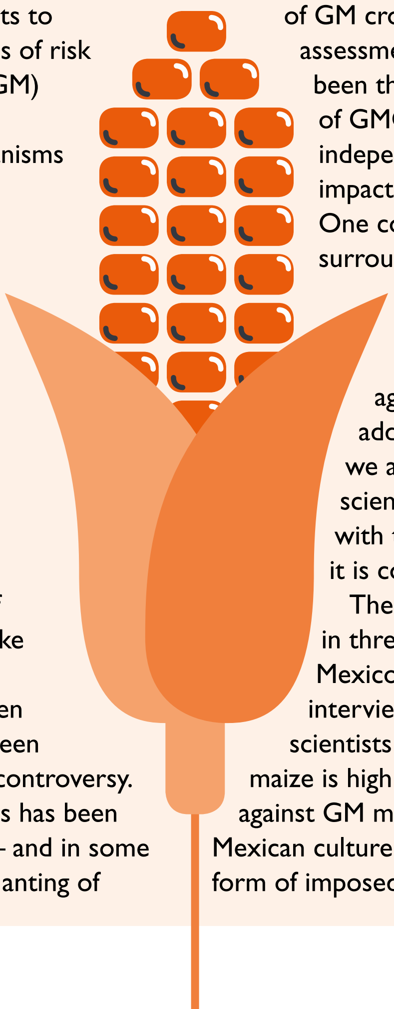
CASE STUDY

RISK AND INNOVATION IN DEVELOPING COUNTRIES: A NEW APPROACH TO GOVERNING GM CROPS

Philip Macnaghten (Durham University/University of Campinas) and Susana Carro-Ripalda (Durham University)

The key objectives of the GCSA's report are to raise awareness of risk and innovation concepts, to share issues of common concern and interest, and to promote learning across borders. A parallel set of objectives informed a recent Durham University project, GMFuturos[1], which was funded by the John Templeton Foundation. The project set out to use novel risk and innovation concepts to examine the adequacy of current models of risk and regulation of genetically modified (GM) crops, and to propose alternatives.

Given that existing governance mechanisms of GM organisms (GMOs) have suffered polarization and controversy in Europe, and increasingly also in North, Central and South America, there is an evident need to encompass broader factors and concerns within science-informed processes. An influential 2009 Royal Society working group concluded that global food security requires the sustainable intensification of global agriculture, with new crop-production methods, including GM and other innovations[2]. Although the rise of GM crops has been dramatic, their uptake has not been the smooth nor universal transition predicted by its advocates. Even those countries where approvals have been impressively rapid have seen significant controversy. All too often the regulation of GM crops has been challenged as inadequate, even biased — and in some settings, such as India and Mexico, the planting of certain crops has been judicially suspended. Our strategic question was to examine why GM crops have not been universally accepted as a public good. If we do not address this, we will fail to understand the conditions under which GM crops may contribute to global food security in an inclusive manner that meets human needs.



Current approaches to the regulation and governance of GM crops have been dominated by risk-based assessment methodologies. The assumption has been that the key criterion mediating the release of GMOs into the environment should be an independent case-by-case risk assessment of their impacts on human health and the environment. One consequence is that the public debate surrounding GM crops has been boiled down to one of safety: are they safe to eat, and are they safe to the environment?

In relation to these questions, we remain agnostic. Our argument is that we need, in addition, to ask different questions — for if we are to govern GM crops in a socially and scientifically robust fashion, we need to engage with the issue within the terms of the debate as it is considered by an inclusive array of actors.

The fieldwork for GMFuturos was undertaken in three of the global 'rising powers', namely Mexico, Brazil and India, and involved ethnographic, interview and focus group research with farmers, scientists and publics[3,4]. In Mexico, we found that maize is highly culturally resonant, and that protests against GM maize have come to signify the defence of Mexican culture and identity in the face of an unwanted form of imposed neoliberal globalization. In Brazil, we contained. The depth of our interconnectedness means that a number of today's global systems have opened themselves up to new systemic risks[34].

The 2008–09 financial crisis provided an illustrative example of how systemic risk can create a global crisis when a system encounters a shock. A complex set of factors, including excessive leveraging and the securitization of financial products, directly led to the collapse of Lehman Brothers. However, it was the transnational networks created by interbank markets, which caused the collapse of Lehman to reverberate across the world. The high concentration of market capital in several nodes — the 'too big to fail' banks — amplified this cascading effect. Thus, when the subprime market collapsed, transnational chains of counterparty risk spread the instability of this single market to the broader financial system, resulting in over $4 trillion in losses around the globe[35].

But while the financial crisis is an oft-cited example of the risk of complexity and interconnectivity, the financial sector is only one of the global systems that are vulnerable to systemic risk. Physical and virtual infrastructure provides another example of the dangers inherent in an increasingly connected world. The organization of infrastructure around several highly connected nodes has created points of potential systemic instability. Moreover, the indispensability of infrastructure for communication and market exchange make this risk particularly significant. Just as the financial sector found itself centered around a few banks, global infrastructure is organized around a few network hubs (such as Chicago's O'Hare International Airport, London's Heathrow airports, and the Suez Canal), which have accumulated a high concentration of global traffic. Disruptions at any one of these major hubs can cause severe disruptions.

When Iceland's Eyjafjallajökull volcano erupted in 2010, for example, it caused several of the largest global airports to shut down, thereby leading to the greatest disruption in global traffic since the Second World War[36]. Resulting in an estimated $5 billion in losses, the volcano eruption showed how a single shock can cause widespread impact by affecting important system nodes[37].

Virtual infrastructure is also vulnerable to disruption. Intentional attacks of cyberaggression and cybercrime carried out through software worms and viruses can significantly impact business and government activity. When hackers used cyberattacks to disrupt online traffic in Estonia in 2007, they managed to shut down dozens of websites, including those of the Estonian president and high-level government ministries. Estonia's strong dependency on e-commerce amplified the damage caused by the compromised cyber networks[38].

Shocks to energy infrastructure can have similarly debilitating consequences. When a tree fell in Ohio in August 2003, disrupting the operation of a Con Edison electricity plant there, the resulting power outage affected 50 million people for over a day[39]. Oil and gas supply lines are equally vulnerable to disruption. In Europe, energy pipelines originating in Norway, Russia and countries in the

found that even though the coverage of GM crops had risen rapidly since 2005 (mostly GM soya and maize), the issue was far from settled, with little evidence of public acceptability or inclusive governance. In India, we found that GM cotton had become a provocative symbol of foreign control and imposition, where regulatory bodies have been routinely criticized for using inadequate procedures for the approval of GM crops. Across all three case studies, we found that the technical regulatory bodies charged with approving the release of GMOs have not provided 'authoritative governance'[5]; that the predominant research cultures in national biotechnology laboratories have little capacity to respond to wider societal responsibilities; and that lay people across the board have tended to adopt negative views when introduced to the technology and its application.

Overall, we found that key factors responsible for the controversy over GM crops are social, cultural and institutional in nature, and transcend questions of technical risk. Yet in relation to these 'non-risk' factors, current policy arrangements have little capacity to respond, with few rules or norms to offer guidance. Such considerations thus tend to become hidden from public accountability and influence. Responding to this 'institutional void'[6], we proposed a novel way to govern GM crops that was informed by recent debates on responsible innovation[7]: that if we are to innovate responsibly and robustly, we need new institutional capacities to better anticipate the wider driving forces as well as impacts of emerging technologies; to open up an inclusive debate with stakeholders and wider publics; to develop more reflexive scientific cultures; and to develop new governance architectures that are responsive to these processes.

The responsible innovation framework has been pioneered in UK research[8] and is being implemented by UK research councils[9]. It offers the potential to reconfigure the debate on the governance of GM foods and crops in the UK, in Europe and internationally, and hopefully to help move the debate away from its current polemic and impasse.

The volcanic eruption showed how a single shock can cause widespread impact.

Middle East and Africa mean that the European continent is largely reliant on activities that occur outside of its borders for much of its energy supply.

In the global production of consumer goods, cost-cutting practices have created supply chain risks that undermine resilience and have the potential to disrupt global systems of production. The trend towards just-in-time delivery minimises inventory holdings and allows companies to more accurately adjust supply to reflect consumer demand. At the same time, subcontracting production to far-flung regions where production costs are lowest creates market concentrations in certain producers and areas. This market concentration is evident in electrical goods. In 2010, for example, two Korean semiconductor manufacturers, Samsung and Hynix, comprised close to 50% of the global market[40].

For individual firms, these practices lower costs and increase profitability. When aggregated across an entire system, however, they create instability and increase risk. With a substantial portion of global production relying on a few production centres and with the just-in-time supply chains sensitive to any variations in production, a single disruption to the supply chain can bring global markets to a halt. When flooding in Thailand, a global manufacturing hub, caused factories to close in 2011, the shut downs resulted in a 28% drop in the global production of hard disk drives, and interrupted the production of goods as disparate as computers and electronics (Toshiba, Western Digital), cars (Honda, Nissan, Toyota), and soft drinks (Coca-Cola, Nestle, Oishi)[41].

Aside from business and market exchange, global connectivity can pose a dangerous threat to health and wellbeing. Population growth and mobility have increased the global risk of pandemic. The concentration of people in urban metropolises raises the risk of disease spread within local regions, and the interconnectedness of these metropolises to global networks through airport traffic and trade broadens this risk transnationally.

The twenty-first century has already seen three potentially global pandemic or pandemic-like events: SARS, H1N1 (swine flu), and H5N1 (bird flu). The SARS virus illustrated how a localized disease can spread rapidly across the globe. SARS first appeared in November 2002 in the Guangdong province in China. The virus remained within the confines of the region until a single carrier — Liu Jianlun, a doctor from the region who had treated SARS patients — traveled to Hong Kong in 2003 (ref.42). From there, SARS spread around the world, and by June 2003, SARS cases had been identified on every continent, with over 8,400 cases in 30 countries[43].

From an environmental perspective, globalization and growing complexity increase risks from the environment, as has been discussed above, as well as increasing risks for the environment. Environmental degradation is caused by a rising output of emissions due to economic growth and increased energy usage[44]. Trade and travel also spread invasive species to new environments causing potential harm[45]. The production of monocultures, incentivized by efficiency and global competition, negatively affects biodiversity and leads to ecological homogenization.

> **Flooding in Thailand interrupted the production of electronics, cars and soft drinks.**

Perhaps equally as complex as environmental biodiversity are the social and political ecologies of a globalized world. Increasing connectivity facilitates information sharing and political mobilization. In a world of growing social inequality, this mobilization can have destabilizing effects for political leaders and governments. After the global financial crisis, only 3 of the 27 democratically elected European leaders in office before the crisis were still in power[46]. The Arab Spring, protests in China and Russia, and the Occupy Wall Street movement are further indication of the agency that citizens have in mobilizing for political change. The Arab Spring protests illustrated that this agency can be infectious, spreading from one country to another.

While systemic risk is an inherent consequence of globalization, steps can be taken to mitigate risk. Diversification and de-concentration in terms of capital and geography can protect companies from major disruptions. Flexible and diverse organizational structures that can respond to major systemic shocks should be implemented by investing in risk management planning. Developing risk-mitigating strategies requires resource allocation, transparent communication and the engagement of shareholders and society at large.

Innovation and integration of global knowledge and the associated flows in ideas, products, services and people are likely to continue to provide significant opportunities for progress. However, these same trends are likely to be associated with increasing systemic risk, complexity and uncertainty. Some recent evidence suggests that the response of societies may be to seek to withdraw from global integration. This would be a mistake, as more coordination is required to ensure that our societies are better able to harvest the opportunities arising from innovation and integration, while at the same time mitigating and building resilience against the resultant systemic risks.

Simon Pollard and Sophie Rocks
(Cranfield University)

CHAPTER 3: A RECENT CHRONOLOGY OF PUBLIC RISK MANAGEMENT IN GOVERNMENT

Government risk management strategies have developed considerably over the past two decades, but policymakers must now look beyond five-year terms to ensure that society is prepared to meet the challenges ahead.

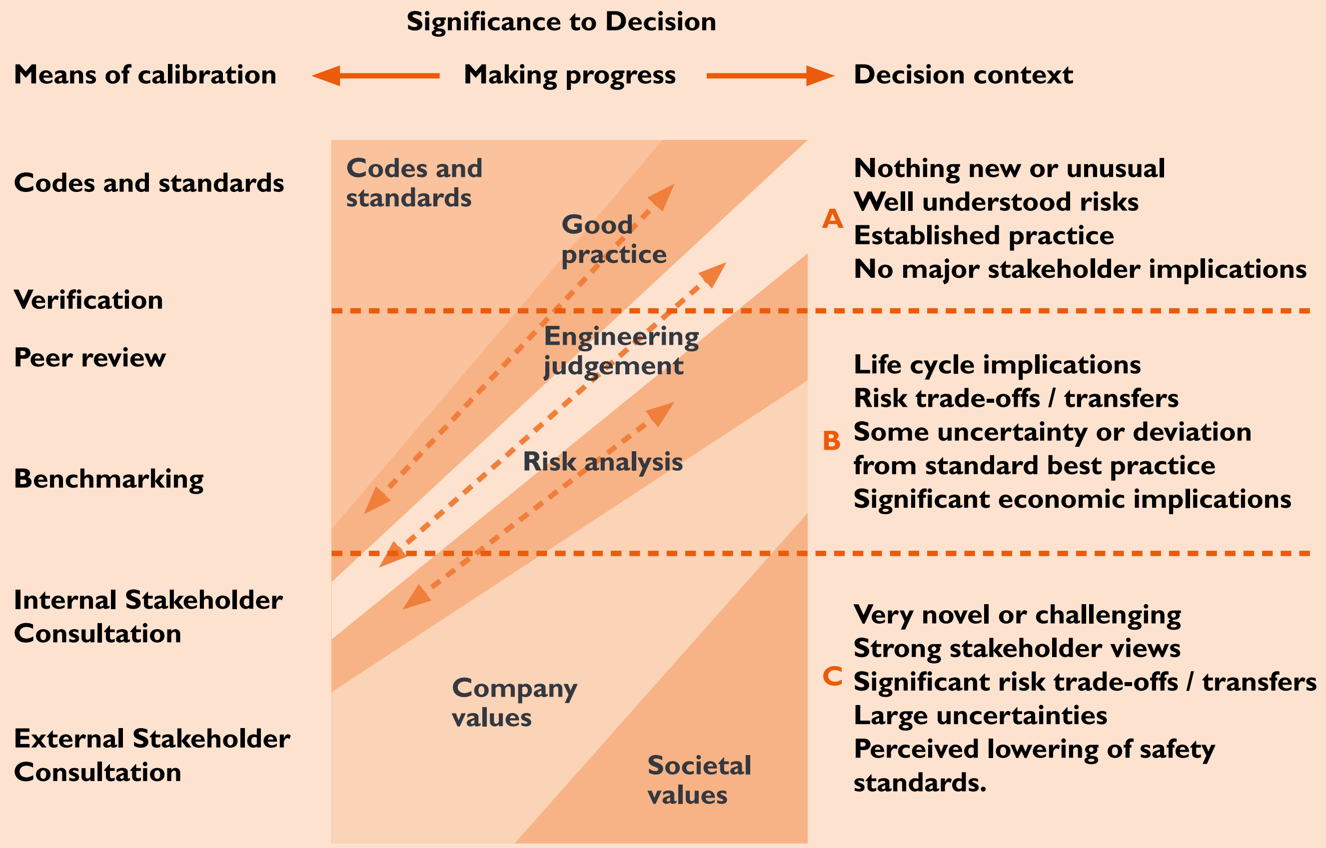
At their core, decisions are about balancing risk and reward; loss and gain[1]. Consequently, risk-informed decisions — those that embody considerable uncertainty (see Figure 1; the case study on synthetic biology that follows this chapter; and the case study on natural disasters in Section 4) — must involve several steps. Managers seek to frame decisions with interested parties; understand the magnitude and character of the risk or opportunity through analysis; decide whether risks need management, and what the options for this might cost relative to the risk; and then implement decisions effectively, reducing the risk to an acceptable residual level while recognizing that zero risk is not achievable[2].

Whilst frameworks and procedures for risk management offer road maps for decision-making, it is ultimately people, organizations and systems that must manage risk, and so the term 'risk governance' has become used to reflect a multidisciplinary field straddling the physical, social and natural sciences (see Chapter 11). Importantly, not all risk decisions require complex risk analysis. Many risks are managed through the adoption of standards and good engineering judgement (category A in Figure 1). Defensible decisions should generate the confidence of interested parties in the strategies devised to manage risk or opportunity, and in their implementation. For industrial operations typical of category B in Figure 1, where there are known uncertainties, stakeholders seek confidence in the safety of activities, and so perceptions of trust in its guarantors are never far away.

Critically, debates on risk also raise questions about individual and societal values: What is it we wish to protect? Why should this subject of protection have priority over other deserving subjects? Whose voice is critical to decisions on risk management? These can become the subject of intense debate, often about the motivations for a specific action or development — the planning of a new incinerator, for example, or access to a new cancer drug. Increasingly, stakeholders appear unconvinced by the risk management intentions of governments without an accompanying discussion of the underlying motivations for decisions (category C in Figure 1). Stakeholders need to know: Who will bear the cost? What benefits will accrue to those who bear the risk? Where is the evidence for the long-term effectiveness of risk management actions? And who is responsible for monitoring the residual risk — the risk that remains once measures are in place? Further, there is a growing recognition that risk decisions frequently expose 'winners' and 'losers', and so the distributions of gains and losses, by reference to who bears the risk, hold intense interest for most stakeholders (see Chapter 5). One might place the debates on genetically-modified organisms, nanomaterials or hydraulic fracturing in this category. Some risk debates might also straddle these categories, as illustrated by the case study on bisphenol A (BPA), which

FIGURE 1

A typology of approaches to decision analysis, by reference to context and the means of calibrating the appropriateness of the decision[3] (UKOOA, 1999).



has necessitated a combination of evidence-informed risk analysis and wide stakeholder consultation[4].

The UK government's role in managing public risk has been the subject of considerable scrutiny over recent decades[5,6,7,8,9]. In this chapter, we summarize some of the discussions since the early 1990s to illustrate progress in this area, and as the basis for the forward trajectory discussed elsewhere in this volume. The general shift over the years has been from recognizing public risk as a product of market failure (and thus a subject for central control) to a more devolved approach to measured risk-taking and value creation, with accountabilities distributed between various actors armed with high-quality evidence and structured accountabilities for shared risk and opportunity management. Public sector reform and modernization, the emphasis on risk-based regulation, and the current approach to risk and cost sharing in government all reflect this shift. The social processes of recognizing and accepting accountabilities for risk management and of delegating and monitoring these are critical to ensuring that risk reduction is secured.

Managing public risk

We recognize risk as a multidimensional concept with social, financial, human and natural resource implications, and with the potential for positive and negative outcomes. Society cannot function without taking measured risks. That is how innovations, discoveries, industrial endeavour and societal developments have been secured. Our industrial and civic societies are challenged when innovation is pursued, however, because social and economic activity inevitably comes with some risk attached. We have historically looked to our government to manage public risk in situations where the market fails[10]. For public risks, those that impact on goods that are readily available to members of the community, government departments have developed and retained expertise to evaluate and manage risk, whether directly or indirectly, ensuring the maintenance of the public good[11]. That said, there is a wide variety of views on the effectiveness of government capacity in risk management and in its maturity in handling public risk, particularly in a climate of cost constraint.

The United Kingdom's stance to risk and its management has evolved considerably, and has been highly influenced by the socio-political landscape. The nature of a risk or opportunity, its familiarity, location and distribution, all influence how risk is perceived (see Chapter 9 for a richer discussion of context, behaviour and agency). Politicians will hear public demands for action, and the political landscape — with all its tensions and influences — frequently determines management action. These decisions are usually, but not exclusively, informed by the evidence base. Political stances also influence how risks are portrayed; and whether the government adopts a directive or precautionary approach, or one that is more risk-seeking in order to capitalize upon the potential benefits[12].

The assessment of public risk alone is insufficient as a basis for managing it. Public risks must be assessed,

The United Kingdom's stance to risk and its management has evolved considerably.

managed, communicated and governed: the political, social and organizational aspects of sound risk management are as critical as the technocratic analysis of risk. Individual and organizational accountabilities and arrangements for managing risk prove critical and in practice, the responsibility for managing most public risk is shared between government, other organizations and the public. An overriding theme of national scale risk events has been the failures in risk management that occur when shared responsibilities for managing risk are unclear, where accountabilities are blurred or where the complexities of systems are insufficiently understood. Fragile, interconnected and excessively lean systems are vulnerable, especially where there is a loss of oversight or where behavioural incentives within systems, or among their custodians, are at odds with maintaining systemic resilience to shock. Successive failures in systemic risk management and oversight by institutions, as illustrated by the global financial crisis (see case study), can cause pervasive, substantive and long-lasting damage that erodes public confidence.

A useful starting point for the recent chronology is the Royal Society's influential 1992 report *Risk: analysis, perception and management*[13], chaired by Sir Frederick Warner FRS, an international authority in the field, which was published as an update to a 1983 report on risk assessment practice. The temporal context of the Royal Society's 1992 report was a catalogue of industrial disasters, including the Piper Alpha oil rig fire in the North Sea, the capsizing of the *Herald of Free Enterprise*, and the King's Cross underground station fire — all national tragedies that had raised considerable disquiet about the management of risk by a variety of actors. The Royal Society sought to address developments in risk assessment practice, to bridge the gap between quantified and perceived risk, and to comment on the merits of risk-benefit trade-offs. The latter parts of the report reflected an increased emphasis on risk communication (updated in Chapter 8 by Nick Pidgeon, a contributor to the 1992 report) and signalled the emergence of an analytic-deliberative approach to decision making that had been in discussion since the 1970s (refs. 14, 15).

Up until this point, one might argue that risk management had been deployed as a defensive approach to reassure publics that consideration had been given to a risk and that action could be taken — displaying a tendency to manage the perception of uncertainty and limit blame. Hopefully, this tenor of approach is now a thing of the past. A fundamental requirement for all risk analyses, once

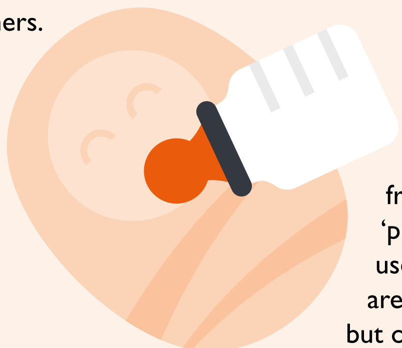
CASE STUDY

CONSISTENCY AND TRANSPARENCY IN EVIDENCE-BASED REGULATION: RISK AND PRECAUTION IN THE REGULATION OF BISPHENOL A

Patrick Miller (Food Standards Agency)

Regulators often need to review and adapt regulations as the evidence on risks develops. But if they are to maintain credibility and trust, they must handle this process in a consistent and transparent way, and always explain the rationale for their risk-management decisions. They should clearly distinguish between hazard and risk; between the uncertainties addressed directly within a risk assessment, and wider uncertainties that may pertain to the risk management decision; and consider the unintended consequences of any new measures. The case of bisphenol A (BPA) illustrates some of the challenges of this approach.

BPA is a chemical used to make plastics, including those used as protective coatings and linings for food and drinks cans, and also in some refillable drinks bottles and food storage containers. Minute amounts of BPA can transfer from these materials into food and drinks. For plastic food-contact materials, EU legislation sets limits for the amount of BPA that can migrate into food. These ensure consumer exposure remains within guidelines established by independent expert risk assessments.



There is some evidence that BPA interacts with hormone systems and may act as an endocrine disruptor. Consequently its safety has been reviewed several times to assess whether these potential effects are relevant for human exposure to BPA. The European Food Safety Authority (EFSA) began its most recent comprehensive review of BPA in 2012, and consulted on two parts of its draft opinion in 2013 and 2014; its final opinion is due later in 2014. The draft EFSA opinion proposes a revised exposure guideline for BPA and concludes that exposures to BPA are below this level for consumers in all age groups. EFSA's initial finding is thus that the health concern for all population groups is low[1].

Regulatory responses to the revised EFSA risk assessment

The UK Food Standards Agency (FSA) is clear that any change in BPA controls should be based on a rigorous assessment of the balance of evidence, and an understanding of how any changes will achieve an improvement in consumer protection in a proportionate way, while guarding against adverse unintended consequences. The UK Committee on Toxicity of Chemicals in Food, Consumer Products and the Environment (COT) has concluded that the draft EFSA opinion does not indicate a risk to UK consumers from dietary exposure to BPA[2]. The FSA will also assess the final EFSA opinion and review the need for any further action, working with the European Commission and EU member states[3].

Some EU member states have already introduced or announced plans for more restrictive controls on BPA, which are described as 'precautionary'. This raises a number of issues:

1. Acting in advance of, or contrary to, an EFSA opinion risks undermining the process of risk-based decision making in the European Union.
2. According a communication from the European Commission, the 'precautionary principle' should not be used to cope with uncertainties that are dealt with during a risk assessment, but only when there are wider, more fundamental evidence gaps[4].
3. Use of precaution should not be one-sided. Regulators need to consider the balance of risks and benefits, and the associated uncertainties, that are caused by a 'precautionary' action, and compare that with the effects of maintaining the status quo. This includes a consideration of unintended consequences — for example, problems with the safety and effectiveness of replacements for BPA.
4. Decision-makers may of course take other factors into account, and do not have to rely solely on the risk assessment — but when they do so, they should set out their rationale and the supporting evidence transparently.

The FSA is working with the network of national food agencies in Europe to try to develop principles and tools to improve consistency and transparency in this process[5].

promoted by the Better Regulation Task Force, is that they are open, transparent, and that they involve deliberative problem formulation from the outset. The expectation since the 1990s (ref. 16) is that risk-informed decision-making is a process involving multiple perspectives on the scope of the risk under investigation. Of course, risk analysis without subsequent mitigation or action on risk provides no guarantee of safety, and as Lisa Jardine discusses in this report (see Chapter 12), ultimately a decision must be made.

Moves for consistency and transparency in risk management

Around the time of the Royal Society report, the handling and regulation of public risk was promoted as a key component of public sector reform for modernising government in the United Kingdom. The white paper *Modernizing Government*[17] placed a firm emphasis on quality public services, including effective regulation, a proportionality of approach to public risk management, and the delivery of good practice in the assessment, management and communication of risks.

Government activity in risk policy and regulation spans its departments and agencies, covering, among others, aspects of defence, education, health service provision, health and safety in the workplace, food standards, and environmental protection. Within these structures, policy and regulatory decisions are made with close reference to statutory or supervisory duties and/or powers within the primary legislation, accompanying regulations, or in policy and guidance from central government. Evidence plays a critical part in decision-making, and has been the subject of successive guidance from the government's Chief Scientific Advisors[18], which is regularly reviewed across government[19, 20].

Recognizing the need for improved risk management practice, the United Kingdom Interdepartmental Liaison Group on Risk Assessment (UK-ILGRA, 1996-2002) was established to promote good practice in risk assessment, management and communication across government departments and agencies, and reported periodically to ministers on progress. This was the first attempt to coordinate risk management capability across government, and in its second report[21] the group reflected on the adoption of the analytic-deliberative approach to risk management, further emphasizing good risk communication and recommending that departments and their agencies publish their policy or regulatory frameworks describing how risk is managed within their areas of control. These set out each department and agency's regulatory philosophy, the first of which — *Reducing risks, protecting people* — was issued by the Health and Safety Executive.

This period also saw the rise of the Government Chief Scientific Advisor (GCSA) and the network of CSA posts within core departments. With onset of the BSE crisis (1986-1992), and the loss of public confidence in scientific decision-making that ensued[22], the Office of Science and Technology issued guidance to government departments on the use of science and evidence in policy making. Successive editions of this guidance emphasized the need to communicate uncertainty and handle different types

Governments must look beyond five-year terms to ensure genuine preparedness and resilience.

and lines of evidence. These principles underscored the importance of early identification and anticipation of risk issues, the use of all available scientific information, the early publication of data, the need for clarity over the existence of uncertainties, and for early thought to be given to the presentation of information to the public. The requirement for government departments, and by extension their executive agencies and associated bodies, to develop and maintain a mature capability to address risks was stressed[23]. The growing need for coordinated best practice and a joined-up approach to public risk management — especially where accountabilities were shared across units, exemplified for the Health and Safety Executive and the Environment Agency by the 1999 Control of Major Accident Hazards (COMAH) legislation — led to a pivotal move in which risk governance became a key focus of the Cabinet Office.

Following UK-ILGRA's influential work[24], and the GCSA's guidelines on evidence and handling decisions in the face of uncertainty, departments began to pursue a platform of risk activity, initially coordinated across government by the Cabinet Office's Strategy Unit (2002) and then HM Treasury (2003). This saw the introduction of headline principles for managing public risk and the issue of the so-called *Orange book*[25], which contained guidance to government on public risk-management principles and capabilities.

Departments responded by establishing dedicated risk coordinator posts, their work typically comprising the development of structured approaches to managing the risks of policy delivery[26] and the publication of domain-specific risk frameworks (e.g. for environmental risk management across Government[27]). Training and support for civil servants on risk was made widely available through the Office of Government Commerce (OGC) and the then Civil Service College, with oversight and review of departmental risk frameworks and their implementation provided by the National Audit Office (see Figure 2 for these and other developments).

The 'better regulation' agenda of the early 2000s then addressed issues such as developing a proportional response to risk, ensuring the effectiveness of response, and the design and targeting of regulatory intervention on aspects of a hazard that contribute most to risk. Here, effort was focused on the wise use of risk analysis to inform where regulatory interventions to manage public risk were best targeted and resourced. Adopting thinking developed within Her Majesty's Inspectorate of Pollution[28, 29], built on by the Environment Agency[30], the European Commission[31] and its Network for the Implementation and Enforcement of Environmental Law (IMPEL)[32] and the Organisation for Economic Co-operation and Development (OECD)[33], approaches to risk-based regulation secured growing traction among the regulated community, including the Confederation of British Industry[34]. The work of the Better Regulation Task Force (1997-2005) and its successors, the Better Regulation Commission (BRC) and the Risk and Regulation Advisory Council (RRAC)[35], resulted in a suite of reviews on regulators' implementation of these principles (known as the Hampton Reviews[36]). They focused on the targeted inspection of regulatees, and on compliance and enforcement strategies, by reference to risk[37]. These reviews, and the changes that emerged from them, sought to offer financial incentives and a lighter regulatory touch for high performing regulatees[38] that offered demonstrable evidence of their ability to manage their own risks, while ensuring greater attention on poor performers that were managing higher-hazard operations. Generally welcomed by industry, these initiatives have stimulated the deployment of a more intelligence-led approach to the management of public risk that has set the foundation for current (2009–) initiatives on smarter regulation[39] as part of the regulatory reform agenda[40].

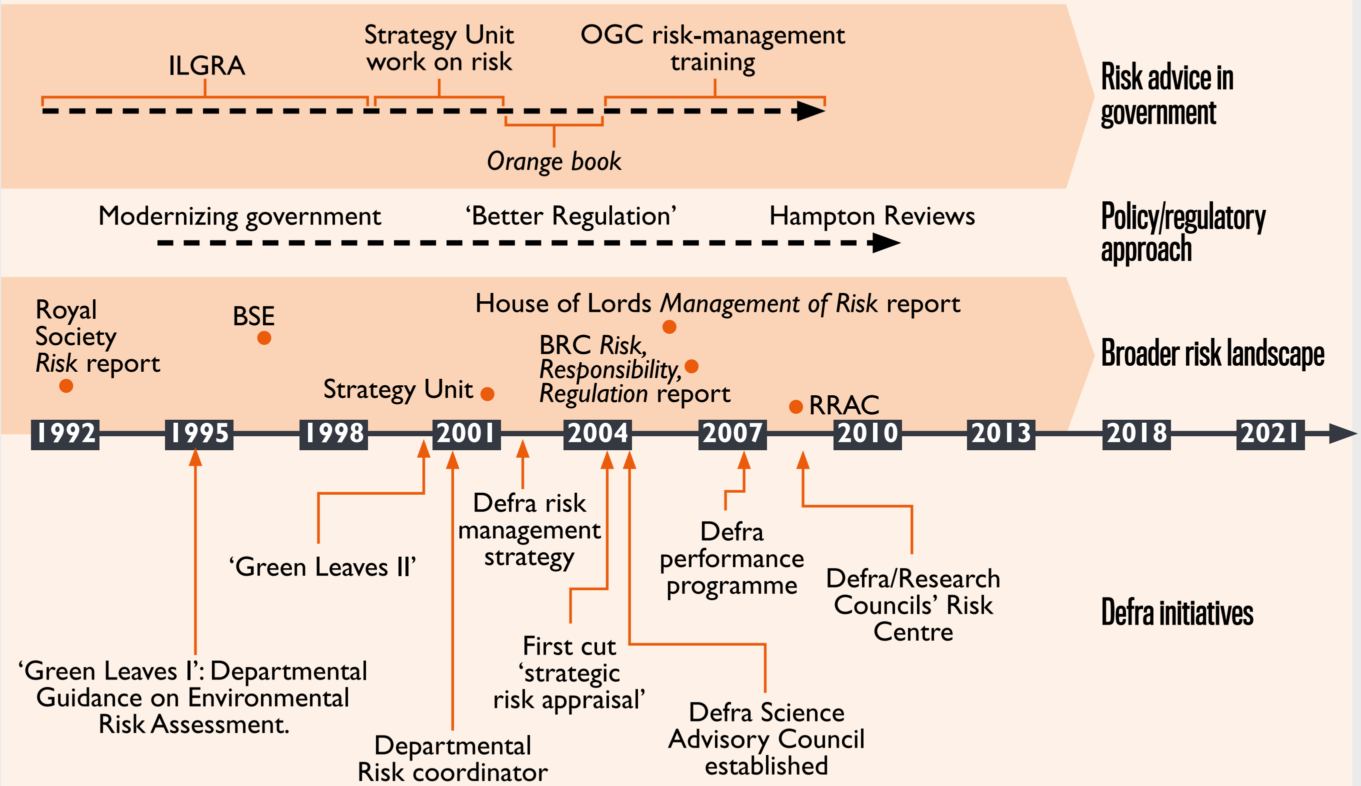
Risk management in local government

It is useful to reflect briefly on the role of local government and its handling of risk across the wide range of public services it manages. The Localism Act (2010) enacted a shift in power to local authorities, including devolved responsibilities for risk management through, for example, neighbourhood planning. Local government is at the front line of public risk management, handling a multitude of issues around local service provision, long-term planning and community cohesion[41]. Yet within a 'paradox of thrift' there is an increased challenge to the consistent management of risk in local government in a climate of resource constraint. Given the variation between local government structures (county councils, district councils and unitary authorities); in the size and scale of local authorities (large versus small, urban versus rural); and their differing priorities about the need for inward investment, or to protect existing structures (rural versus metropolitan versus major conurbation); a single solution or approach is not suitable for all, and a range of options needs to be investigated and considered. Good risk governance is fast becoming a creative discipline for many local authorities.

Table 1 (see page 42) illustrates a wide range of responsibilities and diversity in the operating structures of local government, potentially leading to a separation between policymaking (core strategy) and regulation (technical services). Under these conditions, silo mentalities are a constant threat to joined-up risk management becasue staff work closely within their own divisional structures and may have difficulty working with others outside. In addition to the variation between local government organizations, risks frequently extend beyond administrative boundaries, raising the issue of shared risks, accountabilities and

FIGURE 2

A timeline of risk management developments in the Department for Environment, Food and Rural Affairs, its predecessor bodies, and more broadly across government.



CASE STUDY

FINANCIAL CRISIS

Tom Sorell (University of Warwick)

The failure of the Wall Street bank Lehman Brothers in September 2008 marked the moment of greatest uncertainty and panic in a global financial crisis that is only now coming to an end. It was just one event in a much longer and less visible period of distress in US financial services before 2008, and it ushered in a long period of stress in global financial markets as a whole that has lasted until late 2014 in the UK, and will last longer elsewhere. There may be other financial crises in the offing in Europe in the near future, connected to sovereign debt and the solvency of banks that have made loans to highly indebted governments. But these will be different from the one we have already experienced.

The ingredients of the distress in the US included the following:

1. The development of novel financial products in the mortgage market.
2. Sales of those products to people with meagre assets and low financial literacy.
3. Huge foreign and domestic demand for collateralized (and therefore safe-looking) US dollar investments.
4. The invention of investment vehicles to cater for that demand.
5. The development of new savings products in a relatively new and uninsured retail and commercial banking market — so-called money market funds.
6. The development of a private market in esoteric financial products — derivatives — without the liabilities of the institutions in the markets being clear to market participants, and without the products being understood by the senior management of banks.
7. The deregulation of US banking in 1999, which permitted ill-considered mergers and acquisitions and uncertain valuations of banking shares.
8. Proprietary trading — where investment bank subsidiaries of universal banks invested retail depositor assets, or similar monies, in very risky products.
9. Poor modelling of prospective house price movements, which were crucial to the calculation of the value of collateral for securitized real-estate products.
10. Poor commercial credit-rating of banks holding very large quantities of securitized assets.
11. The US government's indications to banks and other financial institutions — just before the time of the Lehman collapse — that it would subsidize losses.
12. An internal culture in banks that rewarded short-term profits from trading shares and derivatives rather than from long-term commercial investment.
13. An over-reliance on money-market borrowing, as opposed to deposits for investment and operating costs.
14. International regulatory agreements (especially the Basel II agreement) that allowed bigger banks to be their own judges of the adequacy of their capital to cover liabilities.

UK subsidiaries of US banks, including Citibank, were exposed via their parent companies to the risky behaviours in this list, and UK-owned banks were sometimes significant investors and traders of securitized products. Royal Bank of Scotland (RBS) in particular was highly exposed through its US subsidiary, Greenwich Capital Markets, which RBS acquired with its takeover of NatWest in 2000. The resulting losses contributed to the near-failure of RBS and its rescue by the UK government in October 2008. The government had already acquired mortgage provider Northern Rock in February 2008, following a decline that was marked by long queues of depositors trying to withdraw their savings. Northern Rock was affected by declines in the values of some of its mortgages through points 2 and 13 in the list above. Another big bank, HBOS, sought to be taken over when write-downs in its commercial loan book made the business unsustainable. It, too, incurred risk from point 13. Lloyds, the bank that acquired HBOS, in turn required government rescue when losses inherited from HBOS materialized.

There are three main lessons to be learnt from the financial crisis:

1. The speculative operations of big universal banks are systemically damaging, where those systems stretch across borders, and take in whole economies, not just the banking sector of a single economy.
2. Risks from esoteric financial products are extremely difficult for either banks or government to manage effectively.
3. There are continuous, big incentives to introduce new, esoteric financial products.

A partial antidote to some of these risks is for governments to incentivize the traditional banking function of intermediation: turning insured deposits with capped interest rates into profitable commercial loans and mortgages that prospective borrowers prove they can repay. This kind of banking is easy for all parties to understand, relatively easy to regulate, and beneficial to depositors, lenders and borrowers.

A more general lesson is that big banks are not the only systemically-important institutions: energy and telecommunications companies also pose systemic, cross-border risks. In this respect, being a customer of Gazprom may not be so different from being a shareholder in Lehman Bros.

liabilities.

The coalition government has introduced changes to reshape risk management practices across local government. The emphasis on breaking up public monopolies and transferring power away from central government allows local government to innovate and develop new solutions to past issues, drawing on the professional judgement of local government officers. A key challenge involves providing officers with relevant information so they have an appropriate evidence base to take informed risk management decisions and to partake in measured risk taking, whereby well-evidenced risks are assessed on their probability and consequences. Under these conditions, local authorities may reform their risk management approaches by passing on the responsibility for some risks through contracts, insurance or delegation (to other bodies or individuals); and by engaging with new actors so they understand the challenges these risks present, as well as how to take precautionary and preventative action in order to protect them from harm. This seems to offer support to individuals who can assume greater responsibility and proactively manage their interests, rather than relying on state intervention. But it also recognizes that certain risks require onward scrutiny and oversight, because they are too important to devolve.

National registers, risks and futures

A natural outcome of pan-government risk analysis has been a capacity to compare and contrast many different types of risk that have national strategic significance. What distinguishes one risk or opportunity from another is its character[43, 44]: not only its magnitude, dimensions and significance, but also the means by which it might be realised, how likely it is to come to fruition, the individual mechanisms by which this might occur, the knock-on consequences that may emerge, and how it is understood and managed by those that engage with it[45]. Emerging naturally from a more joined-up, pan-government approach to risk management, the UK Civil Contingencies Secretariat, was established in 2001 as the Cabinet Office department responsible for emergency planning in the United Kingdom. The role of the secretariat is to ensure the United Kingdom's resilience against disruptive challenge. By working with others, it aims to anticipate, assess and prevent risks; to prepare and respond in the event of major threats; and then recover from risks that are realized.

Since 2010, the emphasis of government's risk management has been on national resilience — a focus on the systemic features essential to ensuring society is robust to shock and able to recover quickly when adverse events occur. The National Risk Register of Civil Emergencies and the National Security Strategy set out government thinking and embody a strategic perspective[46, 47]. In compiling these registers, frameworks for analysing and presenting strategic risks adopted within business settings[48] have been deployed across government. Notwithstanding the debates on method[49, 50, 51], one cannot argue with the impact these national risk analyses are having in shaping policy discussions on the effectiveness of public risk management[52]; the societal appetite for the current levels of residual risk; and on how national risks might evolve under a variety of possible futures.

Looking to the far horizon[53] is now widely recognised as a reserved responsibility of government with respect to public risk management. Recent reviews of capability have called for a centrally-coordinated approach to horizon-scanning and foresight activity that, in some ways, mirrors the policy initiatives on risk of the late 1990s discussed above. This can only lead to a maturing capability and lend support to a long held view that governments must look beyond five-year terms to ensure genuine preparedness and resilience in society's ability to meet the intergenerational and existential challenges ahead[54] (see Chapters 2 and 10).

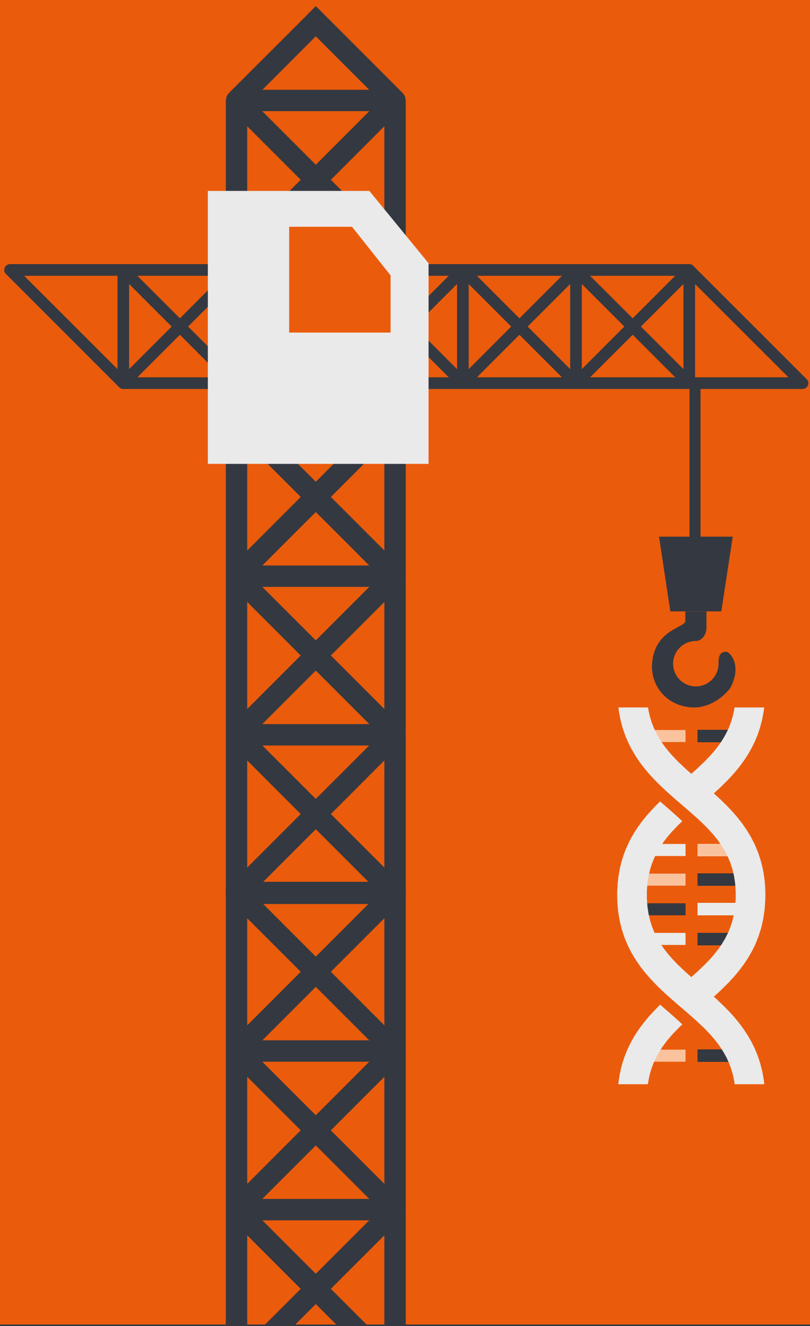
TABLE 1

Simplified account of local authority responsibilities within England[42]

	Met. areas		Shire areas			London		
	Single purpose	MD	SC/UA	SD/UA	Single purpose	City	LB	GLA
Education		✔	✔			✔	✔	
Highways		✔	✔			✔	✔	✔
Transport planning		✔	✔			✔	✔	✔
Passenger transport	✔		✔			✔		✔
Social services		✔	✔			✔	✔	
Housing		✔		✔		✔	✔	
Libraries		✔	✔			✔	✔	
Leisure and recreation		✔		✔		✔	✔	
Environmental health		✔		✔		✔	✔	
Waste collection		✔		✔		✔	✔	
Waste disposal	✔	✔	✔			✔	✔	
Planning application		✔		✔		✔	✔	
Strategic planning		✔	✔			✔	✔	✔
Police	✔				✔	✔		✔
Fire	✔		✔		✔			✔

MD = metropolitan district; SC = shire county; SD = shire district;
UA = unitary authority; LB = London borough;
GLA = Greater London Authority
Source: Local Government Financial Statistics, England, CLG

Lionel Clarke (UK Synthetic Biology Leadership Council), Richard Kitney (Imperial College London) and Roland Jackson (Sciencewise)



HIGH LEVEL CASE STUDY: SYNTHETIC BIOLOGY

Advances in the life sciences continue to deliver significant benefits to society across a broad spectrum of application areas, ranging from health products to sustainable materials. Rapidly advancing technologies and deepening understanding are now generating the potential to deliver increasingly effective and beneficial solutions, such as targeted diagnostics (including infection and disease monitors), personalised therapies, and speciality chemicals from a range of sustainable feedstocks. Synthesis — a mainstay of the chemical industry for nearly two centuries and currently enabling the production of tens of thousands of useful chemicals ranging from aspirin to Lycra — plays an increasingly important role in supporting these advances. For example, whereas insulin extracted from the pancreas of pigs was originally found to be an effective therapy for diabetes nearly a century ago, since the early 1980s the large-scale synthesis of genetically modified forms of insulin and its analogues now enables the delivery of more effective and affordable treatments.

Synthetic biology represents a leading edge in our understanding of the relationship between molecular structure and function at the genomic level. This capacity stems from rapid developments since the beginning of the twenty-first century in high-throughput, low-cost data-analysis techniques such as DNA sequencing, combined with remarkable advances in computational power and data handling, and the field continues to assimilate new tools and techniques. This builds on more than forty years of complementary and contributory advances in the life sciences, with origins stemming back to the discovery of the structure of DNA in 1953. Introducing engineering design principles into the design–build–test cycle can also enhance the predictability and robustness of these innovations, and accelerate the development of more bespoke and cost-effective solutions.

Yet the commercialization of effective solutions depends not only on technological feasibility, but also on their affordability and their social acceptability. To ensure that intended benefits are delivered, it is important to recognize the existence and significance of a wide range of stakeholder interests, societal as well as technological, and to generate an environment in which relevant issues can be identified and addressed transparently and unambiguously. The UK government's Synthetic Biology Leadership Council provides a multi-stakeholder forum in which such issues may be addressed.

What exactly is synthetic biology?

A clearly expressed and widely adopted technological definition of synthetic biology was outlined in the Royal Academy of Engineering report on synthetic biology[1], and in the UK Synthetic Biology Roadmap[2]: "Synthetic Biology is the design and engineering of biologically-based parts, novel devices and systems as well as the redesign of existing, natural biological systems". This highlights the key differentiator between synthetic biology and other fields: the application of systematic design through the implementation of the engineering principles of standardization, characterization and modularization. Adopting these principles allows for the application of systems theory, control theory, signal processing and a range of metrology techniques and standards. These themes are reiterated in the European Commission's recent definition of synthetic biology[3].

However, it cannot be overlooked that other definitions exist and the term is sometimes applied more loosely, forming a potential source of ambiguity. This partly reflects the evolving nature of synthetic biology, the different interests and needs of stakeholders, and the various purposes to which the term is applied. Non-specialists may sometimes apply the term 'synthetic biology' as a shorthand descriptor covering a broad range of leading edge bio-technological developments. But a technical specialist, funding agency or regulator may require a much sharper definition to be clear what is or is not being considered in a particular context. Such diversity of language is common to many technical fields and not peculiar to synthetic biology. It is not therefore a significant issue, as long as the purpose and context of any definition or description is understood. Here, we adopt the definition expressed above as representing the core characteristic of synthetic biology, and supplement this definition with a clarification of its scope as follows.

A key goal of synthetic biology is to translate innovative concepts developed at a laboratory scale into potentially useful and commercializable options. This is not simply a matter of seeking uses for an emerging new technology. Market pull — the need to develop effective solutions to ongoing challenges — will often provide the inspiration and goal. These activities enable the identification of a product or service concept that will then have to be assessed against available marketplace alternatives before committing to full-scale commercial investment. Regulatory conformance is just one of a wide range of checks and balances that will determine whether a particular option ever reaches market. To scale up into a robust and viable market product or service, many other considerations ranging from process engineering and economics to customer value assessment may need to be taken into account. For example, pharmaceuticals will need to pass clinical trials, speciality chemicals will need to meet product performance specifications, and so on. In this context, synthetic biology may often serve as an innovative front-end to established market-facing sectors such as industrial biotechnology, agri-tech and healthcare, each sector being subject to its own specific, stringent regulatory frameworks and marketplace dynamics.

Synthetic biology is essentially an enabling discipline. Meeting the underlying objective of introducing engineering design principles — by generating robust and reliable biological parts, devices and systems — directly focuses attention onto sources of uncertainty. Identifying and reducing those sources of uncertainty is key to increasing predictability. In its current early stage of development, this objective restricts synthetic biology to the incorporation of a limited number of parts at a time, but as we gain greater understanding of the complex interactions and internal control mechanisms that occur within biological systems, so the potential of the approach will expand. Historically, the redesign of biological systems has been a predominantly empirical 'trial-and-error' activity, but the ongoing establishment of relevant standards and metrology will facilitate the introduction of engineering-related design and performance standards.

The successful functioning of designed biological systems is already confirming the growing extent of our understanding. The concept of a design–build–test cycle reflects the evidence-based nature of the synthetic biology process. Improving design capability reduces the number of iterations of the cycle required to achieve a specific performance target, and may therefore improve the efficiency and cost-effectiveness of identifying potential solutions. Even when public or private sector incentives are specifically applied to address a given challenge, the benefits may not be realized unless sufficient cost-effectiveness is achieved to underpin sustainable commercial production. Improving the design and synthesis processes not only facilitates the automation of novel system development — it may also permit practitioners to focus less attention on the mechanics of construction, and place more attention on the robustness of the resulting system's performance.

Regulatory challenges

Synthetic biology has the capacity to deliver solutions where conventional methods are ineffective, too expensive or simply do not exist. In the near- to mid-term, such solutions are expected to fall within the range of established channels to market, each subject to its particular operational constraints and prevailing regulatory standards. These standards are regularly reviewed, and the considered expert view is that such applications remain adequately addressed by current regulations.

Nevertheless, because synthetic biology represents a leading edge of current understanding, it is reasonable to anticipate that further innovations will emerge over time that could present regulatory challenges. To ensure that society benefits from synthetic biology in a timely and affordable manner, key stakeholders must continue to identify and address any potentially new risks that could be associated with such future innovations.

Every conceivable application will have its own particular benefit/risk profile. To manage risk, it is important to maintain a broad perspective across the whole opportunity space. This requires balancing the assessed risks of an innovation against the loss of opportunity associated with failing to move forwards. Attempting to reduce potential risk by blocking a particular activity may inadvertently block access to even greater future benefits in related areas. In these respects, the principles of risk management relating to synthetic biology are no different from those that apply to other cutting-edge areas of innovation.

Taking a long-term view of the future provides a structured opportunity to anticipate risks and associated issues, and also gives more time to reflect upon and address them. The UK Synthetic Biology Roadmap[2] has paid considerable attention to mapping out a multi-decade vision of the future, raising awareness of the underlying directions, values and envisaged timelines. In addition to the ongoing process of review by regulatory bodies, numerous other checks and balances have been put in place. The Synthetic Biology Public Dialogue[4], for example, provided an opportunity to engage a wide range of stakeholders outside the scientific community, identifying concerns and viewpoints that have helped to shape current responses. As potential applications emerge, wider societal conversations may be required. Such conversations should not only be about potential risks but also about desirable trajectories and priorities, set against alternative solutions to given challenges. These conversations need to take place well before specific regulatory consultations.

From bench to marketplace

From the perspective of industrialists and investors, the presence of effective (but not excessively bureaucratic) mechanisms for managing risk in the marketplace — ranging from clear regulatory frameworks to best practice guidelines and standards — can be highly welcome, because they provide a reliable basis for overall risk assessment and strategic investment decisions. Industrial interest covers a broad spectrum of organizational structures, ranging from specialist start-ups to broad-based multi-nationals. For the larger established companies, successful product lines and services, and satisfied customers, provide the benchmark. Commercial choices will be based not only on confidence in technical delivery, strategic fit and reputational impact, but also on current and anticipated marketplace needs and values. Synthetic biology is increasingly forming the core of specialist start-ups, which may help deliver toolkit advances or address very specific challenges. At present, the United States has well over 100 such companies, with the United Kingdom hosting almost 50. Such a broad-based community of practitioners helps to ensure that a wide spectrum of practical experience is becoming available to inform ongoing discussions.

The potential of synthetic biology also attracts many students, and the field is benefitting from their enthusiastic engagement, innovative capacity and critical judgment. A prime example of this is the International Genetically Engineered Machine (iGEM) competition[5]. Over the past decade, many hundreds of student iGEM teams from the world's top universities have taken part in this annual competition, discovering how synthetic biology can generate a wide range of potentially beneficial applications. In many cases, iGEM projects have led to more detailed professional research projects, and even to the formation of start-up companies. Examples of such projects include a cost-effective arsenic sensor to verify the safety of drinking water, and a system that can address a challenging health issue such as gluten intolerance.

Synthetic biology is inherently multi-disciplinary, stimulating constructive challenges and the sharing of best practice. This reinforces a culture of 'responsible research and innovation'[2], which helps practitioners to consider the potential implications and impacts of their work beyond its immediate focus.

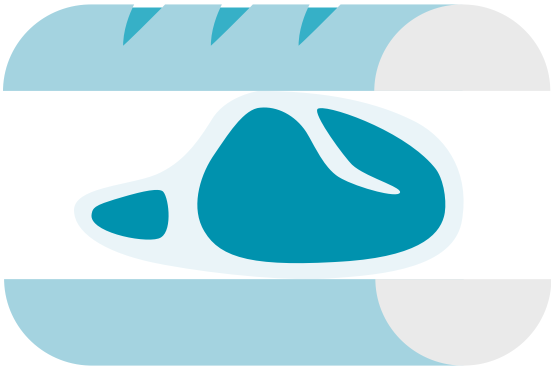
Proactive approaches such as these must be encouraged, because effective risk management is key to instilling confidence both in potential investors, and in society as a whole. After all, it is society that stands to benefit not only from the products and services delivered by synthetic biology, but also from the jobs and economic growth arising from successful commercial operations.

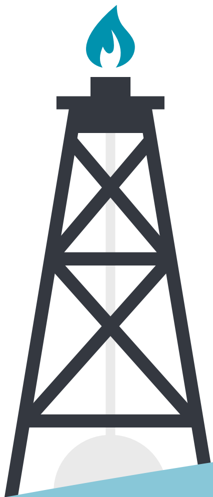
SECTION 2: UNCERTAINTY, COMMUNICATION AND LANGUAGE

Neonicotinoids were introduced in the 1990s and now make up about 30% by value of the global market in insecticides.

It takes a lot of effort for people and organizations to adapt to and capitalize on new technologies. These 'sunk investments' can reinforce commitments to a particular innovation pathway – even if it widely seen as unsatisfactory. Exhibit A: the QWERTY keyboard.

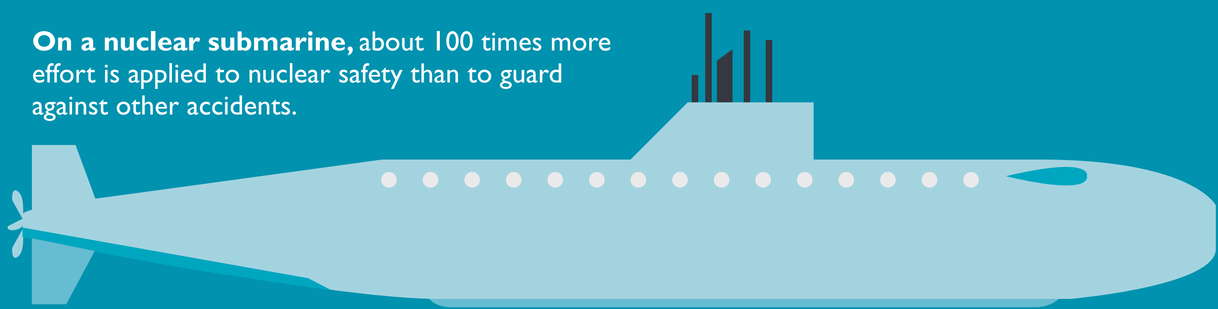
UK shale gas development will require estimated supply chain spending of £3.3 billion per annum and generate 64,500 jobs.





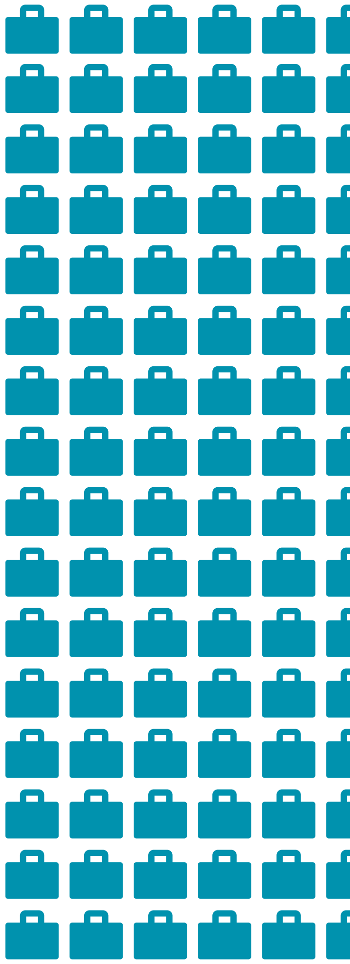
Relative measures of risk can be misleading: being told that regularly eating a bacon sandwich increases your lifetime risk of pancreatic cancer by 20% may be somewhat unconvincing if the baseline is extremely low and the bacon sandwich is rather pleasant.

On a nuclear submarine, about 100 times more effort is applied to nuclear safety than to guard against other accidents.

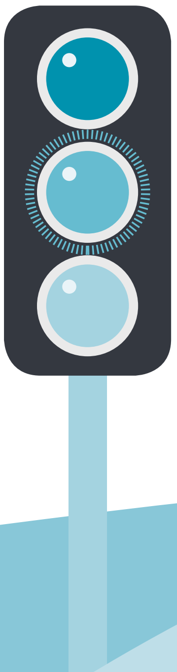


Sciencewise has guided 17 experimental dialogue projects on issues ranging from nanotechnology and stem cell research, to the uses of DNA in forensics and geoengineering to combat climate change.

The chemical and pharmaceutical industries are the United Kingdom's biggest manufacturing export earner. Together, they have a turnover of £60 billion and support 500,000 jobs.



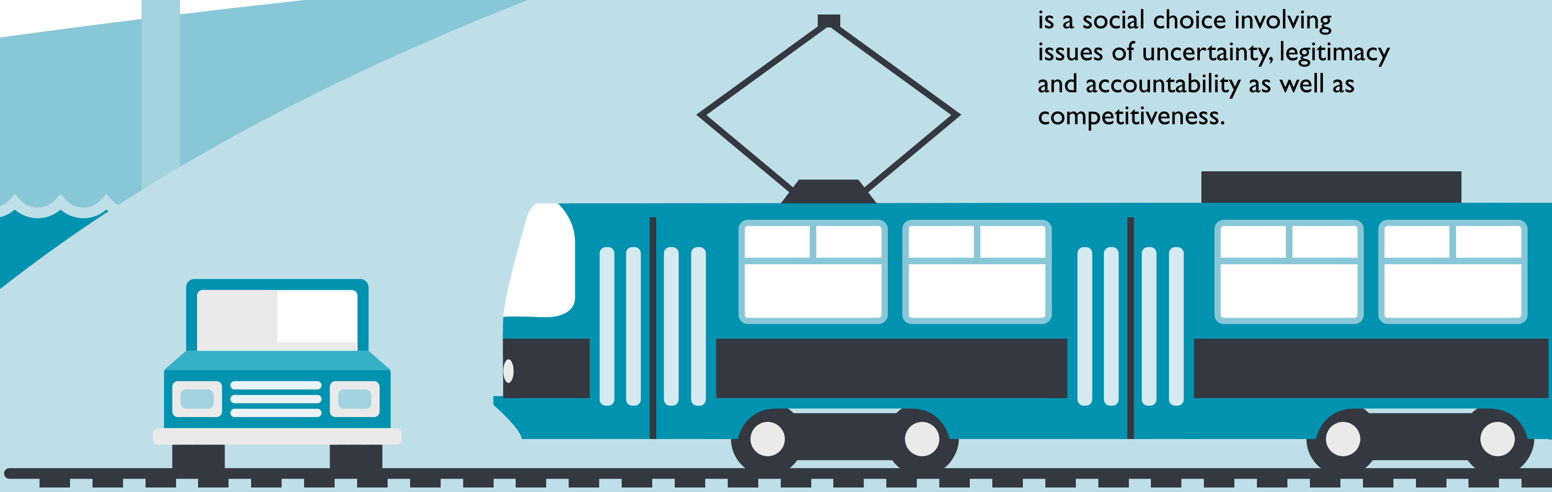
Many major global industries are built around once-marginal technologies, like wind turbines, ecological farming, or super energy-efficient buildings. Grassroots social movements were all involved in their pioneering origins.



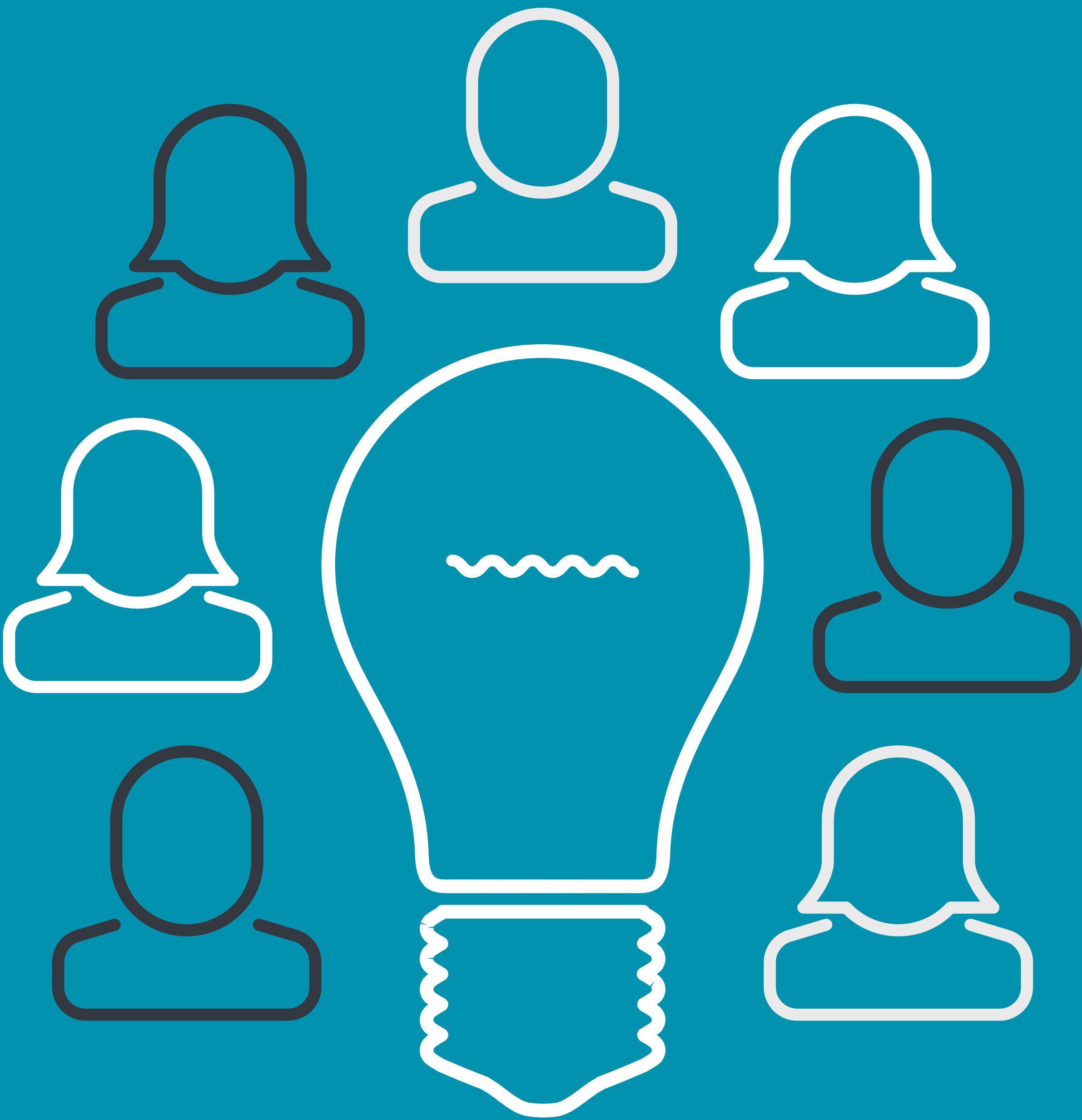
If there is still considerable scientific uncertainty after quantifying risks, then it is reasonable to be cautious as a temporary holding position: amber, rather than red.

Between 2002 and 2007, the UK invested over £150 million in research into the development and impact of nanotechnologies.

Innovation is not a one track race to the future. Each direction for innovation is a social choice involving issues of uncertainty, legitimacy and accountability as well as competitiveness.



Andy Stirling (Science Policy Research Unit, University of Sussex)



CHAPTER 4: MAKING CHOICES IN THE FACE OF UNCERTAINTY: STRENGTHENING INNOVATION DEMOCRACY

Innovation is not so much about a race to optimize a single pathway, but a collaborative process for exploring diverse alternatives — as such, we need to nurture a more realistic, rational and vibrant innovation democracy.

Innovation is not just about technological inventions. It encompasses all the many ways of furthering human wellbeing. This includes improved production and use of goods or services in firms and other organizations[1]. But it also includes new practices and relations in communities, households and the workplace[2]. Advanced science and technological research can help to drive and enable innovation[3], yet many other new forms of knowledge and action are also important[4]. Innovation can be created and guided by social mobilization[5] as much as commercial entrepreneurialism[6], for example. So grassroots movements[7], civil society[8], creative arts[9], and wider culture[10] feature alongside small business, service industries[11] and the public sector[12] in being as important for innovation as universities, research labs and high-tech companies.

Of course, there are no guarantees that any particular innovation in any of these areas will necessarily be positive. To take extreme examples that most may agree on, new forms of torture, financial fraud or weapons of mass destruction are all areas for innovation that might be judged to be generally negative. For other kinds of innovation, the picture is varyingly ambiguous. But it is rare that any given innovation is entirely, unconditionally and self-evidently positive[13]. And these judgements are always relative. So the unqualified claim in the UK government's slogan adorning venues used during the preparation of this report — "Innovation is Great… Britain"[14] — is not automatically true. Like other prevailing talk of 'pro-innovation' policy — around the European Union's 'Innovation Union' strategy, for instance — this misses the crucial point that the most important queries are about 'which innovation?'. Whether or not any given innovation is preferable on balance to the alternatives — let alone 'good', still less 'great'— is not just a technical issue. It is also a fundamentally political question. This means that even quite detailed aspects of innovation policy are legitimate matters for democracy.

In these widest of senses, however, well-conceived innovations can undoubtedly offer important aids not only to economic productivity[15], but also to enhancing many kinds of human flourishing or the public good[16]. This need not be a bone of contention, even under the most critical views[17]. The more ambitious the aspirations to progressive social change, the greater the need for broad, diverse (and carefully scrutinized) kinds of innovation[18, 19]. An example lies in the imperatives for transformations towards a more sustainable[20], equitable, healthy and peaceful world. Whatever forms these possible futures are held to take, they require radical kinds of innovation in the widest of senses[21].

Some innovation opportunities can be addressed by well-governed fair and efficient markets[22]. So one important role for innovation policy lies in helping to foster commercial innovation in the public interest[23]. But not all benefits, risks or impacts are restricted to those private actors who are typically most directly involved in steering business innovation[24]. The established understandings, motivations and incentives that drive the most powerful market actors often fail to prioritize wider relevant social values and interests[25]. In areas like health, agriculture, energy, environment, water, mobility, security, waste and housing, many of the least privileged (and most vulnerable) people around the world are disproportionately excluded from conventional global patterns of innovation[26]. Nor, as we shall see below, are many important forms of uncertainty and ambiguity always fully or appropriately addressed by relatively narrow market-based signals or official statistics[27].

Depending on the context, then, market processes alone do not necessarily drive the best orientations for the kinds of innovation that are most needed from broader social viewpoints. This is true both across different domains of policy as well as within any given sector. For instance, the single largest area for public expenditure on research and innovation — in the UK[28] and worldwide[29] — is military. Innovation towards less violent means for conflict resolution are relatively neglected[30, 31]. The most strongly-pursued energy options are those that offer greatest returns on established infrastructures and supply chains[32, 33]. For its part, biomedical research tends to focus more on health disorders of the rich than the poor, and on therapeutics rather than prevention[34]. This is especially so in speculative (but potentially lucrative) new areas like 'human enhancement' and 'life extension'[35–36], with the Royal Society raising particular questions about patterns of prioritization in neuroscience[37]. Consequently, there are important roles for public policy in helping to prioritize across sectors, as well as in encouraging and supporting appropriate scales and directions for innovation in particular areas. Public policy is also crucial in helping to address the many uncertainties and ambiguities — by promoting greater analysis, deliberation and political accountability[38].

In nurturing these qualities, public policy can also fulfil other significant roles. Alongside higher education, business and civil society, government policy can do much to promote the knowledge, capabilities and environments that best facilitate socially-effective innovation[39]. The more demanding the challenges for innovation (such as poverty, ill health or environmental damage), the greater becomes the importance of effective policy[40, 41]. These challenges of innovation policy go well beyond simplistic notions of governments trying to 'pick winners'[42, 43]. In any case, this dilemma does not exclusively afflict the public sector, but also applies to powerful market actors[44]. Indeed, essentially the same uncertainties and intractabilities are equally experienced by government, business and civil society[45]. Instead, the central challenge in innovation policy is about helping to culture the most fruitful conditions across society

> **There are no guarantees that any particular innovation will necessarily be positive.**

as a whole, for seeding and selecting across many alternative possibilities and together nurturing the most potentially beneficial[21]. This is about collectively deliberating, negotiating and constructing what 'winning' even means, not just how best to achieve it. These are the questions on which this chapter will focus.

Policy and the Politics of Choice

The most important (but neglected[46]) issue here is that innovation of all kinds in any given area is not a one-track race to the future[47]. Instead, it is about social choices across a variety of continually branching alternative pathways for change[48]. In this sense, innovation is more like an evolutionary process than a race[49, 50]. It is as much about exploring a space of different possibilities, as optimising any one[51–53]. As already mentioned, it is rarely self-evident — and often hotly contested — what should count as the most desirable directions for discovery. This is true, for example, of particular domains like sustainable agriculture, zero-carbon energy services or clinical and preventive responses to improving public health. In all these areas, there unfold many radically contrasting pathways for innovation. Two of the most pervasively important qualities in choosing which pathways to prioritize are therefore: (i) attending fairly to a *diversity* of possible directions and strategies[54]; and (ii) including a *plurality* of perspectives in appraising any one[55]. The ways in which such social conversations are most effectively achieved is discussed further in Chapter 5.

Consequently, it is not only important that innovation be efficient and competitive in any particular direction. It is also crucial for economic and wider social wellbeing that the prioritized directions for innovation are as robustly deliberated, accountable and legitimate as possible[56]. An economy that fails to do this exposes itself to the risk that it will become committed to inferior innovation pathways that other more responsively-steered economies may avoid. In other words, innovation may 'go forward' quickly, but in the wrong directions.

History presents plenty of examples of innovation trajectories that later proved to be problematic — for instance involving asbestos, benzene, thalidomide, dioxins, lead in petrol, tobacco, many pesticides (see case study), mercury, chlorine and endocrine-disrupting compounds, as well as CFCs, high-sulphur fuels and fossil fuels in general[58, 59]. In all these and many other cases, delayed recognition of adverse effects incurred not only serious environmental or health impacts, but massive expense and reductions in competitiveness for firms and economies persisting in the wrong path. As discussed in Chapter 1, innovations reinforcing fossil fuel energy strategies[43] — such as hydraulic fracturing[59] — arguably offer a contemporary prospective example. And similar dilemmas are presented by the exciting new possibilities of nanotechnology (see case study later in this chapter)[60] — both internally within this field and externally with respect to alternative ways to address the same priority social needs[61].

The key conundrum is that each alternative innovation pathway in any given area (such as food, energy, health or military) will typically display contrasting pros and cons under contending perspectives. Animated differences emerge, for instance, around infrastructures for urban automobiles or cycling[62], nuclear power or renewable energy[44] and violent or peaceful approaches to national security[31, 63]. Each involves different innovation trajectories. Competing pathways will also routinely differ in their social distributions of benefits and harms, winners and losers. And — in any view — many deep unknowns further obscure the whole picture. Crucially, a decision *not* to innovate will also present its own mix of pros, cons and uncertainties. Innovating in any particular direction will typically diminish innovation in others, not least through foregone resources and opportunity costs. Whether deliberate or inadvertent, each direction for innovation is a social choice involving issues of uncertainty, legitimacy and accountability as well as competitiveness.

> Innovation is not a one-track race to the future.

It is important to acknowledge these complexities of choice, because innovation debates in particular areas often become quite simplistic and polarized. For instance, innovation in fields like food, health, energy or human security is frequently discussed as if it were a one-track race[47], rather than an exploratory process, and simply about whether to 'go forward' or not. But the crucial questions in such areas are typically not just about "yes or no?", "how fast?" or "who's ahead?". What often matters more are queries over "which way?", "what alternatives?", "who says?" and "why?"[64]. The scope for uncertainties under these wider questions compound the scope for controversy, so conflicts can become especially intensive and disabling (and potentially economically disastrous) if these broader questions are ignored.

Across all fields, the key challenge is that there exists no single definitive scientifically-sound or evidence-based way to calculate the most rational balance of resources to expend on alternative innovation pathways within or across different domains[65]. A robust knowledge base and rigorous analysis are both necessary. But these are typically insufficient. The merit rankings constructed in this way for different innovation choices invariably overlap — and may often be inverted — under contrasting equally reasonable assumptions and value judgements[66, 67]. Decisions concerning which kinds (or areas or aims) of innovation to prioritize are therefore inherently partly subjective and political, rather than purely technical or economic. This is why research and innovation remain intrinsically matters for democracy. The more this point is denied or neglected, the more imperative it becomes.

This makes it all the more important that high-quality

CASE STUDY

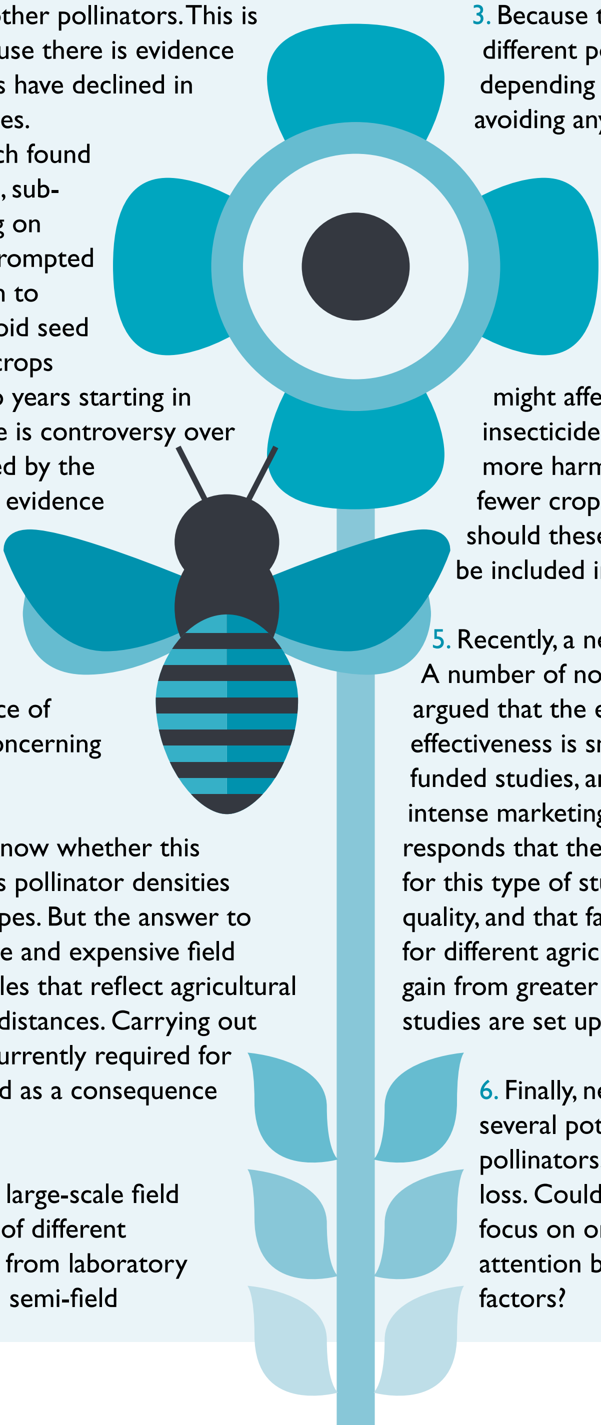
NEONICOTINOID INSECTICIDES AND INSECT POLLINATORS

Charles Godfray and Angela McLean (University of Oxford)

Neonicotinoids were introduced in the 1990s and now make up about 30% by value of the global market in insecticides. They can be used in different ways, but most commonly they are applied as seed treatments, with the insecticide being taken up systemically by the growing plant. Because the compound is present in all plant tissues, it is potentially very effective in reducing the damage done to crops by insect pests. However, the presence of the insecticide in pollen and nectar raises the possibility that neonicotinoids may harm populations of beneficial insects such as bees and other pollinators. This is a particular concern, because there is evidence that pollinator populations have declined in Europe over recent decades.

A series of studies[1] which found that bees suffered harmful, sub-lethal effects after foraging on treated flowering plants prompted the European Commission to ban the use of neonicotinoid seed treatments for flowering crops for an initial period of two years starting in December 2013. But there is controversy over whether this ban is justified by the strength of the underlying evidence base.

The debate over neonicotinoids highlights a number of issues concerned with making decisions in the face of uncertainty, particularly concerning environmental questions.



1. Policymakers need to know whether this type of insecticide reduces pollinator densities in real agricultural landscapes. But the answer to this question requires large and expensive field experiments, at spatial scales that reflect agricultural practice and bee foraging distances. Carrying out such experiments is not currently required for insecticide registration, and as a consequence few have been conducted.

2. In the absence of these large-scale field trials, data on the toxicity of different compounds chiefly comes from laboratory experiments and so-called semi-field studies, which typically involve administering known doses of the insecticide to pollinators in the field. Experiments with neonicotinoids clearly show they can harm individual pollinators, but the most severe sub-lethal effects occur when insects are exposed to concentrations higher than they are likely to receive as a result of routine agricultural practice. Less severe effects can be observed at more realistic concentrations, but whether these are bad enough to affect pollinator population densities is much less clear.

3. Because the evidence base is limited, different policy conclusions can be drawn depending on the importance given to avoiding any potential negative effects of low-dose exposure to different compounds or combination of compounds.

4. It is unclear what farmers will do without recourse to neonicotinoids, and how this might affect pollinators. Will they use less insecticide overall, or switch to potentially more harmful chemicals? Might they grow fewer crops that benefit pollinators? How should these behavioural and economic factors be included in policy formulation?

5. Recently, a new area of debate has opened up. A number of non-governmental organizations have argued that the evidence base for neonicotinoid effectiveness is small and dominated by industry-funded studies, and that farmers are subject to intense marketing to buy insecticides. Industry responds that there is no other source of funding for this type of study, their experiments are of high quality, and that farmers are sophisticated customers for different agrichemical products. Would all sides gain from greater openness in the way industry studies are set up and reported?

6. Finally, neonicotinoids are only one of several potential explanations for the loss of pollinators, chief among them being habitat loss. Could there be a danger that the policy focus on one threat might lead to reduced attention being paid to more important factors?

information concerning public policy in and around innovation, is available for wider scrutiny and debate. But the recent House of Lords Select Committee on Science and Technology report on the setting of priorities for publicly-funded research identified several important areas for improvement[68]. The Committee confirmed that there remains significant scope for enhancing the quality of official statistics concerning public support for contrasting innovation pathways. It made recommendations that this information be clarified in several particular ways. Yet these recommendations remain to be implemented. Consequently, further deliberate efforts are required in order to enable more transparent and accountable democratic politics concerning the directions and rationales underlying UK innovation policy.

Steering Innovation Pathways

One reason why it is important to address the politics of choice in innovation is that chosen pathways can quickly become effectively irreversible. A diversity of well understood social, political and economic processes exert various kinds of positive feedback as innovation pathways unfold. These can act to reinforce the trajectories favoured by the most powerful interests, and exclude others that may be more widely beneficial.

Typically, it takes a lot of effort for people and organizations to learn about any new way of doing things, capitalize on the opportunities and adapt to the changed requirements. As these efforts become 'sunk investments' in a particular innovation, they can help reinforce commitments to the associated pathway. This can occur, even if the innovation in question is widely seen to be unsatisfactory[69]. Although complicated[70], a classic example of this remains the QWERTY keyboard[71,72,73]. This was originally designed for nineteenth-century mechanical typewriters, specifically to slow down typing in order to reduce jamming of the type bars for letters frequently used together. But this very property of modulating typing speed helps to aggravate office injuries[73]. Better keyboard configurations do exist[74]. Yet the deeply socially embedded familiarity of QWERTY makes it difficult for alternatives to become established. So the problem persists through successive innovations in

> **Another rational measure is to extend scrutiny beyond anticipated consequences and also look at the driving purposes of innovation.**

> **There remains significant scope for enhancing the quality of official statistics concerning public support for contrasting innovation pathways.**

automatic typewriters, computers and touchscreen tablets, continuing several technological generations after the initial rationale lapsed. Even where the incumbent innovation is essentially a product of historical chance, then — with no powerful backing — it can prove very difficult to reverse the associated path dependency.

This dynamic of path dependency makes it especially important to do whatever is achievable at the earliest stages of innovation, to give confidence that unfolding directions are as appropriate as possible[75]. The dilemma is, of course, that this is precisely the time when the positive and negative implications are most uncertain[77,78]. So there can be enormous pressures on all sides to exaggerate the confidence with which evidence can be interpreted, and to understate the scope for competing interpretations[78]. One reasonable response to this is to be much more open and questioning about uncertainties[65]. This will be returned to below and in Chapter 6. But another rational measure is to extend scrutiny beyond anticipated consequences and also look at the driving purposes of innovation[79]. Whilst the variously claimed positive, negative and indirect effects may remain uncertain, the motivating values, interests and incentives that lie behind particular innovation pathways are typically much clearer[80]. In this way, critical appraisal of the driving forces behind alternative innovation pathways (not just the claimed aims) can be undertaken with confidence at an early stage, despite the uncertainties[81].

This kind of careful broad-based societal consideration is, however, rarely evident in mainstream innovation. More often, it is a narrower range of expectations about the future that most strongly drive directions for change. The values upheld by particular communities of researchers themselves may be influential, as well the interests of leading firms, powerful financiers or particular users[82]. If a specific pathway is strongly held to be more likely than others by these kinds of influential actors, then this can become self-fulfilling[83]. Examples include competing media formats or software operating systems, where early market penetration can be driven more strongly by expectations about future adoption, than by assessments of performance[50]. Some degree of performance shortfall is often the price for

CASE STUDY

NANOMATERIALS

Kamal Hossain (National Physical Laboratory)

'Nanotechnologies' describes a broad group of technologies that focus on the engineering and manipulation of materials at the nanoscale (1nm–100nm). At these scales, many materials exhibit novel properties that are not seen in their bulk forms. For example, quantum dots made of nanoscale semiconductor materials exhibit excellent and novel properties for display and lighting applications, and gold nanoparticles exhibit optical properties that make them excellent tools for medical imaging.

In 2004, the Royal Society (RS) and the Royal Academy of Engineering (RAE) published the world leading report *Nanoscience and nanotechnologies: opportunities and uncertainties*[1]. This report acknowledged both the significant opportunities in nanotechnologies for UK industry, as well as the challenges that their development posed. As with the development of many emerging technologies, these challenges focused on uncertainties around risks to health and the environment.

Researchers had already begun to investigate the toxicology and environmental impact of a range of nano-objects prior to the publication of the 2004 report, which stimulated further investment. Between 2002 and 2007, the UK alone invested over £150 million in research into the development and impact of nanotechnologies.

Despite this investment, issues still remain. Conflicting results and differing scientific opinion mean regulators still cannot always make adequate risk assessments and policymakers may lack the evidence to develop effective policy. For example, the European Commission's Scientific Committee on Consumer Safety published its latest opinion on the use of nanoscale titanium dioxide in consumer products in 2013 (ref. 2), which stated that there were still uncertainties over the risk assessments used for nanomaterials, despite knowledge gaps being highlighted in the first opinion on the use of nanoscale titanium dioxide published 13 years ago.

One reason for this continued uncertainty is largely due to an issue raised in the 2004 report: a "need to develop, standardize and validate methods of measurement of nanoparticles and nanotubes". This development is essential for the accurate quantification of any potential risk. In layman's terms, you cannot measure the toxicological or environmental impact of a material if you don't know what it is or how to measure it correctly.

With UK government support, work is underway to address this issue. The National Physical Laboratory (NPL) is the UK's centre of excellence in measurement research and represents the United Kingdom globally in measurement standards development. NPL undertakes research that aims to develop robust, repeatable measurement technologies and methods that can be applied reliably to understand, predict and manage potential risks of engineered nanoscale materials. By removing uncertainty around the impact of nanotechnologies on health and the environment, this work benefits regulators, policymakers and industry by increasing confidence in policy decisions. NPL's world-renowned expertise and work in nanoscale measurement is being applied to the development of international standards that UK industry can follow, helping the United Kingdom to maintain a leading position in the field.

Foremost in these activities is the NPL's work with the International Organisation for Standardisation (ISO) technical committee (TC) 229 Nanotechnologies. The BSI (British Standards Institution), in close co-operation with NPL and UK industry, put forward the case for TC 229, which was formed in 2006 and is chaired by the United

Kingdom. It has 34 participating and 13 observing countries, along with liaison bodies including the European Union. TC 229's remit spans four work packages, providing internationally agreed language; characterisation protocols; material specifications; and health, safety and environmental standards. ISO TC 229 has published 39 documents, and over two dozen are in progress.

TC 229 is now eight years old, and the standardization framework is beginning to have an impact as published guidance and standards are taken up by regulators, academia and industry. For example, in 2011 the European Commission recommended a definition of a nanomaterial[3] that cited the work of TC 229. Other international standards have been published in the areas of metrology, toxicity measurement of engineered nanoparticles and carbon nanotube characterization methods. Guidance on the contentious issue of voluntary labelling of consumer products has just been published[4].

Ten years on, the recommendations of the RS and RAE report are having a meaningful impact, such as:

- National centres for nanotoxicology being set up, with advice from NPL on instrumentation and measurement procedure.
- A library of reference nanomaterials to support researchers, which is available from LGC Standards in Teddington. These were one of the key outputs from a global project, led by the Organisation for Economic Co-operation and Development, in which NPL played a central role undertaking physical and chemical characterisation of some of the most important nanomaterials in use.

Much work remains to be done, but the next few years will see a range of new standards, reference materials and improved instrumentation and methodology, all leading to:

- More reliable toxicology and eco-toxicology testing, which will reduce uncertainty around risk.
- Better regulation and policymaking.
- More reliable industrial processes and quality control, and the removal of barriers to international trade in nanomaterials, leading to increased economic benefits.

collective compatibility[84]. Consequently, expectations can add to path dependencies mentioned above, compounding the 'locking in' of a particular innovation, and the crowding out of alternatives[85]. This is an issue that arises, for instance, from the conditions described in the nanotechnology case study[36].

Processes of learning, volume production and economies of scale can add to these positive feedbacks. For instance, 'lock in' can be significantly further reinforced by measures to standardize infrastructures[86], establish organizational momentum[87], appropriate intellectual property[88,89], build monopolies[90], realize rent on value chains[91], condition user preferences through marketing[92], 'capture' regulators[93] and 'entrap' competing political interests[94]. The overall result of such so-called network externalities are a range of powerful increasing returns that can entrench a particular favoured trajectory and exclude other paths[95]. Despite being ignored in the apparently simple policy language of 'going forward', these more complex dynamics in science and innovation do not go unnoticed by interests wishing variously to reinforce (or disrupt) particular pathways[96, 97]. If innovation policy is to be fair and effective, it is therefore important that it attends to these processes in explicit, direct and accountable ways.

These challenges are formidable enough. But, as indicated above, problems of 'lock in' are intensified by the deliberate exercise of powerful interests at the earliest stages of an innovation process, in order intentionally to promote particular favoured pathways or disadvantage others[98, 99]. For instance, automobile manufacturers and allied industries sought historically to promote the car by suppressing competing urban public transport systems[100]. Lead compounds were also promoted as anti-knocking agents in transport fuels, at the expense of less profitable alcohol-based products, even though these were very early known to be less harmful[57]. Further examples of this more deliberate type of lock-in include the strategies of the tobacco industry over the past century to maintain high levels of consumption[101]. Before it was finally abandoned in most countries, the nuclear fuel reprocessing industry worked for many decades to condition continuing government support[94]. Likewise, ostensibly disinterested debates over alternative radioactive waste management

> **Problems of 'lock in' are intensified by the deliberate exercise of powerful interests at the earliest stages of an innovation process.**

strategies also inherently depend on – and help condition – future prospects for new nuclear power[102,103]. More recently, pharmaceutical industry strategies have been challenged for neglecting innovation of socially vital antimicrobials due to their low profitability[104]. Where innovation systems are driven by these kinds of dynamics, there are especially important roles for democratically responsive government policy and collaborative international pressure.

It is crucial not to misunderstand the implications of 'lock in'. In order to be successfully achieved, even the most positive innovation pathway will require some closing down in associated standards, regulations and practices[105]. So some degree of 'lock in' is not in itself necessarily always a bad thing. But it remains a significant policy dilemma, since it means that not all potentially good innovations that are technically practicable, economically feasible or socially viable will actually prove to be historically realisable. The most important point, then, is that these issues need to be discussed and addressed openly — and democratically — rather than brushed under the carpet or drowned in simplistic and polarising 'pro' claims, or 'anti' accusations, over innovation in general.

Opening Up Innovation Portfolios

Many of the retrospective examples above are judged with the benefit of hindsight. Looking forward in any given area, it becomes even more difficult to conclude definitively which of a variety of innovation pathways offers the most favourable balance of pros and cons. One especially important prospective example lies in the field of innovation for more sustainable global food systems[106]. How will a growing world population be fed at a time when natural environments are increasingly stressed[107]? Here there exists an especially rich diversity of possible innovation pathways, each with contrasting implications[108], and many kinds of diversity are possible[109]. But public debates display a shared tendency on all sides to close down discussions, as if they were about simply being 'for' or 'against' the single family of innovations around genetic modification (GM), for example, which are favoured by the most powerful interests in this sector.

With resulting policy debates polarized by this especially deep form of power play[110,111], it is often portrayed as if GM were — self-evidently and in-principle — either individually indispensable or uniquely unacceptable. Whatever reasonable political perspectives are taken on the pros and cons of the many disparate innovation pathways in this field, neither of these positions is actually tenable. In fact, the much-discussed (apparently specific) innovation of 'GM plant breeding' is much more complex and ambiguous than often suggested by either critics or advocates alike. Technical variations like transgenics, cisgenics, apomixis, gene editing, genomic assist and marker selection[112] each offer partly overlapping and partly contrasting benefits and risks — and present important differences in their potential social, political, economic and ecological implications[113].

For example, among the more striking recent claims made for UK government-supported research towards enhanced sustainability in global staple crops, are the remarkable flood-tolerant qualities reported for 'scuba rice'[114]. But these have been achieved through marker assisted backcrossing, rather than any form of transgenics[115]. So the most important factor typically differentiating GM technologies is not that they offer a unique means to secure crop improvement. The crucial distinction lies more often in the potential for innovating firms to recoup investments by obtaining rents on intellectual property or global supply and value chains[116]. For instance, transgenic crops are often deliberately engineered for tolerance to particular proprietary broad spectrum herbicides, thus expanding their sales[117]. Or the inclusion of particular transgenes can make the resulting organisms patentable, and thus more reliable sources of royalties[118]. It is the resulting commercial forces and counterforces that help make the ensuing discussions so regrettably polarized[119].

This point becomes even more important as attention extends beyond science-intensive innovations. Outside the techniques of molecular genetics, there are many other promising innovations for improving global food sustainability[108]. These include participatory breeding[120], agricultural extension services[121] and open source seed sharing methods[122], which harness the innovative capacities of farmers themselves and help tailor crop development to important local conditions[123]. Likewise, there exist many innovations in wider agricultural practices that also offer significant benefits to the productivity of small farmers[124], including intercropping[125], integrated pest management[126] and other methods of ecological farming[127] and sustainable agriculture[128].

Likewise organizational innovations in the food chain also offer potentially major benefits, including reforms to distribution systems, storage provision and better food waste management[129]. Arguably the greatest implications for global food provision, however, are presented by innovations that are still wider in scope[130], including reforms to land tenure and agricultural property rights[120], income support for marginal famers[131], social equity between different rural groups[132], or moving diets towards lower meat consumption[108]. These kinds of innovation may often offer significantly greater benefits to poor farmers or consumers than science-intensive technological solutions. But their less attractive commercial benefits mean they remain, like

Outside the techniques of molecular genetics, there are many other promising innovations for improving global food sustainability.

Cinderella, too often uninvited to the innovation party.

What is shown by this food sector example, is that — even in a specific area — innovation is not about simply 'forging ahead', 'lagging behind' or 'catching up'[133]. It is not a single-track race driven by a particular privileged field of science. Instead, it is about diversity, exploration and choice. This is why it is misleading to uphold particular pathways as offering exclusively 'sound scientific' or uniquely 'pro-innovation' options (or for all contingently-emerging innovation to be asserted necessarily to be "great"). And this is why exaggerated 'no alternatives' language (on any side) can polarize controversy and so also impede effective innovation policy. By seeking to invoke the general authority of science and technology in partisan ways, this kind of language does not only threaten effective innovation. It also risks compromising science and undermining democracy itself[134]. More mature and rational debate recognizes that choosing between the pros and cons of alternative innovation pathways like those exemplified here are less technical than they are political.

A more reasonable and productive way to handle these crucial issues in innovation policy is to be more transparent, deliberate and accountable about when it is right to 'open up' and when to 'close down' in any particular field[135]. This means that no particular innovation should be unduly favoured by policy making, simply because of its appeal to particular powerful vested interests within a given innovation system. Nor should it be treated on these grounds as self-evidently uniquely unacceptable. Either position requires context and perspective-specific argument. In other words, what is needed is mature political debate, as much as ostensibly definitive analysis[136]. What can be recognized as well, though, are the benefits of some requisite degree of diversity[137]. And this is a general quality that can be achieved in many different ways — even to the extent of potentially excluding any particular innovation.

This can be illustrated by the further example of the challenge of mitigating climate change by building zero-carbon energy infrastructures. Here, decades of intensive research by government and industry bodies has shown that there exist (despite the formidable constraints) a range of alternative innovation pathways that are viable under contrasting equally-informed understandings[138]. For some, the solutions centre around nuclear power[139]. Others highlight large scale use of carbon capture and storage[140]. In the wings, momentum is growing behind expedient and idealized aspirations somehow deliberately to control the global climate through geoengineering[141–145] – a technology threatening particularly acute and irreversible forms of 'lock in'[146,147]. Yet all the time, a rich array of renewable energy technologies is available for addressing climate change in a diversity of radically different distributed or centralized ways[148–151].

The key point is that there is no definitive technical or economic reason why any of the energy strategies above cannot (for better or worse) provide a basis for a variety of zero-carbon UK or global energy futures. Crucially, this includes the clear feasibility (equally for the

It is remarkable how many major global industries are building around once-marginal technologies.

UK and Europe[147–153] and the world as a whole[118,119,136,154]) of strategies built entirely around energy efficiency and renewable energy. Yet one of the main obstacles to this lies in high profile self-fulfilling assertions to the contrary, including by authoritative policy figures[155,156]. In energy, as in the food sector discussed above, the obstacles to less favoured strategies are typically more commercial, institutional and cultural than they are technical. Amongst the most potent of these political obstructions are claims from partisan interests — such as incumbent nuclear or fossil fuel industries — that there is no alternative to their favoured innovations and policies[155]. Even given the formidable constraints bearing on sustainable energy and agriculture[157], there remains much hidden scope for radical choice. And this is a matter for critical democratic deliberation as much as technical analysis[21].

There are many ways to resist such unhelpful syndromes and to develop more reasonable debates about innovation. Some are about the style of discourse — for example, developing a greater tolerance on all sides for embracing adverse public reactions to particular innovation pathways. When they transcend privileged 'not in my backyard' parochialisms, general public preferences offer an important guide to the general orienting of innovation. And just as scepticism is one of the crucial constituting qualities in science itself[158,159], so space for public scepticism and healthy critical debate can help improve the quality of innovation more generally[160,161]. With mainstream institutions often especially strongly disciplined by incumbent powerful interests, the role of delivering on this important quality of scepticism often falls disproportionately to civil society[162].

And this important role of wider society extends beyond debate and controversy. It is remarkable how many major global industries are building around once-marginal technologies like wind turbines, ecological farming, super energy-efficient buildings, or green chemistry[7]. All of these owe key elements in their pioneering origins to early development by grassroots social movements[163]. For instance, without the small country of Denmark remaining partly below the radar of international nuclear interests, able to nurture alternative energy strategies in the 1970s that were driven strongly by anti-nuclear social movements, it is arguable that the present global wind industry might never have become competitive[164]. This is just one of the examples of innovations that were systematically marginalized — sometimes actively suppressed — by incumbent interests in science, government and industry[165].

It is of course important not to become too romantic about the dynamics of social movements and their favoured innovations[162]. These too warrant exactly the same kinds of healthy scepticism appropriate to other actors in innovation debates. But history does reveal the origins of many of the ostensibly driving environmental and social justice concerns, which currently play such prominent roles in justifications of current innovation policy. Without decades of struggle by social movements dedicated to humanitarianism, environmentalism and social justice, it is doubtful that high-level global agenda-setting developments like the Stockholm Environment Conference or the Brundtland Commission or the Millenium Development Goals would ever have become as formative as they have[166–170]. And this pattern is arguably reinforced by the history of continuing crucial roles played by civil society in other emancipatory transformations around colonialism, racism, women's and gay rights[171–177].

Just as the famous dark matter in cosmology stabilizes the visible structures of galaxies, so these apparently intangible distributed social forces help condition the gradients that ultimately help forge and steer new directions for innovation[172]. The greater the critical interest in the most progressive orientations for innovation — rather than those that preserve the status quo — the more this is generally true.

Risk, Uncertainty, Ambiguity and Ignorance

These policymaking challenges are compounded because the pros and cons of different innovation pathways are — under all views — subject to seriously incomplete and problematic knowledge. As discussed further in Chapter 6, the normal way to address these dilemmas is by means of regulatory risk assessment[173, 174]. Although often not implemented in full, this prevailing approach invokes the apparent authority of probabilistic analysis[175, 176] to assert a notionally single 'sound scientific' or 'evidence-based' picture[177, 178]. This task can be approached in many variously complex ways[179, 180]. But at root, it involves alternative possible positive and negative outcomes being weighted by their respective likelihoods to aggregate a single overall 'expected value' for the balance of future benefits and harms[181, 182].

In conventional innovation policy and regulation, it is simply assumed that whatever products or technologies are most energetically advanced for risk assessment are in some way self-evidently beneficial[183, 184]. Questions then typically focus on whether any associated risks will be tolerable[185, 186]. It is rare for the claimed benefits themselves to be rigorously scrutinized[57, 187], let alone compared in a balanced way with other potential benefits of alternative innovation pathways[58, 188]. Therefore existing forms of risk regulation do little to address the wider issues in innovation politics discussed above. Innovation pathways backed by the most powerful interests typically prevail.

Further challenges arise in the reliance of risk-based regulation on the methods provided by probability theory[189, 190]. Probabilistic tools can be useful in tackling familiar, high-frequency, relatively unchanging challenges, as found in the risk regulation of many urban transport or public health systems[191, 192], for example. Where empirical evidence arising from past experience is held to be a reliable guide to the future, these tools can be very powerful — as in established responses to familiar safety risks[193]. But where an innovation pathway (or its context) is novel, complex or rapidly changing, uncertainties cannot confidently be reduced to single definite probabilities[194]. Such inabilities to justify a single picture of probabilities can arise, for instance, in the regulation of nanotechnologies[195] (see the case study in this chapter), endocrine disrupting chemicals[196], or novel living organisms[197]. Under these conditions, it can be irrational to assert a single definitive 'evidence-based' picture[198]. In these fields (as more widely), policy making must often contend with contrasting — but equally reasonable — interpretations of uncertainty[65, 78]. These cannot reliably or rationally be reduced to simple numerical probabilities.

These are not the only limits to risk assessment. Beyond uncertainty in the sense discussed above[199–200], there exists a further array of challenges[201, 202]. These involve not the relative likelihoods of different outcomes, but the meanings of the possibilities themselves. For instance, divergent views may exist over how to categorize or partition different kinds of benefit or harm. Or there may be questions over exactly how to frame the various dimensions under which these are defined[203]. What are the appropriate imaginations, understandings, values, or interests according to which they should be interpreted or prioritized[204]? There may also be differences over which innovation pathways to include or exclude from scrutiny, or how to allocate attention[76].

These are challenges of ambiguity — contradictory certainties[205] — rather than strict uncertainty[206, 218]. And risk assessment is no more able to resolve these disagreements over meanings as over likelihoods[207]. Indeed, Nobel Prizes

> **In conventional innovation policy and regulation, it is simply assumed that whatever products or technologies are most energetically advanced for risk assessment are in some way self-evidently beneficial.**

have been awarded in rational choice theory, for axiomatic proofs demonstrating there can be no definitive way to guarantee the calculation of a particular optimum balance between contending ways to interpret, measure or prioritize possible outcomes[208, 209]. Yet such challenges remain not only the norm in many innovation debates, but constitute the key issues in contention in controversies like those over alternative agricultural, energy or health strategies[210]. Under ambiguity, claims to derive single definitive 'sound scientific' or 'evidence-based' prescriptions are not only seriously misleading, they are an oxymoron[211].

The above difficulties may seem tricky enough. But even more intractable than uncertainty and ambiguity is the further challenge of ignorance[77, 201, 212, 213]. Here, possibilities are not just disagreed upon, but at least some are entirely unexpected[202, 214]. This was the case, for example, in the early regulatory history of bovine spongiform encephalopathy (BSE)[215], endocrine-disrupting chemicals[216] and damage by CFCs to stratospheric ozone[217]. Like many other cases[55, 56], these involved mechanisms that were not just thought unlikely at the inception of the issue, but were at the time 'unknown unknowns'[218]. Whenever we don't know what we don't know[219], the prospect of possible 'black swans' is raised[220]. These challenges are not about calculable risk, but inherently unquantifiable surprises[222,234, 235]. To seek to assign single definite values for risk in these circumstances is not just irrational but dangerous[223].

Surprise is not necessarily always a bad thing. It is intrinsic to the rationale for blue skies science — as well as research and innovation more generally — that positive benefits can also be entirely unexpected[221]. An example might be the laser — a novel laboratory phenomenon that was for a long time a tool without a use[224]. Likewise, although it raises many variously questionable applications, the internet has also undoubtedly given rise to a host of benefits that were initially entirely unexpected[225]. But it is also clear — for instance in areas like nanotechnology — that there is no guarantee that further research will necessarily reduce uncertainty, ambiguity or ignorance[226]. As Albert Einstein famously observed, it is often the case that the more we learn, the more we find we don't know[227]. This is not necessarily bad — indeed, it is a key motivation in science[228]. It is instead political pressures that resist the humility of acknowledging ignorance[229]. Either way, it is clear that some of the greatest dilemmas in innovation governance extend well beyond risk, because they are about surprises. With conventional regulatory risk assessment entirely unable to deal with this deepest form of incertitude, the importance of robust critical deliberation and wider political argument about innovation is seriously reinforced.

Precaution and Diversity

One widely established and intensely debated response to these challenges in innovation policy is the precautionary principle[230, 231]. Although it comes in many forms[232], a classic general expression of precaution is that scientific uncertainty is not a reason for inaction in preventing serious damage to human health or the environment[233]. By explicitly

> **Precaution remains a subject of much misunderstanding and mischief.**

hinging on uncertainty rather than risk, precaution helps to promote recognition that social choices in innovation are not reducible to ostensibly precise, value-free, technical risk assessments[234]. These dilemmas are instead explicitly recognized to involve wider issues and alternatives requiring overtly value-based — and thus political in this sense — deliberations over policy.

This message is inconvenient to many powerful partisan perspectives wishing to dragoon the authority of science as a whole in favour of specific interests[235]. Often driven by such motives, opposition to precaution rests largely on assertions (or assumptions) that established 'science-based' regulatory risk assessment offers both a sufficient general response to the challenges of social choices across alternative innovation pathways, and a particular way to justify favoured technologies[236, 237]. So, precaution remains a subject of much misunderstanding and mischief[238, 239,241]. This often involves ironically emotive rhetoric in supposed defence of reason[240]. It is on these grounds, for instance, that arguments are sometimes made that it is somehow irrational not to always use probabilities to qualify potential hazards. In this way, many critics of precaution mistakenly ignore uncertainty, ambiguity and ignorance, insisting instead that these be treated as if they were risk[182]. The precautionary principle has played a crucial role in fostering more rational reflection about these highly political pressures on the use and abuse of science in technology regulation.

Treating general dilemmas of uncertainty, ambiguity and ignorance as a simple state of risk perpetrates the misunderstandings discussed above: that probabilistic analysis is universally applicable, and that innovation is a single-track race. When these misapprehensions are corrected, precaution can be recognized simply as a guide to the more rational and realistic steering of social choice among possible innovation pathways[242]. So precaution is not (as often alleged) about being somehow generally 'anti-innovation' or 'anti-science'[240, 243, 244]. Instead, it simply urges greater rational consideration of different aspects of incertitude than can reasonably be reduced merely to risk [56, 231, 236, 260, 261].

Consequently, precaution does not automatically mean abandoning any particular innovation, still less innovation in general[247]. Contrary to many claims[248], there is nothing inherent in the precautionary principle that automatically requires bans[249], or makes it biased in its applicability to innovations of contrasting provenance[250, 251]. Precautionary action inhibiting any one innovation pathway inevitably favours another[245]. And precaution does not even mean abandoning risk assessment[204, 267]. It simply reminds us that risk-based approaches do not offer a complete response to the deeper challenges of choice[252].

Precaution is also a guard against the error of treating the absence of evidence of harm as evidence of absence of harm[253]. This is often a particular danger for innovations whose novelty means there has been little time for evidence to accumulate, or where incumbent interests discourage research or assessment of the requisite kinds[254]. Before invoking a lack of evidence of harm, it is necessary to think about how visible this evidence might actually be expected to be if it existed, or how vigorously it is sought[255]. Uncovering false negatives is often more important than identifying false positives[57]. In this respect, precaution is a guard against misleading blinkers favouring the status quo[256].

In essence, precaution simply highlights that innovation policy and associated politics should pay more careful attention to the intrinsically problematic nature of knowledge, as well as its vulnerability to economic and political pressures. But it does not just highlight problems. The precautionary principle also opens the door to solutions — pointing to a range of rigorous and practical strategies for dealing with the realities of uncertainty, ambiguity and ignorance in innovation[257]. These 'Cinderella methods' can be neglected if there persists a sense that risk assessment alone is sufficient[223]. Practical examples include a range of different practices for opening up regulatory appraisal, research strategies and innovation policy[258], as well as the prioritising of qualities like reversibility[259], resilience[260] and flexibility[261].

Rather than resting hubristically on an ostensibly definitive picture of the pros and cons at some particular point in time, these precautionary strategies acknowledge stronger grounds for greater humility[229]. They prioritize measures to maximize learning[201] and adaptability[262] in careful step-by-step implementation rather than optimistic wishful thinking[263]. This in turn means taking particular care when appraising or pursuing innovation pathways that might lead to irreversible effects[249], or whose associated infrastructures might prove to be especially inflexible[250]. All else being equal, when a range of innovation pathways look as if they present similar balances of pros and cons, precaution simply highlights that it is reasonable to prioritize that which is more reversible over the less flexible alternatives[264].

At root, a key value of precaution lies in helping to free policy debates from the Panglossian fallacy that the most powerfully favoured innovation pathways are somehow necessarily the best or only option[265]. It reminds us that particular values also need to be applied, especially around human health and environmental integrity[266]. This enables societies to discuss rationally and directly when it is right for governance deliberately to discourage or discontinue a particular entrenched trajectory[267]. The crucial point is that precaution makes this possible without incurring existential anxieties over innovation in general. As a general principle, it offers a flexible means to avoid simply relying on hopes that powerful vested interests will be spontaneously relinquished. And in this, precaution points to a further quality in research and innovation systems, namely diversity.

Even though it is neither a panacea, nor a 'free lunch'[268], nor self-evident in its composition, diversity is a vital consideration in research and innovation policy[54]. Like other strategies, it brings its own challenges and remains intrinsically a matter for political judgement. But in any given area, recognition of the importance of diversity encourages caution about concentrating resources in support of the particular innovations that happen to be favoured by the most powerful interests[269]. Diversity urges instead greater attention to alternatives, leading to more deliberately and systematically-constituted portfolios comprised of some balanced variety of disparate innovation pathways[54].

In these terms, diversity offers a remarkably practical way to help address several otherwise intractable innovation problems. It offers a 'resource pool'[270] helping to nurture creativity[55], mitigate lock-in[95], hedge against surprise[271], accommodate ambiguity[272], resolve irreconcilable interests[273] and cultivate resilience[274]. And by fostering more intensive encounters between varying kinds of knowledge and practice, deliberate diversification can also help enhance innovation processes themselves[275], and make them more effective and socially responsive and robust[276]. It is remarkable to find so many otherwise intractable challenges addressed (albeit always provisionally and incompletely) by a single operational strategy. And there exist plenty of useful tools to help focus more concretely at the level of innovation portfolios[277, 278].

Consequently, deliberate diversification is one key pragmatic way to deliver greater precaution, while also helping to diffuse unhelpful polarisation in debates over innovation[279]. This is aided by more explicit and measured pursuit of portfolios of innovations in particular areas, rather than single, privileged, supposedly uniquely 'scientifically-sound', 'evidence based' solutions. Moreover, a focus on diversity may also help to develop greater political tolerance for the otherwise difficult — but inevitable — kinds of failure that are so essential to effective learning[280]. If commitments lie at the level of diverse portfolios rather than single supposedly 'no alternative' solutions, then it

> **Precaution is also a guard against the error of treating the absence of evidence of harm as evidence of absence of harm.**

becomes easier to accept and justify the kinds of failures that contribute so much to learning.

To help realize these concrete benefits, however, diversity must move away from being a fig leaf or argument-of-last-resort for some otherwise ill-favoured but powerfully-backed choice[281]. It is all too easy to support otherwise indefensible proposals on the basis that "we must do everything"[282]. This invites powerful interests to continue insisting on the adoption of their own favoured policy, simply on the grounds that every option must be pursued[283]. There are typically many kinds of diversity, each exclusive in some ways and inclusive in others[269, 284]. As with individual innovation pathways, the detailed constituting of diversity also involves inherently political judgements. By urging this greater attention to diversity (as in other ways), precaution can be as much a spur to innovation in general, as a brake on any specific kind.

Three Key Conclusions

Formulating an adequate response to the challenges discussed in this chapter requires being clear about the resulting practical implications for policy. There have been many recent reports outlining concrete recommendations for research and innovation strategies, and the wider policy procedures and political debates in which these are set. The European Science Foundation usefully reviewed key background issues on the relations between research and innovation systems across wider European societies[285]. The Expert Group on Science and Governance put this in the context of the European 'Knowledge Society'[246]. The Nuffield Council on Bioethics looked at the most effective institutional practices for governing newly-emerging technologies[36]. The UK's Engineering and Physical Sciences Research Council helpfully identified a number of responsibilities to be encouraged across all actors in innovation systems[286]. A 'new manifesto' funded by the UK's Economic and Social Research Council explores some of the global implications[287]. Many other international initiatives contribute much further detail[288, 289, 290]. But the general practical implications are quite readily summarized in terms of three overarching principles: participation, responsibility and precaution[256].

First, there is *public participation* in innovation. Policymaking should more explicitly and transparently acknowledge the inherently political (rather than purely scientific or technical) nature of the interests and motivations driving contending pathways for innovation. As addressed in Chapter 5, this requires sincere and detailed forms of participatory deliberation and wider engagement with diverse public perspectives. This is not about fostering credibility, trust or acceptance[291], but about helping to determine the priority directions for research and innovation[292]. Nor is participation about political correctness, or relativism about science (implying a position that 'anything goes'[293]). Indeed, public engagement often offers the most effective way to illuminate how particular extant understandings are inappropriate in any given context. In essence, public engagement is simply about more rigorous exploration of

Policymaking should more explicitly and transparently acknowledge the inherently political nature of the interests and motivations driving contending pathways for innovation.

specific ways in which legitimate judgements about benefits, excellence, relevance, risk and impact all depend partly (but irreducibly) on values and assumptions as well as evidence.

In other words, it is only through effective public participation that policy can address how valid understandings of the appropriate directions for research and innovation are inherently 'plural and conditional'[105]. 'Plural', because a number of contrasting interpretations are typically equally robust. 'Conditional', because the salience of each depends partly on perspectives and circumstances. A rich variety of carefully developed participatory and deliberative practices are available, with varying kinds of value in different contexts[294–295]. And crucially, participation does not just mean talking about innovation, but also inclusion in the means for supporting the actual doing of innovation[7, 296, 297]. So in engagement — as in innovation itself — there are key roles for the creative arts, humanities and civil society. Some approaches are less formally structured than others, involving uninvited as well as invited engagement[298]. But together, these enable more careful scrutiny of how reasonably differing understandings, assumptions, uncertainties, questions, priorities and values can legitimately favour contrasting innovation pathways in any particular area[299]. In short, greater participation helps to open up deeper and wider appreciations of alternatives[258]. In this way, diverse forms of public engagement can supplement, enrich and inform (rather than substitute) the conventional procedures of representative democracy[300]. And freed from the pressures to pretend at ostensibly definitive, 'sound scientific' prescriptions, decisions may become not only more democratically legitimate, but also more efficient and timely.

The second major policy imperative sits alongside, and is reinforced by, the value of public participation. This involves all actors in research and innovation processes — especially the most powerful — taking more direct and explicit *responsibility* for the consequences and uncertainties of their activities. As addressed in Chapter 9, this involves serious effort to be reflective in anticipating, describing and analysing the impacts that might arise, as well as the attendant ambiguities and unknowns. This helps to avoid the 'organized irresponsibility' of otherwise passing the buck to insurers, regulators, victims, the state, or society at large to deal with inevitable unintended and indirect outcomes[301]. Assisted by public engagement, responsibility involves being more open about the motivating aims and interests of relevant actors. Responsibility is not about aspiring — let alone claiming — to predict or control consequences. Nor is it about simple exhortations to trust[302]. Instead, responsibility is about trustworthiness[303]. It means going beyond conventionally narrow institutional and economic interests, to care — and be accountable — for wider social and environmental implications.

Crucially, the aim of responsibility is not to assert a single definitive technical authority, as is too often emphasized in conventional risk regulation. Instead, responsibility informs engagement by helping illuminate a range of contending directions for decision making. There is nothing about this process that should make decision making more protracted or burdensome. Indeed, by helping to avert ill-advised trajectories at an early stage, engagement and responsibility can enable innovation to become more effective in addressing social values[40]. This does suggest particular responsibilities for the media, though. The discussion in this chapter has shown that it is quite simply irresponsible to pretend (as is too often the case) that science and technology are apolitical. What is required instead is a less simplistic and romantic portrayal of technical expertise. The media hold especially important responsibilities for enabling more realistic, mature and open debates about the inherently contestable and power-laden nature of both scientific knowledge and technological innovation.

This leads to the third and final general policy implication: that greater and more deliberate efforts are needed to moderate the powerful forces of closure and 'lock-in' in science and technology. This chapter has described the particular value of *precaution* as a way to address this point. Rather than treating existing patterns of research and innovation as value-free, the precautionary principle strikes a stronger balance under uncertainty, in favour of human health, environmental integrity and social well-being in steering innovation priorities. Thus guided by precaution, engagement and responsibility can elucidate more clearly what might be meant by these values in any given context. Together, these complementary imperatives help to provide a counterweight to otherwise dominant incumbent interests. In particular, precaution directly addresses the tendencies for uncertainties, ambiguities and ignorance to be closed down in the most convenient directions, as if they were just 'risk'.

Once innovation is recognized as a branching rather than single-track process, it becomes clear that precaution is also not about impeding innovation, but steering it.

Innovation is fundamentally about the politics of contending hopes.

Acknowledging the scope for systematic deliberation over values, priorities and alternatives in the context of uncertainty, precaution broadens out risk regulation to allow greater consideration for a wider plurality of issues, options, perspectives and scenarios. This can help enable entrepreneurs, smaller businesses, new entrants, civil society groups and marginalized interests (as well as government) to challenge and reshape established trajectories. As we have seen, precaution also implies a greater focus on qualities of diversity, flexibility and responsiveness. And a final key lesson of precaution is that research and innovation policy should seek to respect and embrace (rather than manage or curtail) public mobilization and critical dissent. In essence, precaution expresses the fundamental principle that — in innovation just as in science itself — reasoned scepticism fosters greater quality.

Further practical implications of these principles of participation, responsibility and precaution are returned to in the Government Chief Scientific Advisor's Annual Report 2014. But in concluding this chapter, we return to a point made at the beginning. In any given area, innovation is not so much about a race to optimize a single pathway, but a collaborative process for exploring diverse alternatives. Current noisy anxieties over single-track competitive innovation races tend to be driven by expedient pressures from incumbent interests. These can conceal or deny underlying motives, uncertainties and alternatives. Instead, the three principles of participation, responsibility and precaution can help innovation policy escape from currently narrow (often fear-driven) supposed technical inevitabilities. They illuminate how innovation is fundamentally about the politics of contending hopes[21]. Most importantly of all, it is perhaps only in these ways that we can move away from narrowly technocratic ideas of a knowledge economy[246], to nurture instead a more realistic, rational and vibrant *innovation democracy*.

A more fully referenced version of this paper is posted at http://www.sussex.ac.uk/Users/prfh0/innovation_democracy.pdf

Tim O'Riordan
(University of East Anglia)

CHAPTER 5: HOLDING A WIDER CONVERSATION

It is necessary – and unavoidable – for innovation policy to include a broader range of views, as the experiences of the GM and radioactive waste disposal consultations demonstrate.

Science has forever been a reflection of changing cultures. In many respects, science advances as a series of unfolding conversations. These conversations take place within the host of scientific communities; between scientists and their funders, sponsors and power brokers; amongst the many social and ideological interests of the various publics that compose democracy and citizenship; and between scientists, policy makers and the multitudinous publics. Andy Stirling has introduced this special engagement in Chapter 4.

Conversation is an art-form which may have to be re-learnt. Daniel Menaker suggests[1] that conversation has many purposes: gossip, grooming, socialising, and learning. For the purposes of this chapter, conversation requires empathy and understanding between the communicating parties; a willingness to tolerate different views through respect and sensitivity; but crucially a commitment to learn and to realize how and when to agree and to disagree. Conversation is both inherent and learned. Social animals communicate for prosperity, for survival and for love, to appreciate danger, and to judge risk. Widening the conversation is a democratic necessity, a reflection of basic human rights, and an expression of responsible citizenship (see case study). Yet in the present age, such a course cannot be taken for granted. So extending understanding and engagement may prove to be a vital cohesive force for an anxious polity.

In an age of expanding global reach and a shrinking local sphere, addressing innovation and risk has to grapple with the changing political and social attention span. (In Chapter 10, Nick Becksted and Toby Ord consider both catastrophic and 'beyond catastrophic' (existential) risks in this larger context). Social attention span in turn is distracted by the social media, with their exuberance of free expression that is usually unencumbered by the restraints of peer acceptance. The emerging discourse is fragmented, but overall it is learning and responding. This creative interaction provides the setting for this chapter. Holding a wider conversation is unavoidable and vibrant. If done well, it will recreate science as an extension of social and political learning. The focus on innovation and risk, with its inherent contradictions and interdependencies from the outset, offers robustness and timeliness to this enlarging conversation.

Political anxieties, innovation and risk

We are experiencing the deepest and most prolonged economic restructuring of the modern era. Across the globe, the future of the next generation of school leavers depends on them acquiring skills over accelerating technology and rapidly changing business management styles, which too few are trained to master[2]. We are in danger of creating a 'lost generation' out of step with preparing for a sustainable age unless we tap the essentials of entrepreneurship[3]. This damaging process could be worsened if observable inequality of income and career development becomes more widely recognized. Thomas Piketty believes that the asymmetry of wealth creation and accumulation will result in considerable social tension in the

We are experiencing the deepest and most prolonged economic restructuring of the modern era.

coming years[4]. His policy prescriptions are controversial, but the basic argument is not disputed[5]. This prospect is leading to a vibrant examination of the links between wellbeing as a basis for judging economic and social betterment; for social investment as a contribution to assisting especially young people to become better equipped for a changing economy and democracy; and for greater equality to be given a higher profile in any consideration of a transition to greater sustainability[6]. Lying behind these themes are considerations of new forms of democracy; new forms of financing sustainability investments, especially at the sub-national level; and new forms of sustainability learning for leadership in schools and in higher education.

Official reports from the UK Office for National Statistics[7] and the Organisation for Economic Cooperation and Development[8] point to a widening of economic and social inequality in many parts of the developing and developed world. Opinion polls, though containing mixed messages, reveal a growing sense of despair in many developed economies among the lower-middle and middle classes (the beneficiaries of innovation and of political stability in the past) that the fortunes for their offspring will forever diminish[9]. This is a recipe for disenchantment and disengagement. Mobility and aspiration are the lifeblood of prosperity and democracy. Snatch these away and the scope for creative and effective dialogue over innovation and risk diminishes. If the benefits of innovation appear to apply selectively to the few (the entrepreneur, the well-connected, the expensively trained, and prosperous elderly), then any associated risks may become linked more to a sense of social disgruntlement than to apparent danger. If this disaffection is reinforced by anxiety (over the outcomes of climate change, or the failure of the shrinking public purse to protect the vulnerable) then the appetite for holding a wider conversation lessens. The debate about innovation and risk has to address the deepening concerns over the indecencies of ill-being and frustrated democratic intervention. This is part of the envelope for successful innovation introduced by Nick Stern and his colleagues in Chapter 1. They also emphasise skills training, encouragement of enterprise and trusting democratic procedures, which I will address in the case studies that conclude this chapter.

In a very challenging manner, the special theme for the emerging debates over innovation and risk lies in addressing the changing nature of economic success and

CASE STUDY

HUMAN RIGHTS AND RISK

Karen Hulme and Sabine Michalowski (University of Essex)

Human rights have an important role to play when considering regulatory responses to new technologies, because they provide a legally binding framework within which such decisions need to be made.

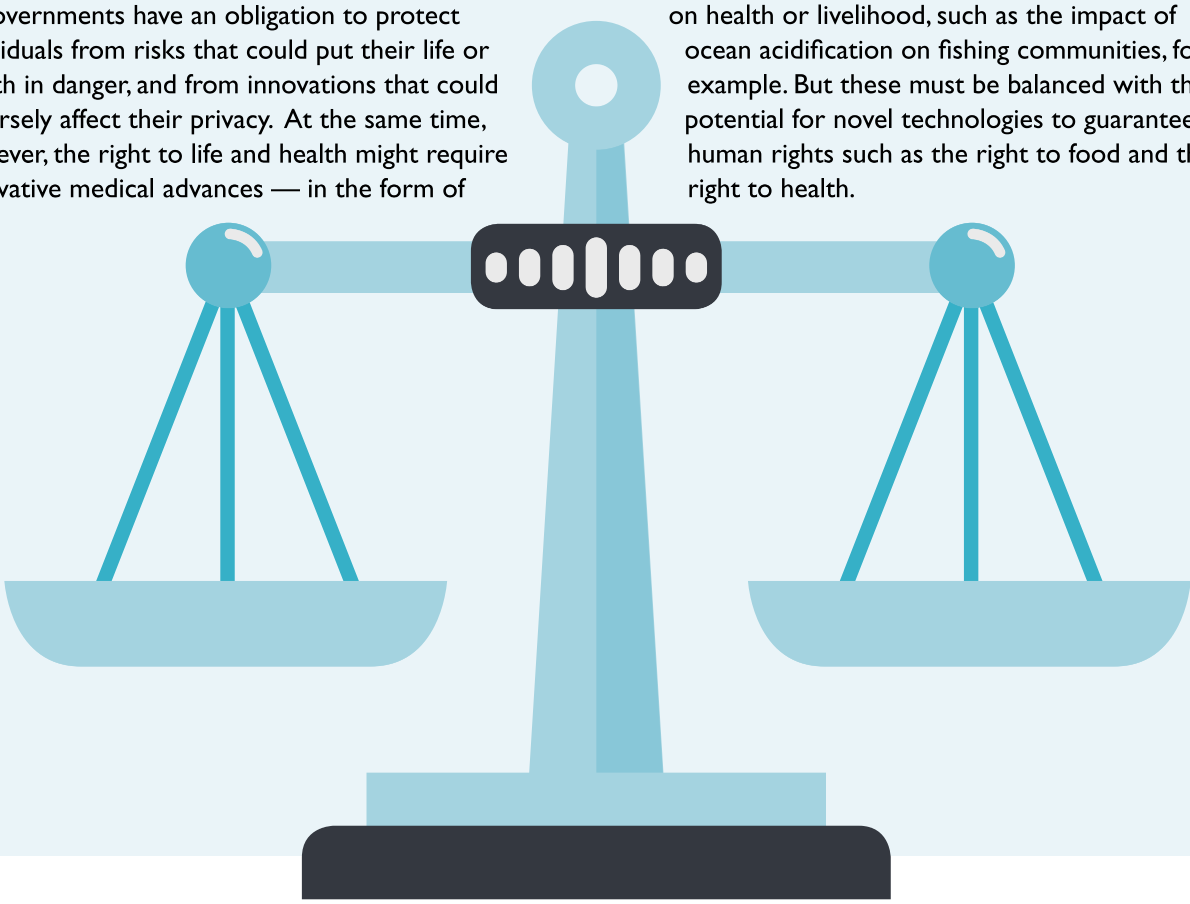
Human rights are often defined in a rather general way, are far from absolute, and they can be limited by conflicting rights and societal interests. As such, they do not necessarily provide clear answers to the question of how government should address risk and innovation. They can, however, set limits and provide a framework for conceptualising the relevant questions and responses, because any approach to risk regulation needs to take into account the rights of those who are potentially affected.

When balancing these rights with those of potential beneficiaries, as well as the broader public interest, policymakers must ensure that any risks associated with an innovation are not disproportionately borne by vulnerable groups in society, who might be more likely to act as research subjects but are less likely to benefit from the associated scientific advances, for example; or they might live in areas that are negatively affected by a particular technology.

Governments have an obligation to protect individuals from risks that could put their life or health in danger, and from innovations that could adversely affect their privacy. At the same time, however, the right to life and health might require innovative medical advances — in the form of mitochondrial replacement therapy, for example — while the right to private and family life may demand access to innovative reproductive techniques.

Many advances in web technology also engender risks for human rights — specifically the right to privacy — such as the increasing availability of medical apps, especially related to the production, storage and handling of sensitive data. Key privacy issues raised by such technologies include: who has access to this information; what information is being uploaded for consumption by others; and how much control does the individual keep over their personal information? These advances create additional risks when people do not appreciate the limits of the technology — as a result, they may trust it beyond its capabilities, with consequent risks to the right to life and health.

In the push to deliver innovative scientific solutions to global problems — such as using genetic modification, nanotechnology and geoengineering — there are equally obvious human rights implications that highlight the need for broad consultation (the right to information, and the right to a healthy environment). Those assessing the risks of innovation must give sufficient weight to any potentially disastrous impacts on health or livelihood, such as the impact of ocean acidification on fishing communities, for example. But these must be balanced with the potential for novel technologies to guarantee human rights such as the right to food and the right to health.



social learning. This places much greater emphasis on the notion of wellbeing with its qualities of personal esteem, confidence building, leadership, enterprise, and cooperation as a basis for improving personal and public health; for enabling capabilities to flourish in everyone; and for offering meaningful ways to change local circumstances for the betterment of neighbours as well as of families. Only a flourishing and more equalizing society can converse across social space with confidence and compassion.

Science can play a vital part in this process. Alex Ryan and Daniela Tilbury argue for new approaches to learning for sustainability leadership for young people[10]. They call for a fresh approach to critical analysis; to more cooperative forms of learning between students and faculty and all manner of stakeholders beyond the classroom; and for much more creative approaches to combining the imaginings of all pupils in laying out future outcomes and consequences for the fair treatment of future generations. Theirs is a plea for much more student leadership in learning, and for much greater freedom to explore fresh approaches to analysing circumstances and devising ways forward. Here is a recipe for a science for sustainability in which holding a wider conversation plays a fascinating and creative role.

This report covers all of the key features of relating innovation to risk. It especially concentrates on the many ways in which risks are judged, and the emerging global and local contexts in which decisions have to be made regarding innovation to better future societies the world over. And it forces recognition of the requirement of resilience in the design of innovative success. Resilience is sometimes misapplied as a byword for sustainability because the essential ingredient of sustainability is self-reliance. Self-reliance can best be visualized and attained by a setting for innovation where wellbeing, fairness, adaptability and leadership enable everyone to converse with shared understanding for a much more fair and tolerable democracy in a limiting but forgiving planet.

Holding a wider conversation, therefore, has to take into account changing perceptions of democracy, fairness of treatment, opportunities for flourishing, and a culture of belonging to the ever-changing worlds of risk and innovation. It is by no means confined to conversing. Nick Pidgeon observes in Chapter 8 that risk tolerance is a function of critical trust formation which arrives with creative forms of engagement and independent referentials of advice and commentary. We shall see that such procedures are now being offered by the government in its recently revised consultation White Paper on geological disposal of radioactive waste[11].

On widening engagement

The Lords' Committee on Science and Technology reviewed the troubled relationship between science and society[12]. It noted strands that are carried forward in this report, namely that science is being dissected for its probity, its sources of funding and its intended audience. The Committee also examined how science is standing in the public dock over who seems to be gaining from its benefits and over what period of time, and to what degree science is attentive to various underlying public concerns that normally transcend scientific analysis. Two particular observations presented in the executive summary of the Committee's report stand out:

- "Some issues currently treated by decision-makers as scientific issues in fact involve many other factors besides science. Framing the problem wrongly by excluding moral, social, ethical and other concerns invites hostility."

- "Underlying people's *attitudes* to science are a variety of *values*. Bringing these into the debate and reconciling them are challenges for the policy-maker."

Four cases of risk in relation to both science and technological innovation emphasize these observations. One is the BSE scare, which highlighted the contentious links between bioscience and the commercial food industry (see Chapter 9). Another similar theme, still very much in evidence, is the long running public hostility to genetically modified (GM) crops and food (see case study in Chapter 11). A third, also yet to be resolved, is the non-acceptance of safe disposal of long-lived radioactive waste (see below). The fourth, also still highly politically contentious, is the hydraulic fracturing of methane-containing shale formations (see case study on fracking at the end of Section 2). These case studies contribute to the evidence base of this chapter.

What characterizes all four of these typical but not exhaustive innovation-risk examples is the science-led initial development; the connection to a profitmaking commercial sector; an unbalanced distribution between those who gain and those who are exposed to the perceived risks; an inconsistency over the seemingly wide ranging general benefit of the technology and the localized or targeted exposure to any residual risks; complicated time frames of immediate gain and prolonged uncertain disadvantages, especially for future generations; and a deeply felt resentment amongst vociferous antagonists that their preciously held underlying values are being excluded from the final policy decision. In essence these case studies

> **Only a flourishing and more equalizing society can converse across social space with confidence and compassion.**

give the impression that certain kinds of innovation are generated to an advanced stage of implementation without either democratic involvement, decency of treatment, fairness of distribution of gain and losses, or a truly listening political class.

The various examples that pervade this report require the attention of a wider conversation. Before and after the Lords' Committee report, there was a general call for much more openness, honesty, transparency and participatory engagement in the whole process of shaping policy when science, technology, public policy and economic prosperity interact. This febrile ferment was also much influenced by an equally influential report by the Royal Commission on Environmental Pollution on incorporating public values in environmental standard setting and regulation[13]. Here the Commission pleaded for a much wider public involvement together with a more normative role for environmental regulation:

- "Better ways need to be developed for articulating people's values and taking them into account from the earliest stage in what have been hitherto relatively technocratic procedures" (page 119).

- "No method for determining or articulating people's values whether traditional or novel provides a guaranteed solution. Novel approaches should be evaluated for their ability to elicit a full spectrum of values on the issue in question from representative participants. So that the procedures used can be refined in the light of experience and their full potential realised" (page 111).

The intellectual and political turmoil over innovation and risk led to a period of intensive academic research. This focussed on the need to look much more critically at the ethical and power-related settings which underpin the emergence of innovation[14]; over the need to place much more emphasis on the earlier discussion of any emerging discovery so as to clarify the 'framing' (biases) and the genuine human needs for any innovation[15]; and for new forms of facilitated dialogue, or 'deliberative mapping'[16, 17].

This corpus of research led in turn to important shifts in the institutional architecture of science-policy studies. The Royal Society created a Working Group on Nanotechnology and Nanoscience in 2004 (ref.18), and with its sister institution the Royal Academy of Engineering formed a wide-ranging consultation on geoengineering[19]. The UK government established Sciencewise in 2005, which took over the work of its Committee of the Public Understanding of Science. And in response to the Council for Science and Technology, Science and Society Subgroup recommendation that the UK government should establish a "corporate memory" to improve dialogue with the public[20], the Sciencewise Expert Resource Centre for Public Dialogue in Science and Innovation was created in 2008. Since then, Sciencewise has instigated a program of capacity building, learning, and embedding best practice in public dialogue across government and beyond. It has also supported and guided 17 experimental dialogue projects in the period 2005 through 2011 on issues ranging from nanotechnology and stem cell research, to the uses of DNA in forensics and geoengineering to combat climate change[21].

The intellectual and political turmoil over innovation and risk led to a period of intensive academic research.

Jason Chilvers reports that much of this activity is based on professional practitioners often associated with consulting firms, as well as outsourced experiments on public consultation by regulatory bodies and governments[17]. Accordingly, there is a tendency towards a form of professionalized 'closed shop' in deliberation because of a format that relies on expertise and highly articulated communication. 'Ordinary publics' do not get a look-in. This practice flies in the face of a huge body of research instigated by Jurgen Habermas on "ideal speech"[22], as commented on by James Johnson[23]. In essence the Habermas doctrine is that much of consultation ("communicative discourse") is designed to meet particular objectives through the controlled use of structured reasoning. As a consequence, those with deeper and wider value biases may be silenced. Hence any agreement is distorted. A more democratic approach would be to ensure that all those involved are treated with respect and encouraged to speak authentically — namely, what they feel and believe to be their true moral expression. As such, the Habermasian underpinning of deliberation is based on a much more empathetic and ethical approach to conversing. This opens up the scope for dialogue to be extended to the workplace, the neighbourhood centre, the household and the church.

For the social scientist this perspective creates a dilemma. On the one hand there is a strong academic demand for carefully managed methodologies designed to ensure some distance between observers and participants. On the other is an emerging normative belief that the role of facilitator should be to widen the basis of science to a much more transdisciplinary perspective, in which the translation process of the mix of values and knowledge is shared between facilitators and participants. This is the view promulgated in the practice of learning for leadership being undertaken by a new breed of sustainability science/knowledge broker, as summarized by Ryan and Tilbury[10]:

- *learner empowerment:* by actively involving participants in learning development and in processes of 'co-creation' of knowledge across disciplines and backgrounds.

• *future-facing education:* by refocusing learning towards engagement and change processes that help people to consider prospects and hopes for the future and to anticipate, rethink and work towards alternative and preferred future scenarios.

• *inter-cultural learning:* by replacing dominant teaching that promotes only Western worldviews, in favour of experiences that extend inter-cultural understanding and the ability to think and work using globally-sensitive frames and methods.

• *transformative capabilities:* by creating an educational focus beyond an emphasis solely on knowledge and understanding, towards agency and competence.

• *crossing boundaries:* by taking an integrative and systemic approach to learning, to generate inter-disciplinary, inter-professional and cross-sectoral learning, to maximize collaboration and shared perspective, while being empathetic to bias and differences of perspective.

• *social learning:* by developing cultures and environments for learning that harness the emancipatory power of interactions outside of the formal curriculum and classroom, particularly through the use of new technologies and internship activities.

We may be at the beginning of a fresh approach to learning, to meaningful engagement and to the role of the scientist/facilitator in the fusion of knowledge and values through authentic processes of conversing. To get there we need to learn from sincere efforts to bring in a wider conversation over innovation and risk.

This raises the matter of the degree to which education, particularly in schools, but also in higher learning, should address capacities for open-mindedness, flexibility in coping with many strands of disciplines and measurements, and citizenship in the form of a sense of moral responsibility for the wellbeing of both present and future generations. It may well be that this is one outcome of this assessment of innovation and risk, namely preparing all future young people for a world of coping and improving learned capabilities of empathy, resilience, compassion, determination, and adaptation.

The experiences of the GM and radioactive waste disposal consultations

In 2002/3 the government sponsored an unusually large scale public debate over the possible commercialisation of genetically modified crops in the UK. This process, called *GM Nation?*, was examined in considerable detail by Tom Horlick-Jones and colleagues[24] (2007). The government established an Agriculture and Environment Biotechnology Commission (2001:12) which argued for a massive public discussion on the grounds that any public policy on GM should "expose, respect and embrace the differences of view which exist, rather than bury them"[25]. The result was a complicated drama of many scenes and acts where a novel mix of "fact", "value" and "learning" unsatisfactorily ill-combined.

The Horlick-Jones study[24] concluded that the *GM Nation?* process was well meaning, sincerely attempted, but ultimately flawed. There was imperfect coordination between the various stages of scientific assessment and public engagement. The government's own decision-making advisory procedures were complex and confusing. It was also breathless and rushed. The briefing materials provided for the public meetings were bland and incomplete. The broad mass of the mostly disengaged public was not involved (a Habermasian observation). The process heightened antagonism rather than reduced it. So the outcome indicated a higher status of outright opposition to GM than was observed in the general public from opinion polls (an observation that is admittedly very time dependent).

These findings reveal the difficulty of creating a consultative process that meets everyone's expectations. This is particularly so because the process was feeling its way, and there were powerful commercial interests involved, both in favour (on the biotechnology side) as well as opposed (on the food retail side). There were important legal features involving the European Union[24]. All this is of great interest in the light of a fresh initiative favouring GM crops in the light of a growing and wealthier population seeking more environmentally and socially demanding food supplies in the face of declining biodiversity and climate change[26]. Even though the stakes are much higher today, it is unlikely that any rapid decision favouring GM crop production in the United Kingdom or the European Union more generally will prove imminent — despite the recent agreement from the EU's Environment Council to give member states more flexibility over GM crop experiments and production. (This would need to be agreed by the European Parliament before coming into force.) This observation underscores the ambivalence with which the general public regard much of innovation and risk, favouring the broad benefits but wary of the uncertain long-term consequences, particularly where traditional science does not seem to have a clear answer. The case study by Phil Macnaghten in Chapter 2 endorses these conclusions. He argues persuasively for a more preparatory institutional capability to be much more aware and sensitive to various bodies of amassed bias in anticipation of 'going public' with an innovation.

This anomaly is particularly evident in the long running and tortuous process regarding the deep disposal of

> **The GM Nation? process was well meaning, sincerely attempted, but ultimately flawed.**

radioactive waste in many countries (though not all, as is the case in France, Sweden, and Canada). In the United Kingdom, the decision track-ways are littered with frustrated consultations, innumerable public surveys, reports by countless advisory bodies and reinventions of inconsistent regulation. At its heart lies a combination of a broad public recognition that there is a legacy of civilian and military nuclear waste that must eventually be disposed of, and an unsuccessful series of attempts to achieve an agreed resting site. Meanwhile the wider public enjoys the benefits of reliable base load electricity whilst expecting some particular community or other to absorb the disruption of traffic and possible danger of being neighbour to a deep repository of waste that is hot and treacherous unless wholly contained for over 25,000 years.

Here the government is listening to the kinds of arguments outlined above. It is facing five critical issues. One is that there can be no approved deep disposal site without agreement over a range of decision-making bodies from national government through regional and local government to the parishes and communities voluntarily selected. A second is that the relative risks of permanent above-ground storage, especially for generations a long way into the distance, should be fully compared. A third is that planning procedures should suitably combine national guidelines with local safeguards. A fourth is that any discussion of community benefits should be additional to the direct financial benefits or incentives to the willing community arising from the investment and jobs creation. But if such benefits are also to address the scope for recognizing community pride in carrying responsibility for guaranteeing the long-term safety of this facility on behalf of the nation, then there may have to be some sort of levy on each unit of waste disposed. Such a levy would recognize the potential open-endedness of the additional waste from any new nuclear stations. It could also form a not-for-profit community administered fund for the permanent betterment of all future generations who are neighbours to any selected site.

The fifth element applies to the focus of this chapter, namely finding ways to hold a wider conversation. Normal consultative procedures do not always work well for this kind of long-term contentious issue, because people often do not understand how their input into the consultation process works. There is also the broader issue of consultation fatigue: people do not want to keep on saying things they think they have said many times before, particularly when they do not know how much weight will actually be given to their response.

One possibility is to instigate a process of decentralized deliberation. This would be specifically designed to build confidence and trust. Ideally, small teams of informed but essentially local people should be trained to converse with community groups in an empathetic approach. Training is vital, for the overall aim is to allow all participants to debate all issues (which they jointly establish) in terms of their own comfortable communication, and in meeting places that are familiar to them. Local authorities and experts

> **GM Nation was a complicated drama where a novel mix of facts, values and learning combined in an unsatisfactory way.**

are not ideally equipped to deal with this sort of intimate and more genuinely representative democracy, nor do local citizens perceive them to be so equipped. There are lessons to be learnt from the GM debate here. Chilvers admits that getting a more comforting and trust-building decentralized deliberative process right is very difficult[27]. It very much depends on the context and the characteristics of the participants and of the decision pathways (past and future). This extended deliberative process has to be proven to be independent. Even then, as indicated earlier, dedicated 'spoilers' could subvert the most carefully designed processes unless they are identified and isolated by the participants whose trust in these innovative procedures has first to be won over.

There can be no guarantee that this community-based set of conversations will work out as intended. Much depends on the political and regulatory setting for the generic stage designed to reassure that there is a technological and geological safe means of disposal somewhere in England. But even more hangs on the mechanisms of creating a learning and listening atmosphere throughout the country, particularly in any locations where there is a willingness to be considered for community benefit, and where the deeper normative components of trusting involvement, authentic forms of conversing, and full consideration of the possible alternatives brings out the essence of informed and appreciated agreement.

Two additional possible obstacles remain. One is the apparently monolithic characteristics of the planning process, especially where "critical infrastructure projects" are externally labelled and treated as "in the national interest", thereby seeming to bypass local protest and confining it to matters of local detail. The other is the social memories of historical resentment and past damaging treatment, as summarized by Bickerstaff[28].

Such a concern with the relational geography of issues suggests a refocusing of attention away from the presences of controversy (the actors, framings, and outcomes), and towards the absences that mark the roots (or routes) of so-called 'not in my back yard' ('Nimby') disputes. It is an approach that brings to the fore the role of distant things, people, and events in the sorts of questions we ask about how publics become involved with an issue; how the issue is articulated (spatially and historically); the power and politics at work; as well as the efficacy, fairness, and possibilities for change associated with siting policies oriented to the future.

In a recent White Paper[11], from the Department of Energy and Climate Change, the government appears to have heeded the points made by various contributors to this volume. It has adopted the approach of consensual and voluntary acceptance across all forms of (especially local) government, with no pressures on time or exploration of evidence. It is to amend the planning acts to enable a much more national–to–local perspective of any "appraisal of sustainability" of a major national infrastructure facility to be reviewed and accepted. It will establish a working group on community representation to consider all forms of local engagement as outlined above. This working group will look at the principles and practices of the sustainability (wellbeing) test, and at the issue of determining community investment funds over and above all other local benefit streams, with the aim of building real community enterprise and pride over many generations. It will also create an independent reference group of authorative third-party, independent and trust-building advice. And it will only proceed when there is an agreed form of a "public test of support" for the actual siting of any facility.

This should be a true process of holding a wider conversation. It is by no means guaranteed that the cantankerous history of this vexed process will result in a creative and purposeful outcome. The White Paper at least sets the test. What also remains to be seen if such a creative set of approaches can also be tailored to other contentious infrastructure projects such as fracking, the London airport saga, and to the final determination of the proposed high-speed rail route through the West Midlands and possibly further north and east. Ironically, by offering an innovative track for geological disposal of radioactive waste, the government may have also created a stick for its own back in the even more tumultuous arenas of fracking and airport runway siting. Given the evidence from the fracking case study in Section 2, it remains much more problematic for any form of community consensus to be reached over fracking, even if the procedures proposed for debating the geological disposal of radioactive waste are adopted. For here is where fundamental values over energy policy, climate futures, fairness of treatment, and love and identity of familiar landscapes impossibly clash.

It remains much more problematic for any form of community consensus to be reached over fracking, even if the procedures proposed for debating the geological disposal of radioactive waste are adopted.

Concluding observations

Holding a wider conversation about the links between risk and innovation will be seen from the examples in this report as being very demanding on science, ethics, trust, and empathetic conversations. This is relevant for a set of decisions involving established risk and genuinely uneven distribution of costs and gains. As noted in the introduction, this applies to a particular set of proposals. But there are important links to the themes of caring for future generations, and of deliberating early when sufficient information is ready for exploration.

Yet these processes require a set of circumstances that are still not commonly found either in scientific or political circles (though the business world seems to be more amenable). This relates to frank honesty over what is known and what is not known; agreed means for assessing future states on a 'what if' basis; a more coherent mechanism for taking into account the distributions of gains and losses for future generations; openness of listening and sharing outcomes; some form of acceptable community investment process to offset calculable costs; and a genuine willingness to commit to a process of trust building without deviation. These are not easy conditions to guarantee in the hectic modern world of hurly-burly politics and science. But it is the purpose of this report to create such felicitous conditions.

David Spiegelhalter
(University of Cambridge)

CHAPTER 6: THE NEED FOR A COMMON LANGUAGE

In discussions about innovation, effective communication between stakeholders requires a 'common language' — a set of core principles regarding the presentation of arguments or analyses.

It is difficult to face up to the risk and uncertainty around innovation. All actions, including inaction, may have benefits and harms, but we don't know, nor can we even imagine, everything that might happen. We cannot be confident about the valuations people might attach to the possible consequences. Nor can we confidently say how likely things are to happen — in fact, the whole meaning of such a statement can be contested.

There are also multiple players who have a stake in decisions about innovations — the public (which should not be treated as some homogenous mass, but as a diversity of 'publics'); the regulators and policy-makers; the innovators themselves; non-governmental organizations (NGOs) and so on. There may be substantial problems of trust between these actors.

Communication between these stakeholders, especially when channelled through media outlets that may not be concerned with balanced reporting, is fraught with difficulties. Any progress that can be made in improving that communication should be beneficial, and hence the search for a 'common language'.

What policymakers might like in an ideal world

The theory of rational decision-making in the face of uncertainty comprises four basic stages:

- Structuring the list of actions, and the possible consequences of those actions.
- Giving a financial or other numerical utility to those possible future outcomes.
- Assigning a probability for each possible consequence, given each action.
- Establishing a rational decision that maximizes the expected benefit.

The real world is a messy place, however. The theory described above only holds in rarefied situations of perfect contextual knowledge, such as gambling on roulette when we know the probabilities of possible gains or losses. These pre-chance problems are the only type in which we might talk about *the* risk: and even then we need to make assumptions about the fairness of the wheel and the integrity of the casino.

What policy-makers actually get

In reasonably well-understood situations, numerical risk assessments can enable appropriate decisions for prioritising actions. The Health and Safety Executive's *Tolerability of Risk* framework provides appropriate guidance: in this chapter, the case study *Nuclear: The Submariner's Perspective* shows how societal valuations of potential consequences can be incorporated, while *Adapting regulation to changing evidence on risks: delivering changes to pig inspection* illustrates that risk assessment can form a basis for evidence-based regulation.

But in some areas of innovation there are likely to be different groups making claims about the risks, raising different issues with different values, and competing scientific claims based on different evidence. Even within a single group there will generally be a range of possible analyses based on different assumptions, while any predictions about how people will react to innovations must be fairly speculative.

Thus a policymaker will be faced with plural analyses that are both contingent on assumptions and inevitably inadequate, whether self-professed as such or not. The resulting uncertainty is far more than not being able to predict the future — it is as much about 'don't know' as 'can't know'.

The problems of language

1. Definition of terms

The crucial distinction between 'hazard' — the potential for harm if mitigation is not put in place — and 'risk' is well-known. But frank discussion about risk and uncertainty is not helped by the variety of language used by people in different domains, not least in the meanings of the terms 'risk' and 'uncertainty'. For example, many scientists would use the term 'uncertainty' for everything that was not certain, including a single coin flip, and only distinguish the extent to which the uncertainty was quantifiable. In contrast, those with an economics and social science background will often adopt the distinction made by Frank Knight between 'risk' — in which extensive data and good understanding of a controlled environment leads to agreed quantification — and 'uncertainty', for when this quantification is not feasible. The term 'ambiguity' is also, ironically, ambiguous: some use it to refer to situations in which outcomes and values are contested or unknown (see Chapter 4), while in behavioural economics it refers to uncertainty about probabilities.

2. Communicating using numbers

Even when numbers are agreed, there is a wide variety of ways in which probabilities may be expressed: as percentages, odds, frequencies, in graphics and so on. For example, the Safety Cases for high-hazard installations provided to the Health and Safety Executive might mention that the individual risk per annum (IRPA) = 4×10^{-4}: it means that each worker has a 4 in 10,000, or a 1 in 2,500 risk of being killed each year, but seems almost designed to prevent comprehension.

Research has shown that the way numbers are framed influences our perceptions. The 99% Campaign, an initiative that aims to dispel negative stereotypes about young people, offered one example of a positively-framed message when it issued advertisements proclaiming that "99% of young Londoners do not commit serious youth violence". This, of

The important lesson from numerical risk communication is that one size does not fit all.

course, means that 1% are violent, and as there are roughly 1,000,000 Londoners between the ages of 15 and 25, a little reflection suggests there are 10,000 seriously violent young people running around — not the image the communicators wanted to conjure up.

It is generally argued that using *relative* measures is a manipulative way of communicating risk, because it has ben shown to increase the apparent importance of a particular action. Being told that regularly eating a bacon sandwich increases your lifetime risk of pancreatic cancer by 20% may be somewhat unconvincing if the baseline is extremely low and the bacon sandwich is rather pleasant.

However, this situation can be reversed in acute low-probability, high-impact events that occur regularly: we all take daily precautions when travelling, for example, which makes small risks even smaller. This point was also dramatically illustrated when Italian earthquake advisors were convicted of involuntary manslaughter for issuing unduly reassuring messages to the residents of L'Aquila in 2009, a few days before more than 300 people were killed in a major earthquake. The advice correctly said that the overall risk was low, but should also have emphasized that the *relative* risk was high: this would have enabled residents to adopt their own chosen level of precaution (see case study in Chapter 1 for further discussion of L'Aquila).

Clearly both absolute and relative risks are required. The important lesson from numerical risk communication is that one size does not fit all, and a variety of methods may be appropriate, with a hierarchy of numerical sophistication.

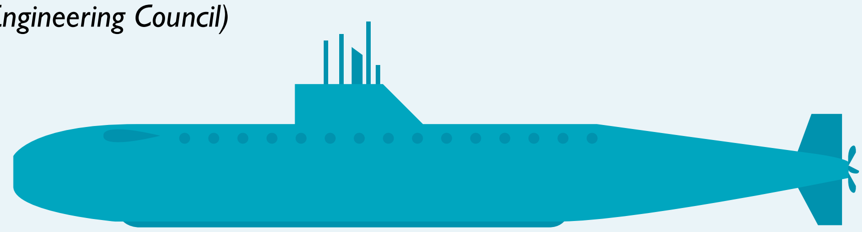
3. Using words

It is important to realize that words such as 'likely' or 'possible' carry meaning beyond mere magnitude, and depends crucially on context. For example, the UK's Terrorism Threat Level scale defines SEVERE as meaning "that a terrorist attack is highly likely", and yet when this

CASE STUDY

NUCLEAR: THE SUBMARINER'S PERSPECTIVE

Rear Admiral Nigel Guild (Chairman, Engineering Council)



A nuclear submarine is one of the most complex engineering achievements known to man, and it contains a unique combination of potential hazards within a relatively small space. These hazards include structural and environmental issues common to all large ships, with the added problem that the vessel needs to remain stable under the water. To these challenges are added nuclear propulsion, explosives and, in the case of the deterrent submarine, nuclear weapons.

The management of submarine safety is critical to the protection of submariners, the public and the environment. The Royal Navy's approach to managing the risks presented by these potential hazards is to assess and mitigate them through the use of a probabilistic safety case. This safety case aggregates the assessment of risks, so that there is ultimately an overview of risk for the whole submarine. This process relies on normal definitions of acceptable risk used by the Health and Safety Executive (HSE), along with widely used diagrams depicting the expectation of death per year against the number of people employed. HSE Basic Safety levels are used for the maximum risk that is normally allowable. Then the 'As Low As Reasonably Practicable' (ALARP) principle is deployed to continually reduce risk from each potential hazard, until the cost of further effort would be grossly disproportionate to the extra safety achieved.

In practice, far greater resources are devoted to managing nuclear safety than for other potential submarine hazards with the same risk assessment. This is required by a public expectation of far greater risk reduction for a potential nuclear hazard, because it is not generally understood and it is held in significant dread. To take a non-nuclear example, the risk of a seamanship accident, such as falling into the sea while working on the casing when the submarine is on the surface, is assessed in a similar way to any workplace potential hazard. In contrast to this, a potential nuclear event requires risk mitigation to achieve two orders of magnitude smaller risk assessment than would be sought for conventional risks. Another way of expressing this is by applying the ALARP principle: the effort required before it would be considered grossly disproportionate to the extra nuclear safety achieved is about 100 times more than for other risks.

Using this logical approach, a consistent set of safety assessments for the whole submarine can be assembled and used to minimize risks using the common language of health and safety assessment. Within the process, however, chosen risks such as nuclear can be managed to different levels of ALARP in accordance with society's expectation.

CASE STUDY

ADAPTING REGULATION TO CHANGING EVIDENCE ON RISKS: DELIVERING CHANGES TO PIG INSPECTION

Patrick Miller (Food Standards Agency)

The UK Food Standards Agency (FSA) has led efforts to reform pig inspection, drawing on evidence about the changing nature of health risks from meat — and about the behaviours of those involved in meat production — to introduce new controls that better reflect the risks and the realities of inspection in practice.

Meat controls are currently based on a traditional inspection approach, developed over 100 years ago to tackle the public health concerns of that era, such as parasites and defects visible to the naked eye. Today, the main causes of foodborne disease are microbiological. Pathogens such as *Salmonella, Campylobacter* and *Escherichia coli* cannot be tackled adequately using traditional inspection methods.

Meat controls are a key part of European Union food safety controls and any changes need the support of the European Commission, EU member states, industry and stakeholders. As such, these changes must be based on solid evidence and reflect practical realities and stakeholder concerns in order to win confidence that any change will be more risk-based, effective and proportionate.

This takes time, but it ensures that we can be clear about our objectives and gather evidence on how best to meet them. For consumers, that means greater confidence in meat safety and better protection from risks from meat; as a regulator, it ensures the effective use of public funds in controlling foodborne pathogens and reducing costs for society from foodborne illness; for business, it lowers the cost of regulation; and for enforcers, it offers a more objective approach and better use of resources, according to risk and impact.

Developing the evidence base

The FSA's research programme on modernizing meat controls aims to:

- establish the effectiveness of current and alternative approaches to meat inspection;
- build a robust evidence base to support a case for reform.

It includes veterinary and risk-assessment research, as well as social science research to understand attitudes and behaviours that affect the effectiveness of controls in practice. The European Food Safety Authority (EFSA) also provided a series of independent expert scientific opinions related to inspection of meat, and together with the FSA's research these formed the basis for initial proposals for changes to pig meat inspection.

Openness and engagement

Alongside this process, FSA followed an active programme of engagement and communication with interested parties, including the European Commission, EU member states, European Parliament the meat industry, UK agricultural departments, EFSA experts, and consumers.

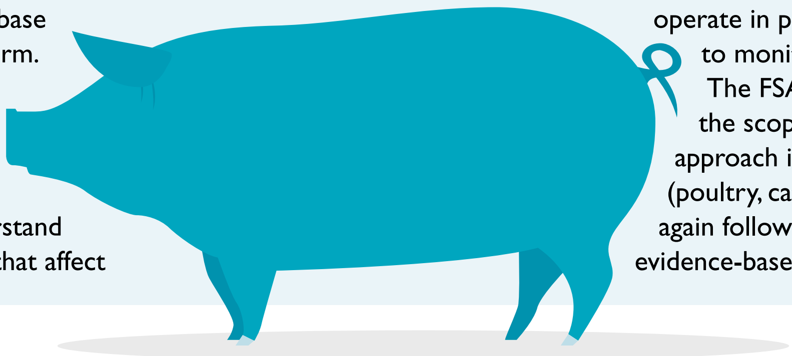
This engagement was aided by a high degree of openness, with information on the programme's objectives, research, developing proposals, and the supporting evidence, published and discussed by the FSA Board in open meetings[1]. A consultation on the proposed changes ran from March–May 2014, with extensive communication on formal introduction of the new inspection regime, and training to support implementation.

Outcome

The new package targets risks better by:

- Removing controls that did not help to reduce pathogen levels in meat, and in fact actually helped to spread contamination (through physical palpation and incision of carcases), thus increasing consumer risk — a serious unintended consequence of the old regime.
- Tightening controls that can reduce contamination levels in meat, including controls on *Salmonella* and risk-based testing for the parasite *Trichinella*.

It therefore targets resources at the real risks in ways that will control them more effectively. The package has received broad support from stakeholders. The FSA is now funding research to help evaluate how the changes operate in practice, and how to monitor their impact. The FSA will explore the scope to extend this approach in other species (poultry, cattle and sheep), again following an open and evidence-based approach.



level was announced on 22 January 2010 the government's Home Secretary felt obliged to say: "This means that a terrorist attack is highly likely, but I should stress that there is no intelligence to suggest than an attack is imminent"[1]. This shows that using words to express uncertainty, without a numerical reference scale, can be misleading unless audiences fully understand their usage in the particular context.

Words can also be used as direct translations of numerical probability assessments. For example, the Intergovernmental Panel on Climate Change (IPCC) has standardized its verbal terms for likelihood using the scale in Table 1 (ref.2).

The IPCC sometimes use these terms for communicating their confidence in scientific conclusions, for example in stating that: "It is **extremely likely** that human influence has been the dominant cause of the observed warming since the mid-20th century". The IPCC only uses these terms of likelihood in situations of 'high' or 'very high' confidence (see below for the interpretation of this term), although it can be argued that such a restriction is unnecessary.

It is important that any numerical scale broadly reflects usage in that domain. The case study in this chapter, *Accurate Communication of Medical Risk*, notes that drug side-effects that are described as 'common' are intended to correspond to between 1% and 10%. This may be reasonable usage for pharmacologists, but not for patients.

4. Being imprecise about numbers

When it comes to expressing uncertainty in quantitative terms, a hierarchy of levels of precision can be assigned, appropriate to the confidence of the assessors. For example:

- Numbers to appropriate levels of precision.
- A distribution or range.
- A list of possibilities.
- A rough order of magnitude.

TABLE 1

IPCC LIKELIHOOD SCALE

Term	Likelihood of the outcome (probability)
Virtually certain	99–100%
Extremely likely	95–100%
Very likely	90–100%
Likely	66–100%
More likely than not	50–100%
About as likely as not	33–66%
Unlikely	0–33%
Very unlikely	0–10%
Exceptionally unlikely	0–1%

No analysis can claim to produce *the* risk of an innovation.

5. Expressing (lack of) confidence in the science

Our uncertainty does not just concern the likelihood of future outcomes. For a whole modeling process, we may have to contend with assumptions about the inputs, the model structure, and the issues of concern. Again, lists of possible values or scenarios can be provided as a sensitivity analysis. These can be supplemented by acknowledging that there are aspects that have been left out of the model, with a qualitative assessment of their potential impact.

Some domains have tried to use a summary qualitative scale to communicate the confidence in the analysis. For example, the IPCC uses the quality of the evidence, and the degree of scientific agreement, to assess a level of confidence in their scientific conclusions.

Seeking a common language

There is room for substantial improvement in the quality of the discourse between the participants involved in innovation and risk, including the public, regulators, innovators, NGOs and the media. But "seeking a common language" does not refer to a restricted use of specific words, such as risk, uncertainty and ambiguity — that would be impossible to impose and counter-productive to try. Rather, by "common language" I mean the acceptance of a set of principles regarding the presentation of arguments or analyses. Five such principles are outlined below.

1. *Acknowledge that any risk and uncertainty assessment is contingent and provisional.* No analysis can claim to produce the risk of an innovation. Such assessments are constructed depending on assumptions, and may change in receipt of further information. The reasons for the uncertainty should also be given. And since there will be competing opinions, not all of which will be based on an adequate consideration of the evidence, the pedigree of an analysis is also important.

It would be useful to have an appraisal of the quality of the analytic framework: this could be self-assessed by the analysts (although this would require considerable humility) but also assessed by the team responsible for formulating the policy in question. The appraisal should be based on the quality, quantity, consistency and coverage of evidence, as well as the quality of the process that collected and analyzed the evidence, and the quality of deliberation. Policymakers can then make a holistic summary of the state of uncertainty and how it influences the confidence in the conclusion (see Table 2 for a possible rough categorization of such an assessment, roughly modeled on the Grading of Recommendations Assessment, Development and Evaluation (GRADE) scale used in health[3]).

Clearly the strength of any recommendation does not depend only on the scientific uncertainty: there may be very good evidence, but if the pros and cons are finely balanced then a strong recommendation cannot be given.

It is essential that the contingent nature of the assessment is retained throughout its passage through policymaking. It is all too easy for important caveats to be lost and for an assessment to become prescriptive, even if this was not the original intention. The phrase 'risk and uncertainty assessment' might encourage this.

2. *Multiple risk and uncertainty assessments should be encouraged.* Policymakers should neither expect nor want a single analysis of the risks. Analyses may come from multiple teams, or from a sensitivity analysis across single team.

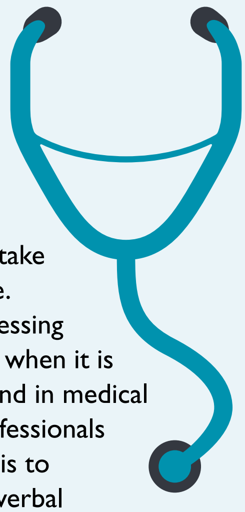
As US President Barack Obama recounted on the Channel 4 programme *Bin Laden: Shoot to Kill* on 7 September 2011: "Some of our intelligence officers thought that it was only a 40 or 30% chance that Bin Laden was in the compound. Others thought that it was as high as 80 or 90%. At the conclusion of a fairly lengthy discussion where everybody gave their assessments I said: this is basically 50-50."

Some have argued that alternative views should have been condensed into a single assessment before being presented to Obama[4], but that could have been considered as withholding important information.

3. *As far as is possible, uncertainty should be expressed quantitatively. But numbers do not speak for themselves: the manner in which numbers have been generated should be clear, and the framing acknowledged.*

CASE STUDY

ACCURATE COMMUNICATION OF MEDICAL RISK



Chris Cummins (University of Edinburgh)

Health professionals have access to accurate, quantitative information about risk, such as the efficacy of a treatment or the probability of various side effects. Nevertheless, accurately and effectively communicating this information to patients or colleagues can be very difficult. Problems include how to frame information impartially; how to ensure that information is expressed understandably; and how to allow for people's tendencies to draw additional inferences from the information they hear. The communication of medical risk is clearly very important in its own right — but it often offers more general guidance for risk communication in other domains.

Tversky and Kahneman first identified[1] the importance of framing by using a fictitious medical example. In their story, 600 people have a fatal disease, and are offered two treatment options. Option one is introduced either as one that "saves 200 lives", or as one in which "400 people will die". Option two uses a probabilistic presentation, offering either a one-third probability that 600 people will be saved and a two-thirds probability than no-one will be; or a two-thirds probability that 600 people will die and a one-third probability that no-one will.

If the two options were presented in terms of how many lives they saved, 72% of readers preferred option one over option two. But if the options were introduced by stating the number of resulting fatalities, only 22% preferred option one. Crucially, the quantitative content of each option was the same.

Research on framing can tell us how to present information in a positive or negative way, but it also raises the question of how we should frame information when we wish to present it purely objectively, so that the hearer can take a decision without undue influence.

People often have difficulty processing quantitative information, especially when it is presented in numerical terms — and in medical communication, this applies to professionals as well as laypeople[2]. One remedy is to gloss numerical information using verbal descriptors: for example, by describing side effects as "very common", "common", "uncommon", "rare" or "very rare"[3]. These verbal descriptors are supposed to correspond to probabilities of, respectively, over 10%, 1–10%, 0.1–1%, 0.01–0.1% and less than 0.01%. However, users systematically misunderstand them: both patients and doctors significantly overestimate the risk of side effects described in these terms[4,5]. Presumably this biases patients against taking medicines (and doctors against prescribing them) to a greater extent than is rationally justified.

The nature of linguistic communication also clouds the picture. For instance, if we say that "More than 10% of people taking this medicine will experience hot flushes", a hearer would be entitled to infer that "not more than 20%" will do so, as otherwise the speaker would have said "more than 20%" (ref. 6). This natural inference is incorrect if, by "more than 10%", we actually mean *anywhere in the range 10%–100%*. There is, nevertheless, ample evidence that hearers draw inferences of this kind, and if we are to communicate risk information objectively and responsibly, it is our duty to take this into account. We cannot defend descriptions that are practically misleading on the basis that they are technically true according to mathematical criteria.

Even in situations with limited evidence and substantial disagreement between experts, it can still be possible to use numerical probability assessments — or at least ranges of probabilities — for well-defined future events.

The analyses underlying the debate whether to introduce plain packaging for cigarettes, for example, could be fairly characterized as '2 star'. Nevertheless, a survey[5] that elicited expert opinion about the possible impact of the policy on overall smoking rates, and on children starting smoking, showed that despite substantial variation in opinion there was an overall view that the impact would be positive but modest (see Figure 1). It is essential to remember, however, that these are subjective judgments with no direct evidence from data.

Transparent and open communication, which attempts to avoid framing effects, requires that the potential harms and benefits of innovations are reported in a balanced manner. For instance, new patient-information leaflets released by the NHS Screening Programme[6] clearly report the numbers of women that would be expected to benefit and be harmed among each 200 attending breast screening. These numbers relied to some extent on expert judgement, and their pedigree was reported using the phrase: "The numbers on the next page are the best estimates from a group of experts who have reviewed the evidence".

It is also crucial that that the potential impact of language and concepts is understood. Climate impact projections from the government's Department for Environment, Food and Rural Affairs (DEFRA) included an assessment of the upper 90% scenario in the distribution of possible temperature increases — that is, the outcomes judged to have a 10% chance of occurring[7]. The media has previously reported such extreme scenarios in terms such as "temperature rise could be as high as X". As a deliberate pre-emption of this style of coverage, DEFRA used the phrase "temperature rise is very unlikely to be greater than X". This change from a negative to a positive frame was successful in deflecting undue attention from the extremes, although a balanced approach would have used both positive and negative frames.

4. *A precautionary approach is a natural holding position in the face of scientific uncertainty. There is no need to promote it to a 'principle'.*

There are many 'precautionary principles' — a weak version says that we do not need to be sure of harm before we take mitigating action (such as in climate change), whereas a strong version broadly says we should not take any action if there is a possibility of harm. The latter view can lead to unnecessary caution, since no actions can be guaranteed to be safe.

But there is no need to cite additional 'principles' above reasonable risk and uncertainty assessment. After weighing up risks in as quantitative a way as possible, if there is still considerable scientific uncertainty then it is reasonable to be cautious as a holding position, but to treat this as a temporary situation: amber, rather than red.

In 2000, John Krebs, as head of the UK's Food Standards Agency, held a press conference on the possible risk of bovine spongiform encephalopathy (BSE) in sheep. He took the view that being open and transparent with consumers meant that he had to be completely honest, with no cover-up. At the press conference he made the following points:

- We do not know whether BSE has got into sheep.
- We are on the case. Here is what we are doing to try to find out.
- In the meantime we are not advising you to stop eating lamb. But if you are worried about it, change your diet.
- We shall get back to you when we have worked more on establishing the actual uncertainty and risk.

"And that worked very well," Krebs later recalled[8]. "There was no panic in the industry, and no panic among consumers either." This is an example of openly communicating scientific uncertainty, making clear that it is being remedied, and acknowledging that a precautionary approach may be taken as a temporary measure.

5. *In the end, the decision-maker must make a judgement, using risk and uncertainty assessments as part of their inputs. They should not expect to be given a prescriptive analysis.*

Although these principles are aimed primarily at policymakers, they may also improve the general communication between the parties involved in innovation and risk.

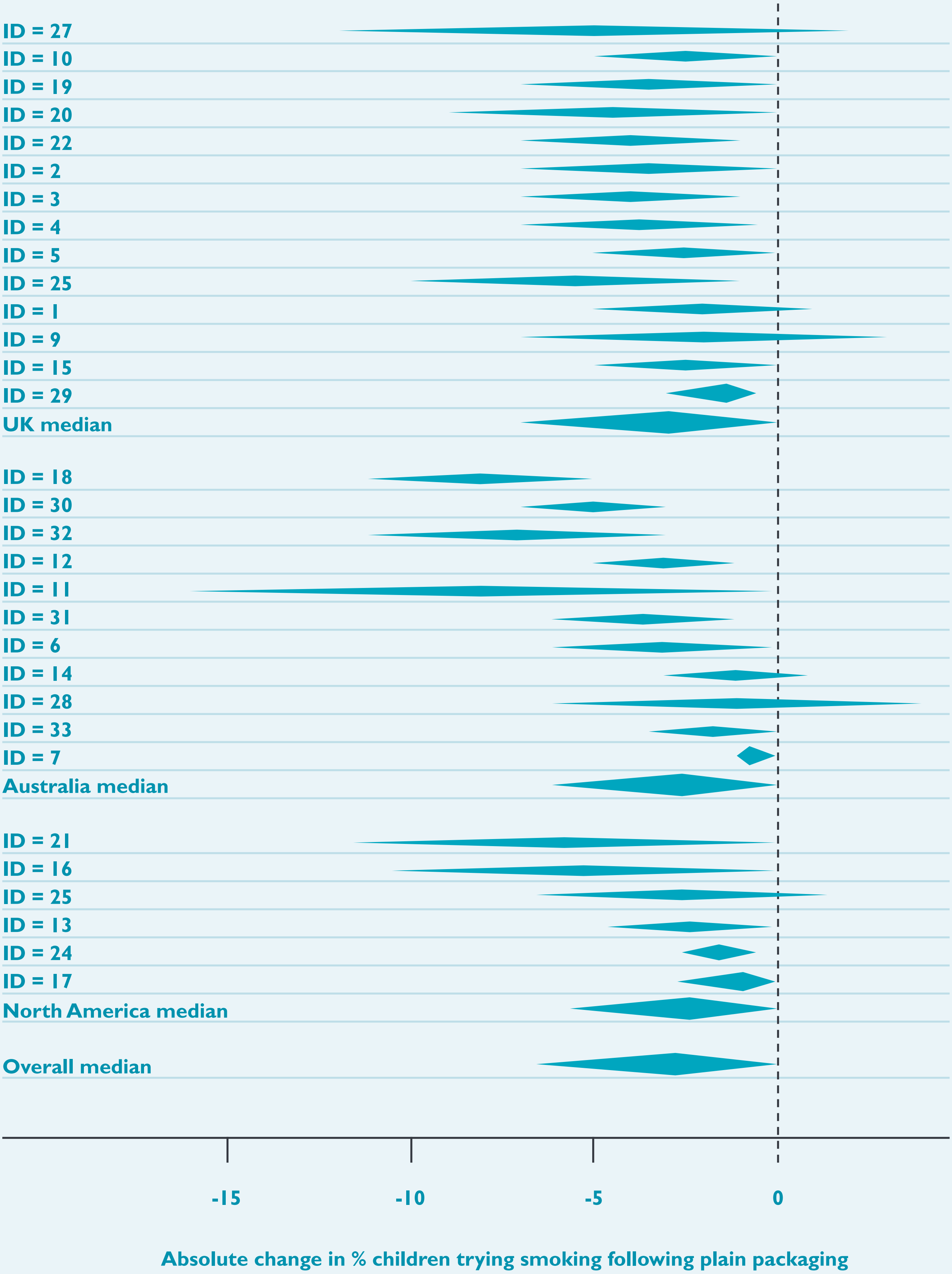
TABLE 2

A POSSIBLE SCALE OF THE JUDGED QUALITY OF A RISK ANALYSIS

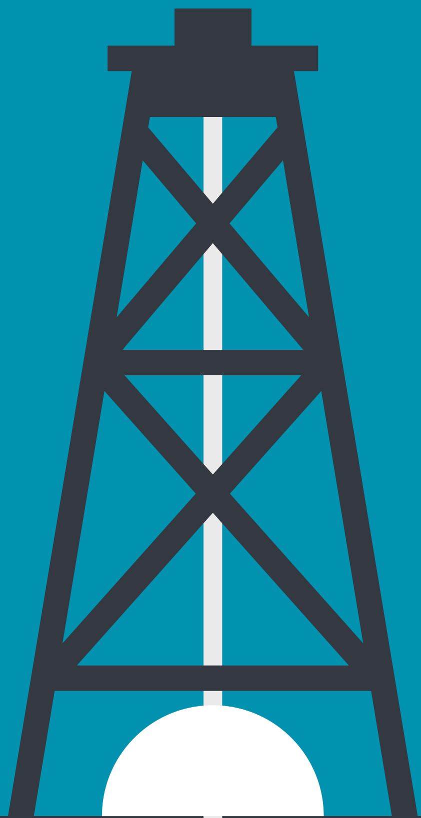
Star rating	Meaning
★★★★ 4 star	We are fully confident of our understanding of the underlying process, so although we cannot predict what is going to happen, we can provide good numerical assessments.
★★★ 3 star	We are reasonably confident in our analysis: we can expect numbers to change as we learn more, but not sufficient to justify major policy shifts.
★★ 2 star	New evidence could have a substantial impact on our assessment, although no major new surprises are expected: we encourage a robust decision-making approach with some precaution and adaptivity.
★ 1 star	We have very limited understanding of the process or possibilities, and so resilience to unexpected occurrences is called for.

FIGURE 1

Assessments by international experts of their uncertainty about the impact of plain packaging on the percentage of children who start smoking. Diamonds represent the median and 99% interval for each expert.



Steve Elliott (Chemical Industries Association), Harry Huyton (Royal Society for the Protection of Birds), Robert Mair (University of Cambridge)



HIGH LEVEL CASE STUDY: HYDRAULIC FRACTURING

THE INDUSTRY PERSPECTIVE

Steve Elliott (Chemical Industries Association)

The chemical and pharmaceutical industries are the United Kingdom's biggest manufacturing export earner. Our products and technologies support modern life, both directly and through the manufactured products that they enable. Our sector is also energy- and trade-intensive, however, so this contribution is critically dependent on secure and competitively-priced supplies of fuel, which provide both feedstocks (raw material) and energy. We are therefore concerned that, for energy-intensive industries, UK energy costs are becoming increasingly uncompetitive and there is a growing reliance on imported gas. Provided it is exploited in an environmentally safe way, we believe that the country's indigenous shale gas resources offer a secure and potentially competitive source of feedstock and fuel.

Until now, chemical businesses have relied on the North Sea for feedstock supplies, but these supplies are diminishing. We use this feedstock to make the basic chemicals that provide key building blocks for almost every sector of manufacturing and the wider economy. In the United States, the shale gas 'revolution' has triggered planned investments in chemical capacity worth $140 billion. While UK chemical businesses are installing facilities to import US feedstock, the development of indigenous shale-gas supplies could provide a more secure and potentially competitive source, and improve the business case for further investments in UK chemical capacity.

We are also paying more for gas as a fuel than many competing production locations, with costs more than three times higher than in the United States. Recent events have shown that the security and affordability of UK energy supplies is a concern both for households as well as large energy users like the chemicals industry. UK policy is driving the replacement of old electricity-generating stock with a low-carbon generating mix, and this will significantly increase electricity prices out to 2020. Far from our dependence on gas diminishing, more gas-fired generation will be needed during the transition if we are to 'keep the lights on', and it will then play a major role in backing intermittent renewable power. Gas will also continue to be the main source of heat in homes and industry. But we already import over half our needs, and this reliance is set to rise to 80% by 2020. This makes the UK more vulnerable to supply uncertainties, with gas prices particularly high and volatile in cold winters. The availability of shale gas could therefore be a key contributor to both secure and affordable energy.

The development of shale gas will bring multiple economic benefits to the United Kingdom. The development of shale gas will bring multiple economic benefits to the United Kingdom. It is a key enabler for our shared vision with government of a 50% growth by 2030 of the chemical and pharmaceutical industries' contribution to the country's economy. We already have a turnover of £60 billion and support 500,000 jobs both directly and indirectly. Such growth will enhance the provision of key building blocks for almost every sector of the economy — from cars and planes through to houses, medicines, televisions and mobile phones — products which also support our modern lives. Estimates suggest that UK shale gas development will require supply chain spending of £3.3 billion *per annum* and generate 64,500 jobs. Communities will also receive direct benefits from local shale gas development.

However, it is vital for communities in the UK to be confident that shale gas can be developed in an environmentally safe way. There is now a substantive evidence base from government and independent expert bodies that addresses concerns on key issues including seismic activity, water use, impacts on ground water and emissions, and the use of chemicals in fracking fluid. The United Kingdom also has a strong regulatory framework for shale gas development. It is now time for government and industry to redouble their efforts to address environmental concerns and explain the economic benefits.

> **The chemical and pharmaceutical industries are the United Kingdom's biggest manufacturing export earner.**

THE NGO PERSPECTIVE

Harry Huyton (Royal Society for the Protection of Birds)

In March 2014, the Royal Society for the Protection of Birds (RSPB) published a review of the ecological risks associated with hydraulic fracturing for shale gas in the United Kingdom, along with a number of recommendations to address these risks. The review was based on literature principally concerned with hydraulic fracturing in the United States, which we interpreted and applied to the UK situation.

The key risks to the natural environment that we highlighted were: water demand in areas under water stress, causing low river flows; water contamination as a result of well-casing failures and surface spillages; pollution incidents as a result of waste handling and disposal; and the loss, fragmentation and disturbance of wildlife habitats. All of these risks increase significantly at the commercial extraction phase, but they are manageable if an effective policy and regulatory framework is put in place.

Crucially, we also argued that this framework should be precautionary, given that the environmental impacts of the industry in the United States have been poorly studied, and because the geological and environmental conditions in the United Kingdom are quite different. Our assessment is that we do not currently have an effective and sufficiently precautionary framework.

It has been a source of frustration that the public and political debate about fracking in the United Kingdom has become so polarized that a discussion about risks and responses has been effectively impossible.

The scope and approach taken by the Strategic Environmental Assessment (SEA) of the current licensing round for onshore oil and gas illustrates this. An SEA is an important policy tool that theoretically allows the environmental impacts of a plan or programme (and its alternatives) to be assessed, and improvements or mitigating measures to be identified and recommended. In practice they have too often become bureaucratic exercises that have little bearing on the policy, and this SEA was no exception.

For example, no meaningful lower-risk alternatives were assessed. In fact, one alternative — reducing the licensing area by screening out the most ecologically vulnerable sites — was explicitly rejected on the grounds that it went against the overarching aim of "comprehensive exploration and appraisal of UK oil and gas resources and the economic development of identified reserves". In effect, any response to environmental risks that result in any restriction on the industry was ruled out from the start.

The public cares deeply about the countryside and the wildlife that we share it with. That means they expect government to be diligent and precautionary in understanding and addressing risks, through open and responsible debate and by applying tools like SEA. If risks are instead downplayed, branded as myths or simply ignored, the opportunity for evidence-based debate and progress by mutual consent is quickly lost.

The public and political debate about fracking in the United Kingdom has become so polarized that a discussion about risks and responses has been effectively impossible.

THE SCIENCE AND ENGINEERING PERSPECTIVE

Robert Mair (University of Cambridge)

In 2012, the Royal Society (RS) and the Royal Academy of Engineering (RAEng) published a joint report — *Shale gas extraction in the UK: a review of hydraulic fracturing*[1] — that had been commissioned by the UK government.

The report independently reviewed the scientific and engineering evidence associated with hydraulic fracturing (often termed 'fracking'). The report addressed two key questions in connection with fracking: (i) what are the risks of earthquakes? (ii) what are the environmental risks, particularly in relation to possible groundwater contamination? It concluded that these risks can be managed effectively in the United Kingdom so long as operational best practices are implemented and enforced through effective regulation. The report's principal conclusions regarding these risks can be summarized as follows.

Fracking is unlikely to contaminate drinking water. The available evidence shows that fractures can be constrained within shale formations effectively. To reach overlying freshwater aquifers, the fractures in the shale would have to propagate upwards towards the surface for many hundreds of metres. The risk of this happening is very low, provided that fracking takes place at great depths (operations are typically at depths of several kilometres).

But it is important not to conflate fracking itself with shale-gas well operations. Groundwater contamination is much less likely to be due to the fracking process than to faulty well construction. The only realistic way that any contamination of groundwater may occur is if operations are poorly regulated and faulty wells are constructed as a result — consequently, the bigger risk to drinking water would be leakage from a faulty well. The report therefore recommended that well integrity should be a top priority if the risk of contamination is to be kept to an absolute minimum.

All wells are lined with steel casing, which is sealed into the ground by cement. If wells are properly constructed, sealed and managed, the risk of contamination is very low. Also, the Environment Agency does not currently permit any hydraulic fracturing near freshwater aquifers based on a risk assessment, taking into account the geology and depth at which fracking is proposed at the particular site.

The other main potential causes of environmental contamination are poor site construction, or control measures at the surface that include treatment and disposal of wastewaters. However, any risks can again be minimized by best practice and good regulation, which the United Kingdom has a good track record of upholding.

The report also recommended that robust monitoring of groundwater should be conducted across the entire shale gas lifecycle: before, during and after operations. This is an important lesson to learn from the US shale gas experience: it has proved difficult to verify allegations of water contamination caused by fracking in the United States due to a lack of baseline monitoring.

Earth tremors resulting from fracking are smaller than those caused by coal mining, and in this context 'earth tremor' is a much more appropriate term than 'earthquake'. There are thousands of seismic events in the United Kingdom every year — those with a Richter magnitude of 1–2 are rarely felt. There are around 25 per year with magnitude 2 and about three per year at magnitude 3. Fracking can cause earth tremors, but these are likely to be small because shale is weaker than other rocks and yields before larger seismic events can occur.

The United Kingdom has a history of induced seismicity from coal mining and the settlement of abandoned coal mines (up to magnitude 4). British Geological Survey records indicate that this mining-related seismicity is of smaller magnitude than natural seismicity; any seismicity induced by hydraulic fracturing is likely to be smaller still. To put fracking-related earth tremors in context, the two induced by hydraulic fracturing near Blackpool in 2011 had a Richter magnitude of 2.3 and 1.5. The RS/RAEng report concluded that these two minor earth tremors were due to the reactivation of a pre-stressed existing fault, and that it was very unlikely that future earth tremors caused by fracking would ever exceed magnitude 3 – and the effects felt would be no worse than a passing lorry. In other words, the risk of earth tremors of any real significance is very low.

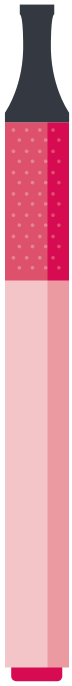
The RS/RAEng report concluded that UK fracking and shale gas extraction can be adequately controlled with its existing strong regulatory system, combined with 60 years' experience of regulating onshore and offshore oil and gas industries. Fracking is an established technology that has been used in the oil and gas industries for many decades, and the United Kingdom has considerable experience of fracking and horizontal drilling for non-shale gas applications. Over the past 30 years, more than 2,000 wells have been drilled onshore in the United Kingdom, approximately 200 of which have been fracked. There is nevertheless a need to ensure that the UK regulatory system is constantly reviewed and fit for purpose if shale gas extraction is to continue in this country with acceptably low risks.

Fracking can be done safely in the United Kingdom, but not without effective regulation, careful management, robust environmental risk assessments and rigorous monitoring. It is also essential to build public confidence: local communities need to be involved and well informed, and to feel that their concerns are being fully addressed.

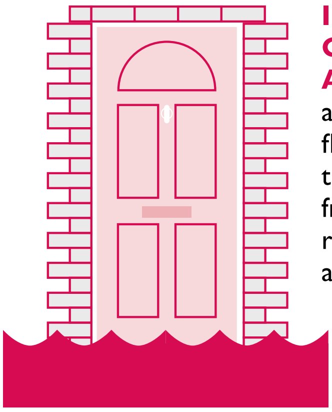
Fracking is unlikely to contaminate drinking water.

SECTION 3: FRAMING RISK – THE HUMAN ELEMENT

When a 7.0 magnitude earthquake devastated Port-au-Prince, the capital of Haiti, in 2010, relief agencies found that there were no detailed maps of the city. It took just two weeks for humans, machines and data — working together as a 'social machine' — to create these vital maps, using tools such as WikiProject and OpenStreetMaps together with data from GPS devices.



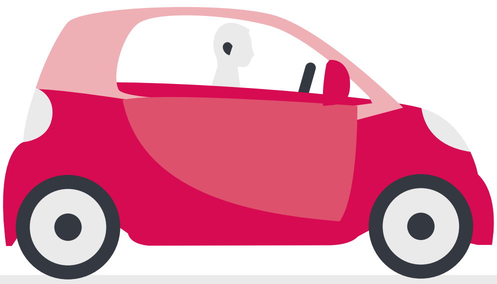
Over the past two years, the number of users of e-cigarettes and vaporizers has tripled.



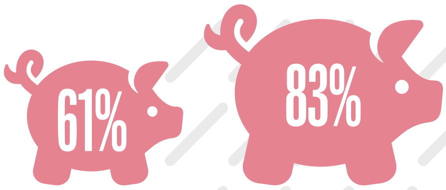
In 2012, the UK's Climate Change Risk Assessment identified an increase in the risk of flooding as the greatest threat to the country from climate change, requiring significant adaptation planning.

Framing quantitative information in the negative ('4 people will die') or positive ('saves 2 lives') can lead to dramatic differences in people's perceptions.

People tend to overestimate the likelihood of high-impact, low-probability events in which many people die at once. In the aftermath of the 9/11 terrorist attacks many individuals avoided travelling by plane — leading to an estimated additional 1,600 in the United States due to road traffic accidents.

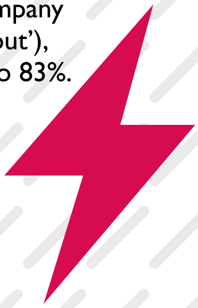


Aum Shinrikyo's sarin attack on the Tokyo underground network in 1995 caused thirteen fatalities; about 5,000 people were injured.



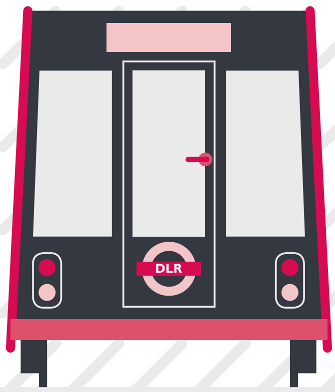
One of the most effective examples of a 'nudge' is to change the way that a default option is set. When the UK government began to automatically enrol people on to company pension plans (with the option to 'opt out'), pension enrolment increased from 61 to 83%.

Dramatic floods in the United Kingdom in the winter of 2013–14 caused flooding in about 7,000 properties — but some 1.4 million properties in England were protected by flood defences, and there was no direct loss of life.



Narrative can be more than a means of escaping from or mirroring situations of change — it is a powerful and effective style of thinking through risk and complexity. For climate change, images of extreme weather can have much more impact than technical presentations.

Potential concerns about the safety of driverless technology on the Docklands Light Railway were addressed in part by downplaying the novelty of the technology.



David Halpern and Owain Service (Behavioural Insights Team, UK Cabinet Office)

CHAPTER 7: HOW PEOPLE ESTIMATE RISKS IN EVERYDAY LIFE

Understanding how our instincts influence assessments of risk can help people to make better choices for themselves.

When professional scientists, insurers and risk assessors consider risks, they typically weigh up the impact of an event against the probability of it occurring over a given timeframe. Car insurers, for example, think about how likely it is that your car will be stolen given its usage and location, and what the cost of replacing or repairing it might be. The UK's National Security Strategy considers what the consequences of numerous plausible worst-case scenario events might be (an attack on UK overseas territories, for example, or severe coastal flooding), and then considers the likelihood that these events might occur.

But this is not the way that most people calculate or assess risk most of the time. Indeed, experiments have shown that it's not even how most experts assess risk most of the time. Human beings instead generally use rules of thumb (heuristics) that help them take quick, instinctive decisions. The vast majority of the time, these mental heuristics serve us remarkably well. But there are also occasions when these same heuristics result in us (in the language of economists) failing to 'maximize our utility'.

The systematic study of how people actually estimate probabilities and risks has had major impacts in psychology, economics, and more recently, in policy. From the early 1970s, the psychologists Amos Tversky and Daniel Kahneman began publishing a series of detailed studies on how people — from the 'man on the street' to trained professionals — estimated everyday examples of probabilities, frequencies and associations. Tversky and Kahneman were especially interested in those situations in which people fail to behave like professional risk assessors, and they gradually uncovered the nature of the mental shortcuts that people were using, and documented the circumstances under which these would lead to error.

For example, Tversky and Kahneman found that people often estimate the probability of an event occurring by how easily they can recall or generate examples of it occurring. Try it yourself. Do you think that there are more English words that start with the letter 'r' or that have 'r' as the third letter?

What you probably did, almost immediately, is to start thinking about examples of words that started with the letter 'r', which you'll find that you can do quite easily. You also will have tried to think of words that have 'r' as a third

CASE STUDY

SOCIAL MACHINES: MANAGING RISK IN A WEB-ENABLED WORLD

Nigel Shadbolt (University of Southampton)

The Kenyan election on 27 December 2007 was followed by a wave of riots, killings and turmoil. An African blogger, Erik Hersman, read a post by another blogger, Ory Okolloh, calling for a Web application to track incidents of violence and areas of need. Within a few days, Hersman had organized Okolloh and two like-minded developers in the United States and Kenya to make the idea a reality. The result was Ushahidi, which allowed local observers to submit reports using the Web or SMS messages from mobile phones, and simultaneously created a temporal and geospatial archive of these events. It has subsequently been extended, adapted and used around the world in events from Washington DC's 'Snowmageddon' in 2010, to the Tohoku earthquake and tsunami in Japan in 2011. How did this happen?

On 12 January 2010, a 7.0 magnitude earthquake devastated the capital of Haiti. As the world rushed to help, relief agencies realized that they had a problem: there were no detailed maps of Port-au-Prince. Too poor to afford a mapping agency, the country had never built this vital piece of digital infrastructure. Two weeks later, using tools such as WikiProject and OpenStreetMaps together with data from widely-available GPS devices, relief workers, government officials and ordinary citizens had access to detailed maps of the entire capital. How did this happen?

As of July 2014, seven projects had contributed hundreds of millions of classifications to the citizen science astronomy website Galaxy Zoo. Beginning in 2007, astronomers at the University of Oxford had built a site that enabled people to quickly learn the task of classifying images of galaxies. The first project comprised a data set made up of a million galaxies imaged by the Sloan Digital Sky Survey — far more images than the handful of professional astronomers could deal with. Within 24 hours of launch, the site was achieving 70,000 classifications an hour. More than 50 million classifications were received by the project during its first year, contributed by more than 150,000 people and resulting in many scientific insights. How does this happen?

The answer lies in emergent and collective problem solving — the creation of 'social machines' that integrate humans, machines and data at a large scale. In the case of Galaxy Zoo, researchers had built the world's most powerful pattern-recognition super-computer. As one of the co-founders noted: "it existed in the linked intelligence of all the people who had logged on to our website: and this global brain was… incredibly fast and incredibly accurate".

The essential characteristics of all of these examples are:

- Problems are solved by the scale of human participation and open innovation on the World Wide Web.
- They rely on access to (or else the ability to generate)

letter and discovered that this is rather harder.

On this basis, most people instinctively conclude that there are probably more words that begin with 'r', whereas in fact there are around three times more words that have 'r' as the third letter. Tversky and Kahneman called this an 'availability heuristic', and you can see why it often works, but also how it can lead us astray[1].

The availability heuristic helps to explain why in the aftermath of an earthquake, Californians are more likely to purchase insurance[2]. It leads us to overweight the probability of high-impact, low-probability events in which many people die at one time. Paul Slovic coined the term 'dread risks' to refer to these phenomenon, which are at play in the case study on nuclear submarines in Chapter 6: far greater resources are devoted to managing these risks than for other potential submarine hazards with the same risk profile.

One sobering study, for example, shows that in the aftermath of the 9/11 terrorist attacks, miles driven on roads jumped by as much as 5% as individuals avoided travelling by plane. It has been estimated that as many as 1,600 US citizens lost their lives as a result of the road traffic accidents associated with this increase in car travel — six times higher than the total number of passengers who died on the planes themselves[3].

Another example is our tendency to overweight positive outcomes that are certain relative to those that are very likely (the 'certainty effect'); and we seek to avoid losses to a far greater extent than we prefer equivalent gains ('loss aversion')[4]. Tversky and Kahneman used pairs of gambles (or 'prospects') to illustrate these phenomena. Consider one such pair, which illustrates the certainty effect and loss aversion in combination (the percentage of people selecting each option is shown in square brackets):

1. Would you prefer an 80% chance of winning £4,000 [20%], or the certainty of £3,000 [80%]?
2. Would you prefer an 80% chance of losing £4,000 [92%], or the certainty of losing £3,000 [8%]?

As you can see, the preference for each of these gambles are the mirror image of one another, depending on whether they are framed as losses or gains. In the positive domain (prospect 1), the certainty effect contributes to a risk-averse preference for a sure gain over a larger gain that is not certain — most choose the certain £3000. But in the negative domain (prospect 2), the same effect leads to a risk-seeking preference for a loss that is merely probable over a smaller loss that is certain — most choose the uncertain £4000.

This example illustrates the importance of how risks are framed. The case study on the communication of medical risks in Chapter 6 uses another example from Tversky and Kahneman, which demonstrates that framing quantitative information in the negative ('400 people will die') or positive ('saves 200 lives') can lead to dramatic differences in people's perceptions.

Understanding how people estimate risks has important implications for public policymakers and regulators. The above finding, for example, has potentially profound implications for financial regulators trying to understand why investment bankers might respond to the prospect of losing a large sum of money by becoming *more* risk-seeking in order to avoid the loss. Alongside some of the other lessons in relation to the banking crisis documented in the above case study, the UK's Financial Conduct Authority has now established a team devoted to the understanding of behaviour.

There are many of these rules of thumb or heuristics that shape how human beings estimate risk. Another important issue, though, is how emotions impact our decision-making and estimates of risk. This is rarely considered by those who manage risk professionally. In a now classic study, George Loewenstein and colleagues developed the 'risks as feeling' hypothesis, pointing out that there are numerous emotionally-driven factors that help to explain how human beings react to risky situations, which cannot be explained by accounts that seek to weigh up coolly the probabilities and outcomes of a given situation[5].

One such factor is the vividness with which these outcomes can be described or represented mentally.

large amounts of relevant open data.

- Confidence in the quality of the data and the processes that underpin the systems is crucial.
- They use intuitive interfaces.

The examples above are dramatic demonstrations of an approach to risk management that the Web can engender and enable. It is an approach that supports the timely mobilization of people, technology and information. It is an approach in which the incentive to participate increases as more people participate. It is an approach that is efficient, effective and equitable.

One challenge to this approach includes maintaining confidence and trust in the quality of data and processes. The very scale of participation means that some will supply bad, wrong or indifferent data. Fortunately, methods have evolved to evaluate and calibrate the results of the crowd. Another is to maintain the Web infrastructure in the face of the problems tackled. However, in an age of satellites, wireless communications and mesh networks the ability to maintain a Web infrastructure has never been greater.

Using the Web, we can build social machines that demonstrate open innovation, managing risks through transparency and wide engagement. The Web enables previously unimagined solutions to some of the world's greatest challenges.

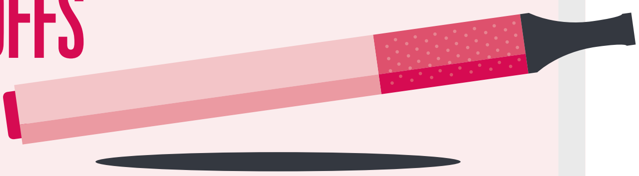
Loewenstein observed that in the United States, people tend to be underinsured for hazards that evoke relatively pallid mental images (such as flooding), which are less capable of causing worry or concern than events that have the ability to evoke more vivid images (such as an act of terrorism). For example, studies have shown that people are more willing to pay for airline travel insurance covering death from 'terrorist acts' (a vivid event) than death from 'all possible causes' (which of course includes terrorist acts).

Emotions do not just affect how we think about the outcome of an event, but also influence how we weight the probabilities of those outcomes occurring. When an outcome is relatively pallid (losing $20, say), participants in a study were relatively sensitive to probability variations: they were prepared to pay $1 to insure against a 1% chance of losing $20, and this rose to $18 to insure against a 99% chance of loss – an 18-fold difference. But when the outcome evoked emotion (for example, receiving an electric shock), the participants were extremely insensitive to probability variations. They were prepared to pay a hefty $7 to avoid a 1% chance of being shocked, but this rose to just $10 to avoid a 99% chance of shock — less than 1.5 times as much.

Another fascinating observation from the literature is the research on 'evolutionary preparedness', which results in people reacting with little fear to certain types of objectively dangerous stimuli that evolution has not prepared them for, such as hamburgers, automobiles, smoking and unsafe sex, even when individuals recognize the threat at the cognitive level. In contrast, other types of stimuli that people are evolutionarily prepared to fear (spiders, snakes or heights) evoke a visceral response even when adequate safety

CASE STUDY

ELECTRONIC CIGARETTES: TRADE-OFFS AND ACCEPTABILITY THRESHOLDS



Fabian Schuppert (Queen's University Belfast)

Regulating risks often requires policy-makers to carefully balance competing objectives and values; trade-offs need to be made and justified in order to arrive at viable acceptability thresholds. Most new technologies and social practices cannot be labelled as either risky, or completely risk-free (in other words, 100% safe). Instead, in most cases new technologies must be considered risky or *safe to a degree*, since absolute certainty regarding a technology's safety is — scientifically speaking — virtually unattainable. Therefore, as regulators, it is our task to assess which risks are acceptable and how to regulate the use and consumption of available technologies. In doing so, one needs to carefully weigh different considerations and values, trying to reconcile competing concerns.

Take, for instance, the case of electronic cigarettes and vaporizers. Over the past two years, the number of users of e-cigarettes and vaporizers has tripled, a trend which some hail as the end of traditional tobacco smoking, while others warn of unknown health risks and a renormalization of smoking. Both sides make valid points: on the one hand, e-cigarettes and vaporizers are innovative technologies that allow their users to quench their desire for nicotine without exposing themselves and others around them to the most harmful risks connected with traditional tobacco smoking. On the other hand, e-cigarettes and vaporizers are not regulated in the same way as tobacco products, meaning that advertisements for e-cigarettes glorifying nicotine use are ubiquitous and a possible risk for teenagers. This obviously raises the question of how regulators should respond to the introduction and widespread use of e-cigarettes and vaporizers.

E-cigarettes and vaporizers are less harmful than traditional tobacco cigarettes, so it seems clear that treating them all in the same way would be misguided. One of the key arguments for the strict regulation of tobacco smoking was the major health risks for smokers (and also exposed non-smokers), an argument which does not apply in the same way to e-cigarettes and vaporizers. While nicotine is highly addictive, its immediate health risks are not greater than those of caffeine. However, this does not mean that e-cigarettes and vaporizers should go unregulated.

Many scientific studies prove the pervasive effects of targeted advertising on young people and their risk-taking behaviour, so it seems advisable to build regulative norms around such knowledge. In so doing, regulators need to carefully balance their interest in protecting vulnerable groups (particularly young people) with concerns over paternalistic interventions in people's free decision-making. Moreover, regulators can take their bearings from the regulation of other substances, such as alcohol (which comes with an age limit), coffee and smokeless tobacco products (such as snus in Sweden). Thus, while electronic cigarettes and vaporizers are indeed novel technologies, their regulation and the associated questions of finding acceptability thresholds based on making trade-offs can draw on existing insights and experiences.

measures have been put in place and they are recognized to be harmless. Some people interpret these findings from behavioural science as demonstrating that ordinary people are irredeemably irrational, or incapable of understanding risks. But the framing of human thought as irrational is itself potentially misleading for a couple of reasons.

Firstly, many of these same effects enable us to process information and act quickly without the need to analyze information comprehensively. Think about how complex your life would be if you had to calculate the trajectory of a falling ball you would like to catch using mathematical equations rather than intuition and simple rules of thumb.

Secondly, lessons from behavioural science do not just show us those situations in which individuals are prone to making errors. They can also show us how to devise systems and processes that support people (professionals and non-specialists alike) in making better decisions for themselves.

This was the central premise behind Richard Thaler and Cass Sunstein's book *Nudge*[6]. They show how policymakers can change the 'choice architecture' to help people to make choices which are better for them and that they are less likely to later regret. For example, one of the best and most effective examples of a 'nudge' is to change the way that a default option is set, in order to overcome our natural tendency to prefer rewards today rather than those that we receive in the future ('hyperbolic discounting'), and more practically, our dislike of doing paperwork. Recognition of this tendency was behind the UK government's decision to automatically enrol people on to company pension plans, so that the default switched from having to 'opt in' to having the option to 'opt out'. The result: overnight, pension enrolment increased from 61 to 83% — and to more than 90% among those who were eligible.

The Behavioural Insights Team has, over the past four years, put in place dozens of randomized controlled trials, encompassing hundreds of variations, which show how apparently small changes such as these can have dramatic impacts on how people take decisions. We have shown, for example, how changing the way that we communicate messages in areas from tax letters to organ donation can increase compliance and sign up rates.

We have also shown how to begin embedding this same kind of thinking in the broader policy making process. For example, the midata project, which we launched with the Department for Business, Innovation and Skills, will enable consumers to access information about themselves that is held by firms. We believe this will herald the start of a consumer revolution, as third-party developers design apps and websites to support consumers' decisions based on easy-to-access data: for example, your energy consumption data will reveal which new tariff is best for you. (See the case study on 'social machines' for further discussion of web-enabled data sharing).

We have also worked with the Department of Health on areas such as electronic cigarettes (see case study), precisely because the behavioural evidence shows it is easy for people to quit smoking if they can substitute cigarettes for another product that feels and looks the same.

Changing the way that we communicate messages in areas from tax letters to organ donation can increase compliance and sign up rates.

Some behavioural scientists rightly argue that we can educate people to become 'risk savvy' by providing people and professionals with information in ways that they can intuitively process and understand. Gerd Gigerenzer, for example, has shown how doctors and patients routinely misunderstand information about cancer screening. In a study of prostrate cancer in the United States, Gigerenzer found that many people, including health professionals, routinely misunderstand the relative risks of different procedures. For example, 'survival rate' data is often used to show the relative efficacy of screening, but this can be highly misleading as individuals diagnosed earlier than they would otherwise have been as a result of screening will naturally tend to have a higher survival date, but not necessarily a lower mortality rate.

Screening for prostrate cancer in the United States does not appear to reduce the overall age-adjusted deaths, partly because it increases the number of people who have a false positive diagnosis that results in unnecessary surgery. Presenting information in terms of relative risks and survival rates turns out to be confusing and unhelpful. In contrast, simple tools like icon boxes that show a population of 100 men and what happens to each can radically improve people's understanding of the relative risks of particular actions

In conclusion, the systematic study of how people estimate risks and probabilities in everyday life has proven to be extremely rich territory. It has revolutionized several academic fields and led to Daniel Kahneman being the first psychologist to be awarded the Nobel Memorial Prize in Economic Sciences. It has also served as a key element of the work of the Behavioural Insights Team, established in 2010 in the UK Cabinet Office, and increasingly being applied by governments across the world.

It should also serve as a subtle caution to all of us: policymakers and experts ourselves use these same mental shortcuts. We are prone to overconfidence; to hold to previous estimates and beliefs, even if arbitrary; and to be strongly influenced by the dynamics of the group around us. That is why the Behavioural Insights Team was established in the first place: to help policymakers understand how they could draw on ideas from the behavioural sciences to encourage, support and enable people to make better choices for themselves.

CASE STUDY

AUM SHINRIKYO AND THE MOVE TO VIOLENCE

Matthew Francis and Kim Knott (Lancaster University)

The case of Japanese group Aum Shinrikyo (Aum) demonstrates the complex and dynamic factors that contribute to explaining extreme criminal behaviour. Aum began in 1984 as a small yoga group, but within ten years it had grown to over 10,000 members with the facilities to produce weaponized chemicals, templates for AK47s and even a military helicopter. In 1995, it released the nerve agent sarin on the Tokyo underground network. Due to an error in its production, fatalities were limited to thirteen, with 5,000 injured.

Aum had used scientists among its membership to produce the sarin (as well as anthrax and botulism spores), whilst simultaneously elevating the idea of sarin as a 'sacred weapon' within the group's beliefs and practices. This fitted within a wider narrative of impending apocalypse that Aum members believed only they would survive, and that led to a culture of group paranoia.

Accusations of kidnapping and murder had been made against Aum in the early 1990s, but law enforcement authorities were indisposed to act because of the constitutional protections given to religions in Japan at the time (which were subsequently amended).

What can we learn?

1. Discursive markers can be identified in Aum's ideological development, and these can be compared to those of other threat groups.

Aum's beliefs were publicly accessible (in Japanese and English), and included repeated mention of sarin and increasing focus on apocalyptic conflict. They made reference to Aum's dichotomous world view (good versus evil, 'them' versus 'us'); its apocalyptic sense of emergency; its lack of common ground with wider society; the symbolic significance attributed to its actions and methods; its violent traditions; and the denial of the innocence of its victims. Not all groups planning violent action will display every trait in their public discourse, but where present they may signal a cause for concern. Although it is undoubtedly easier to reconstruct a developmental trail after the fact, lessons may nevertheless be learned from this example that can be applied to future cases.

2. Beliefs are not enough — context is important.

In the Japanese context, Aum appealed to a young audience dissatisfied with perceived materialism and the strongly rationalist ethic of work and education. Different factors operate in the United Kingdom, which lead to different kinds of risks. The special protections given to religions under the Japanese constitution before the Aum incident have never applied in the United Kingdom, and law enforcement agencies would have been able to act sooner on evidence of violence, kidnapping and murder. The Aum case shows the importance of understanding contextual as well as cultural factors in the move to extreme beliefs and behaviours.

3. Beliefs are not enough — resources are important.

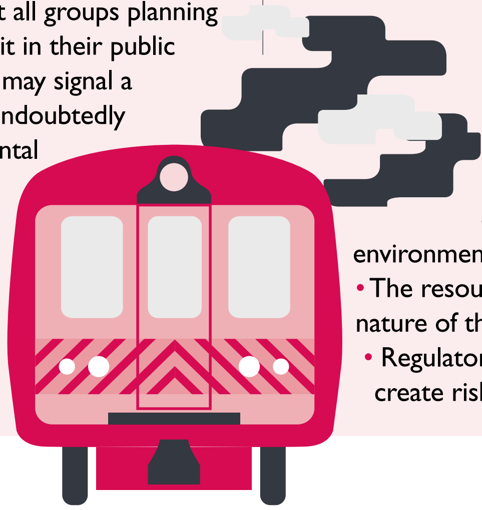
As with other violent groups, Aum's actions and their timing were influenced by external events: the attack on the Tokyo underground was an attempt to deter an impending police investigation. Sarin was identified as a sacred weapon not because it had particular theological significance, but because it was available. Having tried and failed to source the ebola virus and nuclear material, Aum worked with what was to hand.

4. Uncertainty leads to greater extremism.

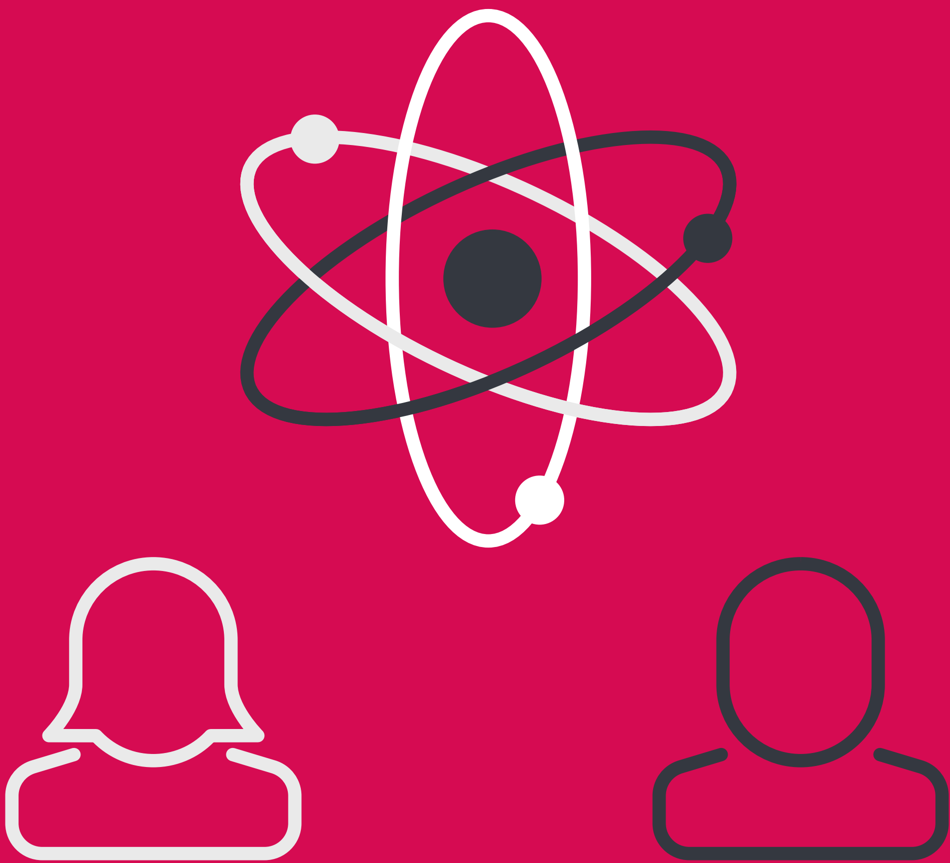
Aum's pessimism, apocalyptic predictions and violence grew in tandem with increasing uncertainty about members' commitment and disillusionment, legal threats, police attention and media lampooning. Psychological research on extremism suggests that individuals are attracted to extreme movements during times of personal uncertainty, and that groups develop sharper, more negative contrasts between members and non-members at times of collective uncertainty.

In summary

- Groups faced with uncertainty are attracted to more extreme beliefs;
- Extreme movements are attractive to those afflicted by personal uncertainty;
- Risks are very much a product of ideological, historical and environmental contexts;
- The resources available to a group affect the nature of their threat;
- Regulatory approaches to risk can themselves create risks of their own.



Nick Pidgeon and Karen Henwood (Cardiff University)



CHAPTER 8: PERCEPTIONS OF RISK

As trust cuts across all of the main approaches to risk perceptions, policymakers need to develop novel strategic capacity and skills in risk communication and public engagement with science.

Although philosophers and social scientists have a long history of raising questions about the appropriate relationship between science and wider society, such questioning is more widespread today as policymakers and members of the public face controversies over potential risks to the environment, to their health and financial futures, and from the introduction of new technologies. Disputes that emerged in the 1960s and 1970s over the risks of chemicals and nuclear power have been followed by concerns in some countries over industrial and transport-related pollution, genetically modified (GM) crops and foods, and latterly so-called 'upstream' technologies such as nanotechnology and climate engineering. Although mathematical descriptions of risk focus upon establishing measures of 'uncertainty' and 'outcome severity', Kates and Kasperson[1] offer a very different conceptualization in terms of "threats to people and things that they value". What people care about in relation to risks consequently affects how they view them, and whether they are acceptable or not.

If we take this broader concept of risk as our starting point then it inevitably sets an epistemological and ontological dilemma, being at once an expression of possible material damage such as deaths, injuries and losses, and at the same time a socially constructed concept in that our knowledge of risk — even that derived from expert assessments — is *always* mediated through social and psychological lenses and judgement processes[2]. A social sciences approach to risk and risk perceptions therefore aims to map out the social and contextual considerations through which people come to comprehend and respond to what they believe is hazardous or not, and helps us to begin to understand why some risks deemed highly significant through expert analysis and risk assessment are seen as unimportant by ordinary people, or vice versa[3].

The Psychometric Paradigm

Research on individual risk perceptions and risk communication first developed during the 1970s and 1980s in response to rising environmental and safety concerns amongst Western populations in particular about industrial chemicals and nuclear technologies. Psychologists of the time aimed to gain an empirical understanding of some of the judgements and beliefs underlying a number of highly visible and complex social and public policy issues. Since then, risk perception and communication research has embraced a diverse set of both disciplines (anthropology, sociology, human geography) and hazards (electromagnetic fields, air pollution, food hazards, climate change, bio- and nanotechnologies, climate engineering). Although the objectives of the researchers are primarily theoretical and empirical, their work touches on significant public policy issues surrounding conflicts over particular environmental, health or technological developments[4].

During the decades spanning the mid-1970s to the mid-1990s, risk perception research was framed either within a cognitive science or a socio-cultural approach, with relatively little interaction between the two. More recent theorising has stressed an increased awareness of and interest in more interpretative approaches which are sensitive to the symbolic qualities of risk perceptions as grounded in context, and which seek to step beyond simple oppositions such as 'cognition' or 'culture'.

Early risk perception studies were dominated by the experimental psychology investigations of Kahneman and Tversky into the mental heuristics or short-cuts which people use in estimating probabilities and rapidly making decisions (see Chapter 7). Over time, some of that work migrated from the psychology laboratory into the field, to encompass study of a richer set of issues within the so-called 'psychometric paradigm'[5]. This work, using primarily quantitative survey methodology, demonstrated that perceived risks were sensitive to a range of qualitative factors, including the controllability of an activity, the fear it evoked, its catastrophic potential, voluntariness of exposure,

> **What people care about in relation to risks affects how they view them, and whether they are acceptable or not.**

BOX 1

Qualitative Characteristics of Perceived Risk. Adapted from the Department of Health's Communicating About Risks to Public Health: Pointers to Good Practice. Revised Edition. (London: The Stationery Office, 1998).

All other things being equal, risks are generally more worrying (and less acceptable) if perceived:

- to be involuntary (e.g. exposure to pollution) rather than voluntary (e.g. dangerous sports or smoking)
- as inequitably distributed (some benefit while others suffer the consequences)
- as inescapable by taking precautions.
- to arise from an unfamiliar or novel source
- to result from man-made, rather than natural sources
- to cause hidden and irreversible damage, e.g. through onset years after exposure

equity of risk distribution, the perceived unnaturalness of the hazard, observability of the risk and so on. Box 1 shows some of the characteristics which make risks more or less acceptable to people. As a result, a new and unfamiliar risk that people feel that they have little control over, as in the driverless train in the Docklands Light Railway case study, may require special actions and communications to be in place to reassure people of safety measures. Subsequent to this early work, we also know that the way people think about and judge risks is influenced by the way they respond to the affective resonances and feelings that it evokes, and analytic information[6, 7].

While it is tempting to view affect, or emotion, as an irrational process that only afflicts people who differ in view from us, we also know that rational decision-making requires elements of both analysis and affect. For example, without emotional commitment in decision-making we would not remain committed to important choices[8]. Benefits also matter to people, as risk is more acceptable if it holds perceived benefits that are equitably distributed, as does trust in risk managers and institutions, an issue to which we return below.

The early psychometric studies provided a model for an extensive research programme and literature[3, 5, 9]. However, while the basic approach of psychometric risk perceptions research provided extensive empirical descriptions of the psychology of risk perceptions, it did not initially yield substantive theoretical progress towards explaining those beliefs, or people's behaviour in the face of risks.

Values, Culture and the Risk Society

Social and cultural factors are important to risk perception because the perceiver of risk is rarely an isolated individual, but a 'social being' defined through a range of relationships with others[10], raising the question of how societal values shape risk perceptions. The best known socio-cultural approach to risk, that of Douglas and Wildavsky[11], develops the worldview idea in conceptual terms, positing that human attitudes towards risk and danger vary systematically according to four cultural biases: individualist, fatalist, hierarchist and egalitarian.

These biases are held to reflect modes of social organization, thought and value, all of which serve the function of defending individuals' favoured institutional arrangements and ways of life, and in particular who to blame when those arrangements become threatened from outside[12]. Risk perception becomes central to the process of institutional defence, with cultural biases orienting people's selection of which dangers to accept or to avoid, the fairness of distribution of risks across society, and who to blame when things do go wrong. Cultural theory has also been valuable in stressing the neglect, within the early psychometric studies, of a concern for the political dimensions of risk, although it suffers from the fact that its categories of worldview are top-down in nature, and from difficulties in measurement[13].

> **Contemporary investigations of energy issues and climate change show how deeper values are bound up with our risk perceptions.**

More recent work on 'cultural cognition', however, draws on this thinking to demonstrate why certain risk issues (handguns, abortion) have become deeply polarized across US society[14]. Contemporary investigations of energy issues[15,16], and climate change[17] also show how deeper values are bound up with our risk perceptions. We know that individuals with political affiliations to right-leaning political parties tend to identify with less egalitarian and more individualistic values, and as a result are more likely to be sceptical about the claims of climate change scientists and risks[18]. However, this work also suggests how some values that are widely endorsed can be incorporated as important components of narratives about risk (see case study on climate change narratives). For example, recent research with US conservatives found that they were more favourable towards environmental messages when these focused on pollution, and the 'purity' of the natural environment, rather than the more conventional set of arguments about a moral responsibility to avoid harm[19].

> **US conservatives were more favourable towards environmental messages when these focused on pollution, and the 'purity' of the natural environment, rather than arguments about a moral responsibility to avoid harm.**

Similarly, a recent report for the Climate Outreach and Information Network[20] argued for the importance of identifying the overlap between the values underpinning centre-right conservatism in the United Kingdom and those which are congruent with sustainability, such as an emphasis on community well-being, intergenerational duty and a representation of the environment not as a 'service provider' but as something that people have a duty to protect. Social values and discourses also shape how men and women orient towards science and technology, and are being explored as explanations for the so-called 'gender effect' in risk perception — the observation that some men come to see environmental and technological risks as less threatening than other groups in society, including most women[21, 22].

Arguably just as important to thinking about cultural issues and risk has been the work of Ulrich Beck[23] and Anthony Giddens[24] in their discussion of 'Risk Society'. Risk society theory starts from an analysis of the macro-structural conditions and consequences of contemporary (late-modern) industrialized Western society. The claim is that late-modernity has been accompanied by the emergence of new classes of all-pervasive and 'invisible' risks, experienced only indirectly through expert systems of knowledge — we may be exposed to risks, but can never fully comprehend their technological and environmental causes.

According to Beck and Giddens, the consequences for the

CASE STUDY

MANAGING RISK PERCEPTION OF AUTONOMOUS TECHNOLOGIES: THE DOCKLANDS LIGHT RAILWAY

Mike Esbester (University of Portsmouth)

Introducing autonomous technologies — those which are not directly controlled by human operators — poses significant challenges, particularly regarding people's perceptions of the dangers to which they might be exposed. This case study focuses on London's Docklands Light Railway (DLR), and considers how the automatic technology of driverless trains was presented to the public. It explores how the risks conceivably posed by the lack of human drivers were perceived and addressed, and is used to suggest lessons for the introduction of future autonomous technologies.

The DLR is an urban mass transit system, proposed in the early 1980s and opened in 1987. It operates on a track separated from other transport users — unlike a tram, for example, it does not run along streets. This meant that it was possible to run driverless trains controlled by computer programs, though a single member of staff travelled on board to operate doors and check tickets.

Driverless trains brought with them the potential perception that they were in some way dangerous, as nobody was in control. However, the records available show no great public concern about the driverless technology. There were fears, but they were mitigated or addressed by those promoting the DLR both before and during the system's introduction, until the DLR's safety record was established in practice.

Proactive communication was key: explanations of the system, its technology and the associated fail-safes tried to remove concerns about the lack of drivers. Exhibitions of trains and promotional literature put forward both the positives of the DLR and the negatives of traditional surface level transportation. They noted (but didn't stress unduly) the potential for human control if need arose. Leaflets and newspaper features noted that it was possible for the member of staff on board to drive the train and that the system was overseen by humans in the control centre.

Potential concerns about the safety of driverless technology were addressed by publicity surrounding the trials of the DLR, which stressed their extensive and thorough nature. Significantly, the novelty of the technology was downplayed. Instead, the DLR's proponents acknowledged the debts owed to existing automatic technologies that the public might be familiar with, in a bid to demonstrate the tried and tested nature of such systems. This included the Victoria underground line, which had used a version of automatic train operation since 1968.

Finally, perceptions of risk were ameliorated by placing the system under the regulation of the Railway Inspectorate, the state agency responsible for overseeing safety (including granting permission to operate new lines). The state, effectively, acted as guarantor on the safety of the DLR.

These factors suggest a number of aspects to explore when introducing new autonomous technologies, in order to address public concerns about potential negative impacts. The public is likely to be interested in new technologies, and may well approach them with an open mind and sophisticated (and varied) perceptions of risks. Therefore providing information at each stage of the process is likely to be beneficial. Concerns should be acknowledged and individual include the emergence of new forms of anxiety and existential uncertainty associated with the privatization of risk decision-making (from the state and institutions to individuals) alongside the fragmentation of traditional social categories such as gender, the family and class. Risk society theorists also point to an interaction between new global-local environmental risks and social changes: in particular, a shift in the locus of responsibility for dealing with risks from state to individual citizens, coupled, paradoxically, with a need to place greater trust in experts in a technologically sophisticated and connected world. Erosion of traditional social identities, such as the certainties offered formerly by class, profession, gender or family units, are also held to make the individual more responsible for the risks that they face (technically termed the reflexive risk subject), who must as a result chart his or her own identity (who I am and who I want to be) and risk biography (what risks must I worry about in the everyday) in an ever more uncertain world[25]

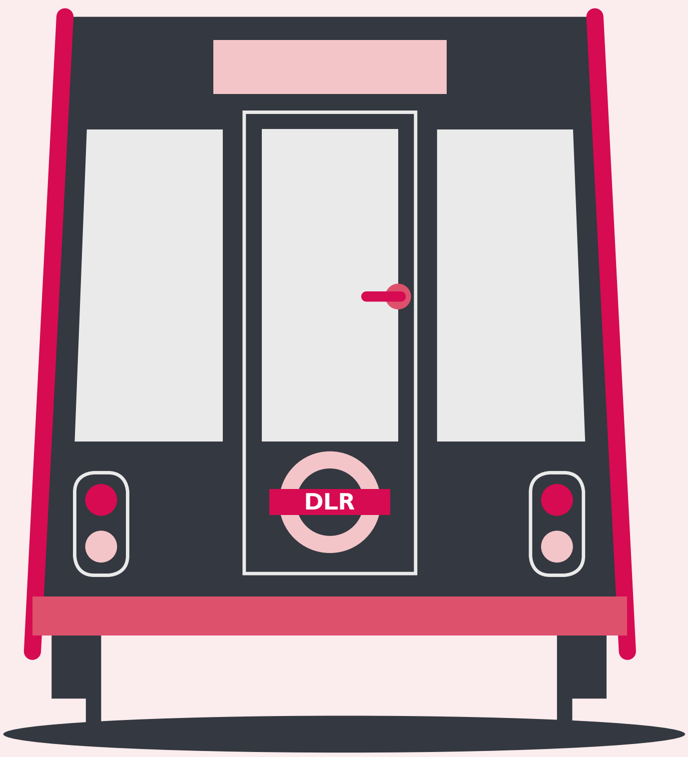
Risk society theory represents, then, a set of arguments about the way changing socio-economic conditions are impacting people's individual risk perceptions and risk identities[26]. Interestingly, while Beck and Giddens highlight environmental risks as the domain where risk society is most acutely felt by people, it may ultimately prove to be the 2008 financial crisis, alongside the 'unwinding'[27] of the traditional social contracts between citizens and the State in many Western Nations, that provides the acid test of their thesis[28].

Interpretive Approaches to Risk Perception

Very recently a range of interpretative approaches to everyday risk perceptions have arisen, stressing the symbolic and locally embedded nature of the socio-cultural element to risks, as well as the ways in which people actively construct their understandings of risk issues. These elements of an interpretive approach can be used to understand the complexly-gendered nature of environmental risk perceptions, and how it can illuminate current ethical debates and philosophical reflections on nuclear energy[29], a matter that has become of particular policy concern in the UK post-Fukushima. Drawing on hermeneutic, phenomenological and discursive traditions, such perspectives recognize the central roles of meaning and interpretation in structuring our social interactions and identity (see also Chapter 9).

Approaches within such a tradition often take a more locally grounded approach to both the content and origins of risk perceptions, and seek to explore discussions and understandings of risk where people are directly exposed to a hazard such as industrial environmental pollution, a local chemical or nuclear plant, or a disease outbreak which affects their everyday lives[30, 31, 32]. The emphasis here is upon understanding the localized logics and rationalities that people bring to bear upon an issue, rather than with

The public is likely to be interested in new technologies, and may well approach them with an open mind and sophisticated (and varied) perceptions of risks.



addressed without playing-up the potential negative aspects, and presented alongside the potential benefits. Factors that might usefully be communicated include: the relationship of new technologies to existing technologies that people have experienced; testing of new systems; the regulatory system that will protect people; and the fail-safes built into autonomous technologies to prevent harm.

reference to an externally imposed concept of technical, psychological or culturally determined 'risk'. During the 2001 UK foot and mouth epidemic, for example, local people in the affected areas in marginal rural communities often understood the risk of transmission in terms of the geographical relationships between infected and uninfected farms, which in turn depended upon their knowledge of local geographical features. When those understandings did not correspond with the quarantine zones around infected farms as defined by the culling policy devised centrally in London, it generated considerable mistrust in risk management and the authorities[33].

Interpretive approaches share considerable common ground with more psychologically-based approaches to perceptions and risk communication design, based upon the mental models technique[34], while a recent development in this area is the use of more biographical and narrative approaches to understand risk perceptions, risk framing and risk valuation[35, 36]. The interpretive approach also forms the foundation for much of the work documenting the social amplification of risk — the idea that both risk controversies, and conversely situations where risk perceptions become attenuated, emerge and are sustained by the dynamics of institutional and media actors who process, transforming and shape our collective understandings of risk.

A recent example of risk amplification comes from the

CASE STUDY

TELLING THE STORIES OF CLIMATE CHANGE

Esther Eidinow (University of Nottingham), Nicky Marsh (University of Southampton) and Patricia Waugh (University of Durham)

"Please don't tell me how the story ends"
(Cormac McCarthy, *The Road*)

One of the most powerful narrative images for climate change is that of the urban apocalypse: Manhattan submerged by snow or rain. These familiar narratives, predicting and often preventing disaster, rehearse the conditions of contemporary agency in situations of risk. They make technocratic knowledge accessible and personal: the risk analyst saves his girlfriend, the scientist his son. The subjunctive qualities of narrative also structure time, exploring and modifying the causalities between past, present and future that risk analysis requires. Popular narratives of disaster, informed by the certainty of their ending, structurally both enact and contain the uncertainties of risk.

Yet the dramatic scale of these apocalyptic texts also makes the agency that they produce seem implausible. The ability to prevent the apocalypse is the preserve of the hero, and some of the clichés of contemporary fiction can threaten the very agency they appear to enable, because they encourage us to identify with the effects but not with the solutions to the crisis. This summer, as 'cli-fi' went viral, and stories about climate change and its effect multiplied across different media, the *New York Times* on 29 July 2014 asked the key question: "Will Fiction Influence How We React to Climate Change?"

Hollywood aims to thrill us, but the realities of climate change require a different kind of story-telling. The mobilizing effect of Rachel Carson's 1962 book *Silent Spring* has been widely touted, but narrative's role in comprehending the extraordinarily complex social and environmental challenges of the moment go beyond a mere call to action. Recent interdisciplinary research across narratology and the cognitive sciences has shown that human cognition functions not just in a logico-empirical mode, but inherently draws on narrative structures to make sense of the world and to understand how it is embedded in an environment that it helps to construct. Think about the kind of cognitive workout we get from reading complex novels attentively: we are educated out of confirmation bias, required to revise hypotheses in the light of new evidence, consider multiple perspectives, note the agency of metaphors in reorganizing the real, and understand our errors as unexpected perspectives emerge towards a hoped-for convergence with an already-written ending (which never turns out to be quite what we'd expected). Narrative is more than a means of escaping from or mirroring situations of change — it is a powerful and effective style of thinking through risk and complexity. After all, there is no narrative without change and surprise.

The discipline of planning has long recognized that narrative presents a powerful tool for describing complex future challenges, such as climate change, where multiple uncertainties preclude simple linear predictions. This is reflected in the increasing use of scenarios for planning, both around climate change itself and related challenges (including food security, land planning, and water sourcing). Such stories can allow technical information to be made comprehensible in terms of lived experience, and help to develop a context of shared understanding for decision-making. But perhaps most importantly, they can offer a method for exploring possibilities: in place of finished narratives, story-telling as a dynamic and creative process can invite engagement and encourage a sense of agency.

But who will tell these stories? Building long-term capacity for collaborative decision-making faces the challenge

We tend to trust people who share our values or are members of our own social group, especially when information about a risk is either uncertain or sparse.

domain of biosecurity risks. In the autumn of 2013, when it became clear that ash trees were vulnerable to the spread of the *Chalara fraxinea* pathogen to the United Kingdom, government and society alike did not anticipate the strong media and political focus on the issue that would follow. Pidgeon and Barnett have documented how a range of cultural and institutional factors underlay this controversy[37]. Climate change, on the other hand, has long been recognized to be an 'attenuated' hazard[38], a risk where people are often resistant to the scientific evidence of its gravity precisely because many of the proposed solutions will threaten some of our most deeply held values regarding the relationship between society, lifestyles and economic growth. This again points to the importance of constructing the right narratives about risk to address such deep-seated value-based and identity issues (see case study on climate change).

Risk Perception and Trust

The past 20 years have seen a surge in interest in the role of trust in people's responses to environmental and technological risks, from both the academic and policy community. In Europe, the crisis over bovine spongiform encephalopathy (BSE) in particular was seen as an event that reduced public trust in risk management processes. Accordingly, rebuilding trust in the science policy process through processes of public engagement and transparency has been a core policy objective of public risk communication and stakeholder engagement processes[39].

The question of trust and risk perception is not a new one, however. As early as 1980, the sociologist Brian Wynne[40] argued that differences between expert and lay views of risk might depend upon the public's evaluation of the trustworthiness of risk management, and of the authorities to act both in the public interest and with regard to best possible technical standards and practice. And indeed one interpretation to be placed upon several of the qualitative dimensions of risk identified in the psychometric studies (for example, control over risk, equity of impacts, whether a risk is known to science etc.) is that they tap more fundamental value concerns about the institutional processes of hazard management. Such concerns are not strictly divorced from the hazard process itself, either. We have to trust risk management and managers to keep modern risks (transportation, energy systems, environmental stressors) within acceptable bounds, and any evidence of a failure to fulfil such a duty means that the risk might indeed be more serious than we thought.

Survey studies have repeatedly shown that trust in risk managing institutions is positively correlated with the acceptability of various technological and environmental risks. For example, with the exception of gender (see above), most socio-demographic and ideological variables are only weakly related to concern about a potential nuclear waste repository or nuclear power, while trust variables have

of creating multi-stakeholder scenarios — stories about the future that bring together different actors and decision-makers with diverse perspectives and expertise. Part of the answer may lie in rethinking our approach to narrative in this context. For effective public engagement we need not just one, but many, simultaneous story-tellings, told not just once, but many times.

substantially higher predictive power[3, 41]. In the United States, distrust in repository management was mainly linked to opposition to the proposed siting of the Yucca mountain radioactive waste repository, because of the perceived risk of the waste site[42]. Other studies show that trust is significant across a range of hazards and risks[43], although the precise underlying reasons for trust and distrust may vary in different risk cases and contexts. In the case of GM crops, for example, it was the ambiguity of risks (see Chapter 4) alongside concern about the activities of large multinational corporations imposing risks on people without their consent; for foot and mouth disease, it was the insensitivity to local impacts of the central management strategies.

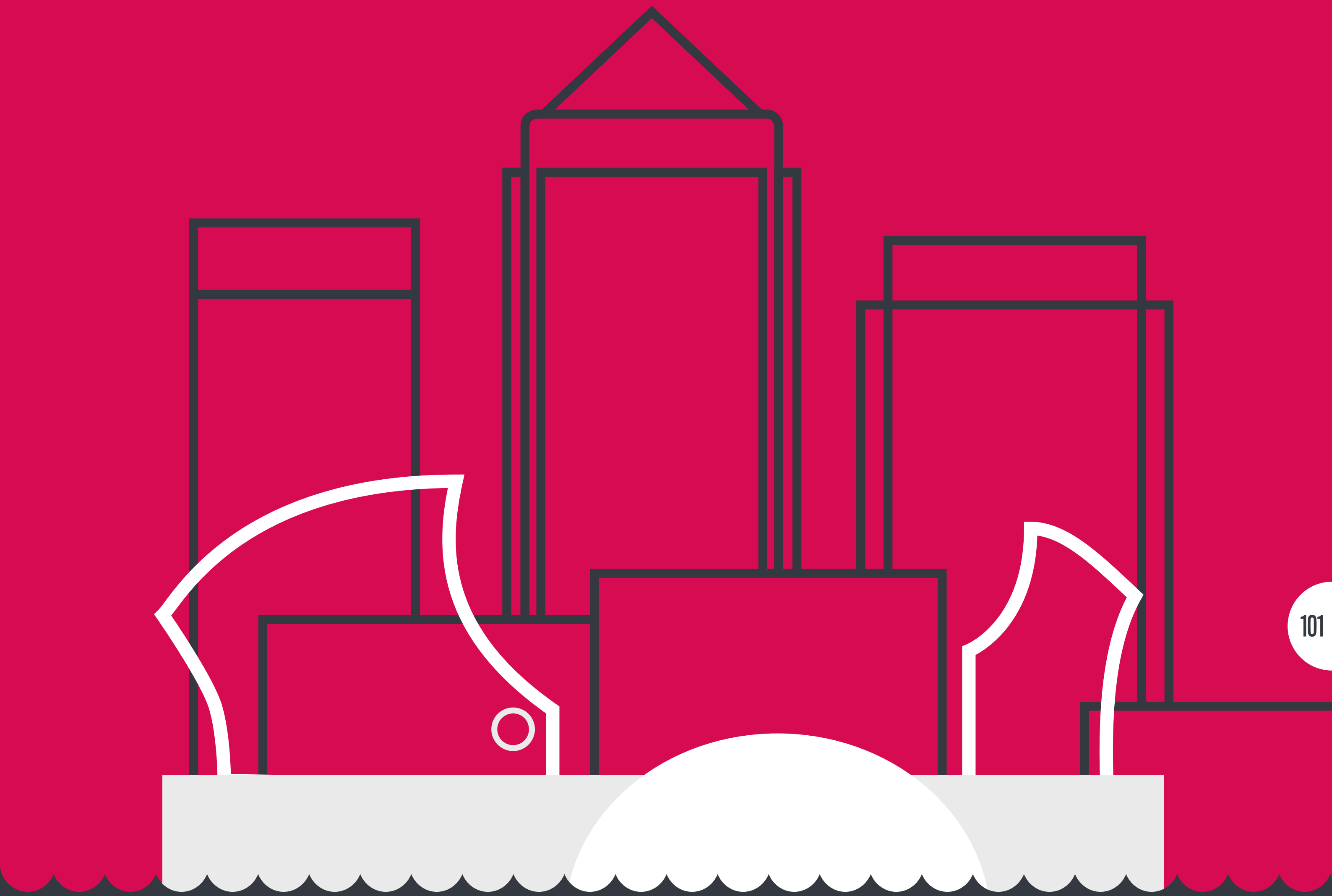
In conceptual terms, trust cuts across all of the main approaches to risk perceptions described above, while a number of recent risk controversies — including BSE and GM crops — have made policymakers aware that the public have become key players in many controversial risk issues, and that (dis)trust may be a core component of this[39, 44]. Trust is often conceptualized as a set of cognitive judgements along discrete dimensions that are primarily related to the (presumed) behaviour of risk managers, particularly around their care, competence and vested interest[43, 45]. We trust people, experts and institutions if they act in a caring way towards us, are knowledgeable about the domain at hand, and are demonstrably free from any self-serving interest or partisan bias (and ideally those who simultaneously exhibit all three!). These three dimensions help to explain why 'independent scientists' remain some of the most trusted social actors in relation to communicating about controversial risk issues. Other more recent work suggests that social trust and cooperation can also be built on the identity-based concepts of value similarity. That is, we tend to trust people who share our values or are members of our own social group, especially when information about a risk is either uncertain or sparse[46].

Walls et al[47] point out that these different components of trust can exist in tension, with social trust likely to emerge as multidimensional and fragmented, as a product of a reconciliation of competing ideas, knowledge and impressions. They introduce the important concept of '*critical trust*' as an organising principle, something which lies on a continuum between outright scepticism (rejection) and uncritical emotional acceptance. Such a concept attempts to reconcile a situation in which people actually rely on risk managing institutions while simultaneously possessing a critical attitude toward the effectiveness, motivations or independence of the agency in question[43,48]. Again, from a policy perspective it is entirely rational not to wish to place complete blind faith on any organization or individual who holds the power of life or death over us or over the environment. And although for many policymakers the 'reclamation of trust' has become an explicit objective, this suggests that risk communication efforts that are aimed at directly increasing trust may not be universally effective in solving risk controversies[49]. Such policies could well be counterproductive where they are based on the incorrect assumption that trust can be simply manipulated in order to increase the acceptance of a controversial risk. If Beck and Giddens are right about the emergence of a risk society, risk communicators will have to find new ways of working under conditions of permanently eroded trust. Accordingly, policy advice today tends to stress the importance of analytic-deliberative engagement and dialogue as the means for exploring the values and perceptions underlying risk controversies and for exploring routes to better risk communication and conflict resolution[50, 51] (see also Chapter 5 and Chapter 9). Although such methods have an established empirical track-record when used to resolve local site-based facility siting and other controversies, scaling up to national-level questions such as national energy strategies or policies to tackle global environmental risks set a range of very difficult conceptual and methodological challenges[52]. Pidgeon and Fischhoff[8] argue, in the context of climate change risks, that all of this points to the need in the United Kingdom, as elsewhere, to develop novel strategic capacity and skills in risk communication and public engagement with science. This requires us to bring together expertise from fundamental domain sciences such as radiation protection, climate change, or biosciences, with the appropriate social sciences of decision analysis and risk communication.

> **'Independent scientists' remain some of the most trusted social actors in relation to communicating about controversial risk issues.**

> **It is entirely rational not to wish to place complete blind faith on any organization or individual who holds the power of life or death over us or over the environment.**

Edmund Penning-Rowsell (University of Oxford), Paul Sayers (Sayers and Partners and University of Oxford) and Andrew Watkinson (University of East Anglia)



HIGH LEVEL CASE STUDY: FLOODING

THE SOCIAL SCIENCE PERSPECTIVE

We know more than we think we do. Through research by social scientists over the past few decades, we have learnt a great deal about how people gather information on risks such as flooding, how they respond to it, and how it informs their actions as individuals and as groups of citizens. But it is hard to translate these insights — some of which have now been known for a long time — into practical advice for individuals and policymakers, mainly because the lessons are that risk is often denied and action is rather less than might be expected. This is a key challenge facing decision makers.

Denial remains a common reaction from those at risk of flooding, even among those with flood experience. The oft-repeated suggestion is that "It will not happen to me", and "I will not be here when the next flood comes". These reactions are not driven principally by ignorance, but by an anxiety about future flooding that people want to minimize[1]. The language of risk is also a barrier: public understanding of return periods or even annual probabilities is poor.

Whatever the risks, the decisions that individuals and communities make are influenced by the traditional social contract with the state: "We pay our taxes and we expect the government to act". Communities at risk are unlikely to respond with community risk-reducing initiatives and innovations until after a major event — known as the "prisoner of experience" phenomenon — rather than in anticipation of a hazard. Moreover, these responses are often limited to areas where existing social capital is extensive, and in relatively affluent and predominantly rural areas rather than inner cities.

Flood events themselves are often followed by a loss of trust in those who manage risk, as well as dissatisfaction at the apparent lack of interventions to reduce risk, which is influenced by the perceived unfairness of the governance process. People have a poor understanding of 'who is in charge', which is unsurprising given the fragmented governance arrangements related to the different sources of flooding (rivers; surface water; groundwater; the sea). They also have a poor grasp of statutory duties and available resources, and of the time taken to implement interventions. Small-scale remedies by individuals or community groups are not trusted to be effective.

Research shows that it is important for decision makers to present the information on quantifiable risks clearly, and to put it in context. Uncertainties need to be explained, and risk-reducing measures 'owned' by those at risk rather than imposed upon them. Denial needs to be understood, rather than brushed aside. Trust in the skills of those in authority — and those with special knowledge and expertise — needs to be carefully nurtured. Human behaviours need to be understood and seen in their cultural context — specifically, political cultures, religious cultures and national cultures — along with the historic tolerance to risk that this brings.

We must also appreciate the types of issues that arise when science gets deeply embedded in culturally contentious areas (such as climate change), and how these issues play out in the various international governance structures for risk and innovation.

THE ANALYSTS' PERSPECTIVE

"All models are wrong — some are useful"
(George Box, 1987)

'Risk' is a rich term, including notions of the chance of harm, consequence and opportunity. In all but the simplest of settings, judgement or intuition are not enough to establish a meaningful understanding of present and future flood risk, so decision makers must rely upon models.

Flood risk management resources are limited and, even if we wanted to, it is not possible to reduce all flood risks for all people to a common level[2]. Any biases within the modelling approach that leads to an over- or under-estimate of risk therefore have the potential to misdirect these limited resources. But in recent years, flood risk analysts have made significant progress in developing models to support better design, planning and emergency response decisions. This has involved reducing modelling bias and incompleteness. But in doing so, a number of significant issues and challenges associated with understanding risk and managing it appropriately continue to be exposed[3].

The 'whole system' challenge

The flood risk system consists of all of the important *sources* of flooding, all of the potential *receptors* that may be affected (either directly or indirectly), and the performance of the intervening system of physical *pathways* (the land surfaces, channels, beaches and engineered channels, defences, barriers and pumps). It also includes the interactions with society (individuals; emergency response teams; businesses and so on) and the broader interaction with physical, ecological and human systems. Traditional modelling approaches have typically focused on individual components of this 'whole system', and thereafter we have tended to manage the analyzed risks and not the complex reality.

Whole system thinking provides a significant challenge to the analyst. The chance of harm is not, as it is often mistakenly supposed, equivalent to the chance that a particular storm event occurs. Equally, the consequence of a flood is not simply the direct material damage, but reflects the inherent susceptibility of a receptor to a flood, its ability to recover unaided in a timely manner, and the value society places on the harm incurred. Whole system modelling approaches are in their infancy but are now, at least, recognized as a worthwhile endeavour.

The fallacy of reductionism and the truth of uncertainty

The behaviour of flood risk systems is intrinsically stochastic

— that is, governed by random processes. Yet significant research is devoted to produce ever more detailed models of single elements in the 'whole system' (featuring, for example, better representations of the hydrodynamic processes, or increasingly fine-grained terrain models). The results of such reductionist models are easily communicated, but they fail to support risk-based choices — for although they simulate inundation in fine detail, they are based on gross assumptions such as the location, timing, and growth of a breach in the relevant flood defences.

But analysts increasingly recognize the need to support robust decisions[4], and to do this their models must represent all important aspects of that decision and be truthful about the uncertainty of the evidence presented. Here lies a bear trap. Any presentation of uncertainty is typically viewed as 'comprehensive', yet it often reflects only a few easily-described uncertainties (known unknowns). These uncertainties may lie in the data, such as errors in the measured height of flood defences, or in model components such as the assessment of defence overtopping. Although significant progress is now being made[5], the ability to communicate uncertainty meaningfully — in a way that reflects data, model, and crucially model-structure errors — remains poor.

THE INFRASTRUCTURE PLANNER'S PERSPECTIVE

The planner of flood risk-management infrastructure faces a significant and growing risk, but also considerable uncertainty. Both coastal and inland flooding remain high on the UK's National Risk Register, with significant concerns around the three main sources of flooding: rivers, surface water and especially the sea. In 2012, the UK's Climate Change Risk Assessment identified an increase in the risk of flooding as the greatest threat to the country from climate change, requiring significant adaptation planning[6].

The challenge of flooding in the United Kingdom was also demonstrated dramatically in the winter of 2013–14, which saw unprecedented levels of rainfall in southern England and the largest tidal surge in 60 years. Transport infrastructure was widely disrupted, and some agricultural land was flooded for several weeks. Yet although some 7,000 properties were flooded, some 1.4 million properties in England were protected by flood defences over the course of the winter storms, and there was no loss of life as a direct result of the December 2013 surge. The 1953 surge of a similar magnitude killed 307 people along our east coast and caused losses that were the equivalent of at least £1 billion in today's money.

There have been some notable infrastructure successes. The past 50 years have seen substantial investment in flood risk management, with significant outlay on forecasting, flood warning and a range of flood defences. These worked well in 2013–14, although they were tested to the extreme in many cases, with approximately £140 million of damage caused to our flood defences. Moreover, controversy remains a constant theme: there were claims that agricultural land and livelihoods were sacrificed to protect assets within urban areas, allegedly the result of a transfer in the risk burden from the town to the country.

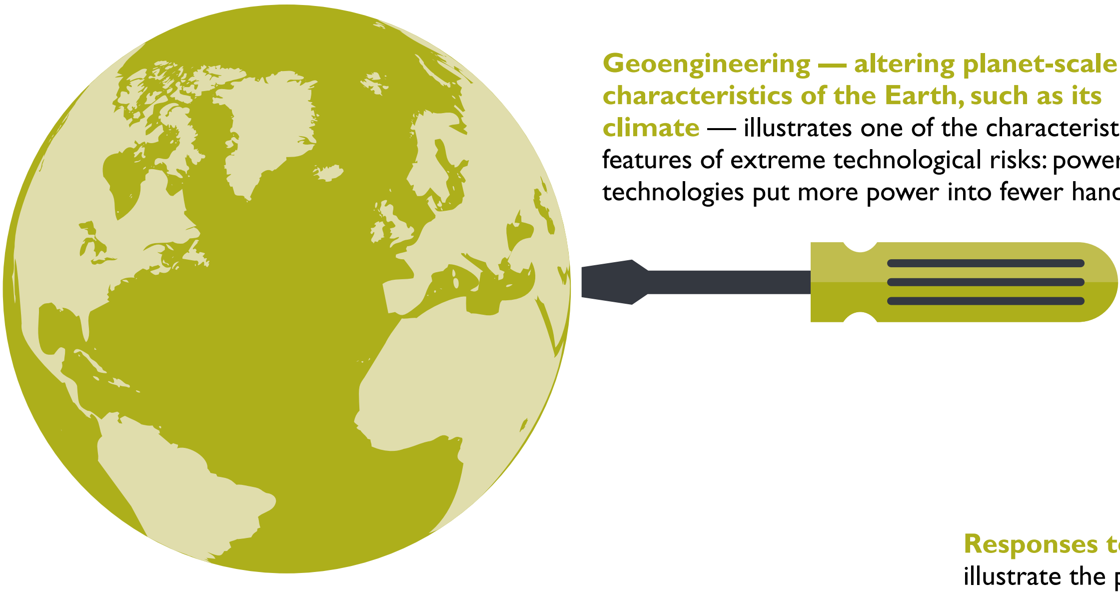
Flood infrastructure planners have been innovative in the past, and this is continuing. Improved forecasting models, better flood warning and world-class defence systems such as the Thames Barrier have all involved innovation in response to risk, requiring political commitment, time and investment[7]. As leaders on this issue, the UK's Department for Environment, Food and Rural Affairs and the Environment Agency are embedding a consideration of long-term risks in their planning, because infrastructure investments are required to meet changing risks up to 100 years into the future. The Thames Estuary 2100 Plan is an excellent example of such foresight[7].

However, the improvements in defences have led to significant developments of homes, businesses and the infrastructure that supports them (water, electricity and telecommunications) in flood risk areas. This in turn changes the risk because the consequences of flooding are now greater. Looking forward, socio-economic growth across Europe is estimated to account for about two-thirds of the change in risk of flooding by 2050, with the remaining one-third coming from climate change.

Managing this changing risk requires a long-term vision for flood risk management and the ability to respond to changing circumstances on a shorter-term basis. It requires us to decide what level of risk we are prepared to accept in protecting existing properties from flooding, and the extent to which we should veto development on flood plains to prevent risk escalation. This demands a robust and transparent implementation of spatial planning policy. The government's new 'partnership funding' approach to flood defence spending also requires new forms of local involvement in order to secure the maximum risk reduction[8]. Meanwhile, effective risk reduction is being greatly assisted by a continuation of the research-led innovation that has served us so well over the past 50 years.

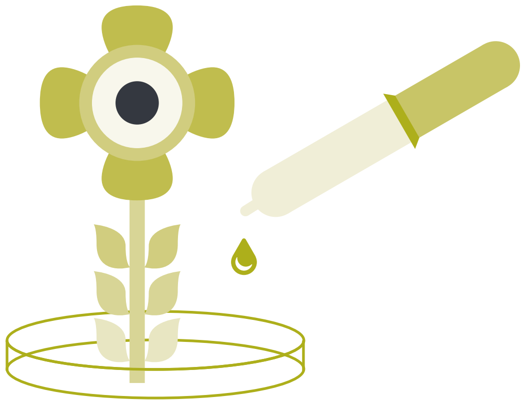
> **Coastal and inland flooding remain high on the UK's National Risk Register, with significant concerns around the three main sources of flooding: rivers, surface water and especially the sea.**

SECTION 4: CONTEXT AND FUTURES



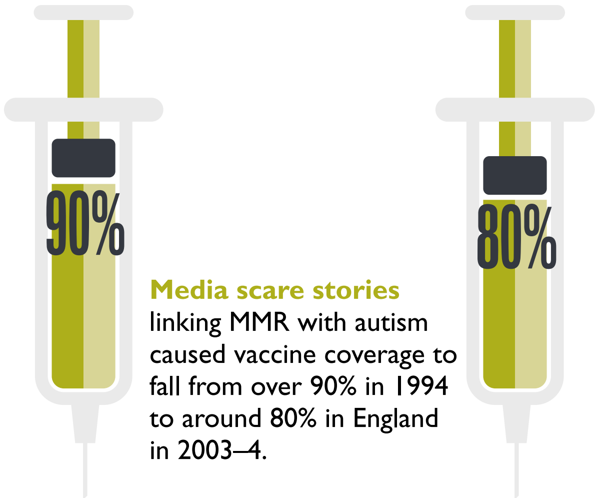
Geoengineering — altering planet-scale characteristics of the Earth, such as its climate — illustrates one of the characteristic features of extreme technological risks: powerful technologies put more power into fewer hands.

Responses to GM crops illustrate the power of fear of threats to basic values.



In 2012, measles cases rose to levels that had not been seen in England and Wales since 1989, reaching a peak of 1912 confirmed cases.

'Not in My Back Yard' responses to potentially hazardous facilities and technologies are strongly driven by a preference for the status quo: such as preserving the same view from your window, the same level of background noise, or protecting the value of your property. Arguments around statistically assessed risks are sometimes used as a form of surrogate for these concerns.



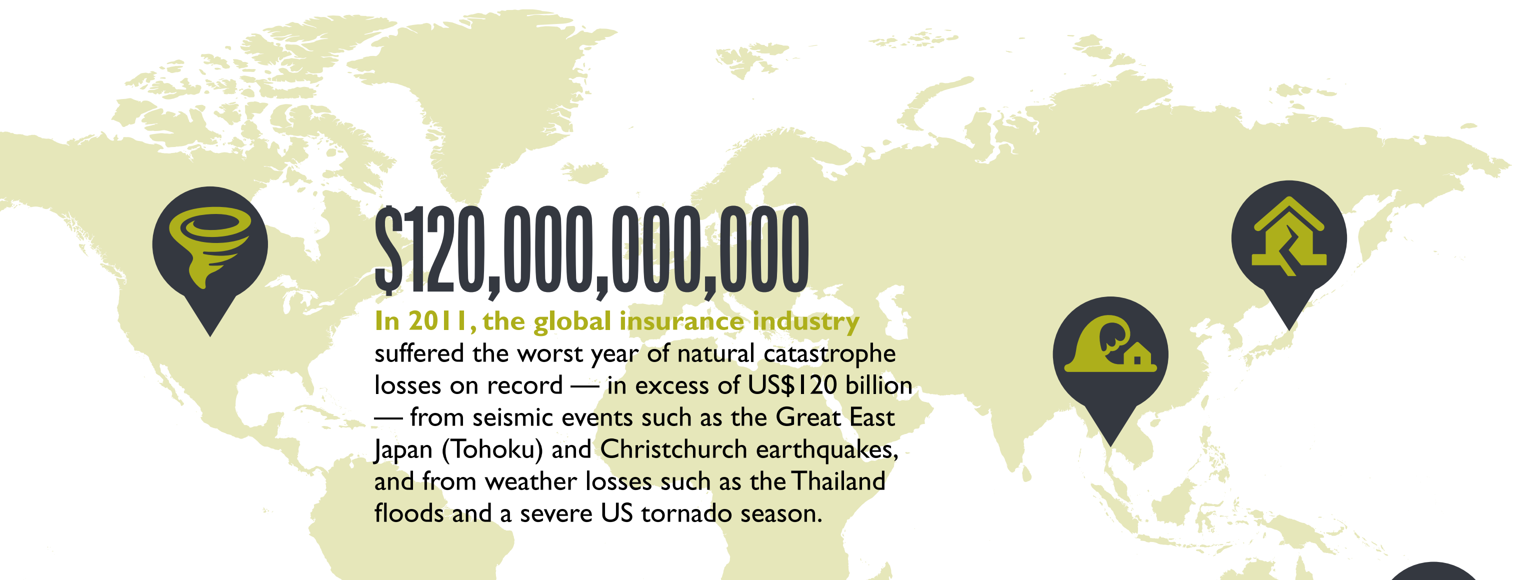
Media scare stories linking MMR with autism caused vaccine coverage to fall from over 90% in 1994 to around 80% in England in 2003–4.

Direct occupational experience of acute harm from chemical exposures can hamper workers' understanding of less visible and more chronic risks such as cancer.

300 MILLION DEATHS

Smallpox was responsible for more than 300 million deaths in the first half of the twentieth century. As the ongoing Ebola epidemic reminds us, disease outbreaks remain a potent threat today.

Technological advances have helped to bring unprecedented improvements in health over the past 150 years, with life expectancy in the United Kingdom steadily increasing by two to three years each decade. From a starting point of about 40 years, it has doubled to 80 years.

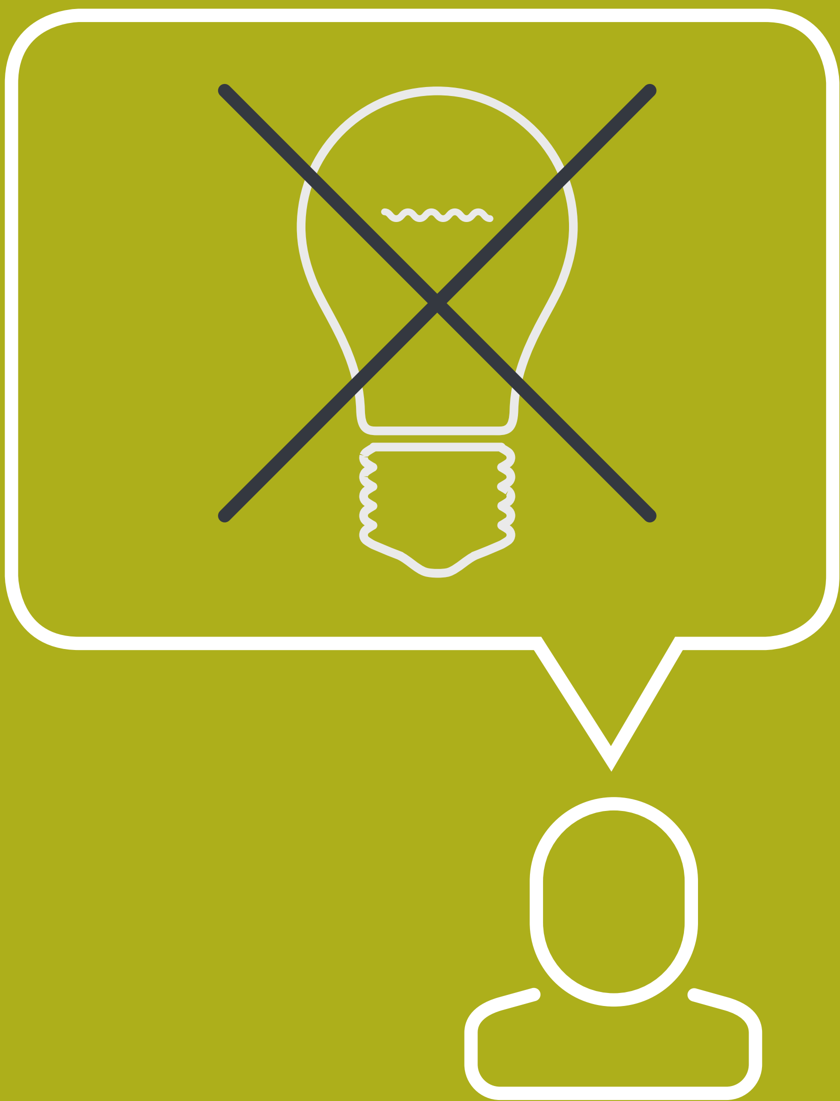


$120,000,000,000

In 2011, the global insurance industry suffered the worst year of natural catastrophe losses on record — in excess of US$120 billion — from seismic events such as the Great East Japan (Tohoku) and Christchurch earthquakes, and from weather losses such as the Thailand floods and a severe US tornado season.

Model-based methods are now embedded within the regulation of insurance in the United Kingdom, and similar approaches are being adopted around the world: earthquake insurance in Canada, for example, is required to meet a 1-in-500 year test.

Judith Petts
(University of Southampton)



CHAPTER 9: CONTEXT MATTERS TO HUMAN PERCEPTION AND RESPONSE

People may choose not to tolerate an innovation for perfectly logical reasons that have little to do with worries about potential risks — instead, their concerns stem from disquiet about institutional motives and behaviour, and perceived threats to the things that they value.

From Chapter 8, we know that the basis of individual responses to risk is multidimensional. The fear of potential physical harm is only one factor driving these responses, and sometimes it is the least important. Concerns about risks are most often based on worries about the adequacy and motives of the institutions that produce, predict and manage them, and of perceived threats to the status quo, social relations, identity and everyday experience.

The concept of 'perceptions of risk' has been challenged for a long time[1]. Technically, risks cannot be 'perceived', just as they cannot be 'sited'. Rather it is the activities or technologies that create the potential for risk that people can be concerned about. But, fundamentally, it is the institutions that are responsible for developing and managing them that are questioned, often from a position of distrust.

Once these underpinning dimensions of human response are understood, it is important to consider how and why responses vary in different cultural (ethnic or national), political, and economic settings (countries, regions, or areas at risk). In a highly connected world, technologies, goods and services (and therefore potential risks) are traded and transferred widely with varying degrees of openness and control. The underpinning science is increasingly generated through international collaborations operating in multiple political, cultural and belief settings. Technological, health (human, animal and plant) as well as natural hazards can cross borders and boundaries. Therefore it is important to understand if, and how, attitudes and responses are likely to vary, not least as the mechanisms and modes of control become trans-national.

Over the past three decades, cross-cultural surveys of risk responses have found that differences depend on the political, cultural and socio-economic bases of different countries[2]. The 'worry beads'[3] of different societies around differing risks require detailed characterization if communication, engagement and appropriate mitigation responses are to be developed and encouraged. This chapter considers the key dimensions of perceptions and response, and the impact of context, drawing on different risk examples. It concludes with a discussion of the implications for responsible innovation and engagement.

Experience, Intuition and Networks

Studies across the full spectrum of industrial, environmental and health risks have shown that the collective memory and expertise that comes from direct, personal experience combined with the influence of everyday social and cultural practices and networks are key contexts in which responses to risk develop, mature and are actioned (or not). Social interactions, context and setting (spatial/physical, experiential and social) all play a role in shaping how people make sense of and construct any risk issue[4].

Judgement and choice under uncertainty usually operate intuitively and quickly. Simple and tangible associations are crucial — including the emotional reactions or rules of behaviour that have been acquired through experience of events and their consequences, and enhanced through cultural and social networks. People's intuitive assessment of a risk is based on the ease with which instances of occurrence can be brought to mind: in other words, its 'availability'[5] (see also Chapter 7). The latter is impacted strongly by the location, and the social and economic context, in which someone lives and works. Intuitive responses can develop and mature as opportunities for learning occur (including through engagement in risk decision-making).

For example, natural hazards are experienced not only through the physical harm they can cause, but as a result of learning processes. Second-hand experience (information) about flood risk has been found to be less likely to produce action than direct knowledge and social interaction[6]. An underestimation of low probability events (such as typhoons, floods or droughts) and decisions about how to respond to them (for example, whether to continue to buy insurance) are strongly impacted by experience. 'Wait and see' reactions to the appropriateness of taking personal protective actions can be strong when a serious event has not occurred or not reoccurred. Such reactions can be particularly important when economic imperatives require risk tolerance, not least when people do not have the resources to respond. This helps to explain why people remain in high hazard areas despite repeated experience of the physical harm. Dependency on an area and lack of personal ability to respond negate risk mitigation.

Direct experience makes climate a particularly strong and salient feature amongst indigenous communities (such as in Australia, Pacific Islands and the High Arctic[7]). These communities often have highly connected daily lives as part of relatively small social networks, as well as a close dependence on their environment. Knowledge passes from generation to generation and is embedded in story and belief, in value systems and institutions. Where climate change impacts directly and tangibly on the ability to continue to undertake basic daily practices — such as fishing, hunting or travelling — then experience is direct and can supplement scientific knowledge.

Such local 'expert' knowledge derived from direct working experience of environmental systems has been seen to show up the weaknesses of expert assessments based on desk-top modelling (for example, among Lake District farmers following the Chernobyl nuclear accident[8]). The intensity of understanding in locally, closely-networked communities differs from the weaker relationships and shared knowledge of more transient communities in large cities where cultural beliefs and socio-economic dependencies may be shared to a lesser extent.

When weather and climate are confounded then responses to extreme weather events are often either slow or partial. Acceptance that the event may become more frequent is low. Even after the devastating hurricane seasons of 2004 and 2005 in the United States, a large number of residents in the high-risk areas still had not invested in loss-reduction means[9]. Their response to risk was actually the same as those in low-risk areas. But the underpinning reasoning was fundamentally different.

The impact of intuition on responses to local proposals for hazardous technologies can be seen in relation to more positive responses to nuclear facilities in different locations in the United States. These responses have been identified as corresponding with local experience of alternative energy sources (no direct contact with alternatives leads to higher tolerance), and even experience of related nuclear industries that bring economic advantage locally[10].

Finally, direct occupational experience of acute harm from chemical exposures has been seen to interrupt the potential for workers to understand less visible and more chronic risks such as cancer. Furthermore, the learning that occurs between workers (particularly in small companies) tends to compound this bias in understanding. Such evidence confirms that notions of hazard and risk must be communicated more directly and personally in the specific work context rather than relying solely on generic safety information[11].

The Status Quo and Surrogacy

A common feature of many cultures is our preference for the status quo, which is a strong support to intuitive responses. Keeping with what you know and are familiar with is generally the easier, less stressful option in life. Overriding the status quo requires commitment to change. Generally, change takes effort and may offer uncertain benefits[12]. Denial of potential risks can serve to protect feelings of security and lower anxiety, both in low- and high-risk areas (for example, in relation to flooding[13]).

It is well known that 'Not in My Back Yard' ('Nimby') responses to potentially hazardous facilities and technologies are strongly driven by a preference for the status quo (such as preserving the same view from your window, the same level of background noise, the same visual amenity, protection of the value of your property, and so on). But this innate desire to protect the current and the personal can be a difficult argument to put or defend in contentious decision processes. Evidence from multiple cases in different locations in the United Kingdom of proposals for waste facilities suggests that arguments around statistically assessed risks are sometimes used as a form of surrogate for very local and personal concerns about impact on amenity and the status quo, as well as concern about the robustness of the risk control institutions and regulation, and the extent to which public interests are protected. Subjective notions of distrust or locally-important ways of life and amenity can be more difficult to argue in expert-led decision processes. Therefore, local residents can find it easier to focus attention on scientific weakness and statistical uncertainties and assessments of risk to vulnerable populations[14]. Fundamentally, Nimby attitudes to siting and new technologies need to be more productively understood as reflecting public demands for greater involvement in decision-making, and not regarded as risk battles between the public and experts that merely require better communication to correct perceived deficits of lay knowledge.

Risk is so intricately embedded in its social context

Notions of hazard and risk must be communicated more directly and personally in the specific work context.

that it is difficult, if not impossible, to identify it *a priori*. One intriguing example of the often unexpected power of context was the responses to multiple house fires in a small town in the French Jura. More than a dozen apparently spontaneous house fires occurred over the period November 1995 to January 1996, destroying property and killing two people. While eventually understood as arson, a form of psychological defence mechanism became evident amongst residents who sought to blame a buried high-voltage cable. Repressed and highly-localized concerns about this 'technological installation' were privileged as reasoning rather than the more likely but perhaps banal explanation of arson. This search for a surrogate — which might allow people to more readily attach blame to an institution — prompted detailed expert and official investigations, and became a major national media story[15].

Ideology and Values

Risk responses are often attenuated by context, rather than amplified — people do not appear to be concerned about hazards that experts regard as significant. In seminal work, involving a large comparative consideration of 31 'hidden hazards' including handguns, deforestation, pesticides and terrorism[16], ideological and value-threatening reasons were identified as two explanations for the failure of hazards to raise political and social concern. Handguns are one example of an ideological hazard: despite the rising annual toll of death, being able to bear arms to defend oneself and one's family has remained an inalienable American right. Contrast this with the opposite ideology in Britain.

The same study also identified ideological impacts on risk regulation. At the time, there were differences in the approaches to protect public health compared with occupational health. Public health standards for airborne toxic substances were tighter than occupational protection in 13 industrialized countries; the same was true in socialist states, which ideologically tended to be less permissive of industry (see below).

Responses to genetically modified (GM) crops illustrate the power of fear of threats to basic values. People respond negatively to GM crops not primarily because they fear the risks, but because genetic modification drives to the heart of concerns about 'mucking around with nature'. Media headlines about 'Frankenstein foods' intuitively resonated with these concerns at the height of the GM debate in the United Kingdom.

The perceived inability of governments to impose adequate controls mixes with these concerns. Such perception is based on clear evidence of regulatory and management controls (and their failures) across multiple apparently unrelated hazards. For example, the fact that GM crops have met with such vehement public reaction in the United Kingdom compared to the United States has been linked, at least in part, to people's experience of the mismanagement of bovine spongiform encephalopathy (BSE). That disease involved risks that obviously are entirely unrelated to GM — yet both speak to issues around the intensification of agriculture and the trans-boundary movement of hazards.

Recent comparative work[17] looking at responses to GM crops in Mexico, Brazil, and India confirms the strength of cultural and political factors (see also case study in Chapter 2). In Mexico, for example, maize has a deep cultural resonance with long-held traditional practices of food preparation, and a symbolic resonance with plants and seeds in everyday lives. Negative reactions to GM maize are therefore a complex mix of concerns about the insult to tradition, and a lack of credibility in seed companies, regulatory bodies and government. In India, negative reaction has particularly been symbolized as a struggle against multinational companies and globalization. In relation to a deeply traditional and important non-food crop — cotton — the deliberate importation of *Bt* cotton led to fears of increased dependency on certain seed companies.

For the United Kingdom, the current rise in local conflicts around proposals to extract shale gas by hydraulic fracturing (fracking) appears to reflect a combination of Nimby-esque responses to the local impacts on the environment (such as noise and water pollution); threats to the social and economic status quo; and a sense of decision-making isolation from the potentially affected communities. Importantly, there is a lack of saliency in terms of the national *need* for alternative energy supplies (see the fracking case study in Section 2 for more on this issue).

Fracking is viewed primarily as an environmental rather than an energy issue, as differences in responses by socio-economic status and rural versus urban locations in the United States have confirmed[18]. However, in local contexts where new exploitation of gas supplies has seen rapid 'boom town' change in rural areas that have endured extended periods of economic decline, risk can be associated with opportunity[19].

The fracking debate resonates with the divergent responses to energy-from-waste incineration. In countries like Denmark and Sweden, the technology is often part of the mix in the local supply of heat and energy. In the United Kingdom it is primarily a waste management solution, and has frequently sparked local concern about the need for large-scale plants with all of the perceived local dis-benefits.

In Scandinavia, plants tend to be smaller because they are sized to meet local heat-supply needs, and to process lower volumes of feed material that arise within reasonable travel distances. In general, a more nuanced understanding of 'place based' as opposed to 'project based' concerns seems important, not least when national policies need to be implemented locally (such as in relation to large-scale energy infrastructures[20]).

Regulatory Cultures

Normal and sustained cultures of trust can be dramatically challenged by new risks. This is evinced by the differing regulatory approaches to interpreting 'hazard' and 'risk', and to dealing with uncertainty, that reflect cultural scientific differences.

The difference between the UK approach to risk management and the European precautionary regulatory approach to hazards has long been evident. One well-known and particularly economically-damaging impact of this difference was seen in the response to BSE. When this previously unknown cattle disease erupted in the United Kingdom in the mid-1980s, it was acknowledged that a new variant (nv) of the human encephalopathy, Creutzfeldt-Jacob disease (nvCJD), might be caused by exposure to BSE. This led the European Union to impose a ban on the worldwide export of beef products from the UK, plunging the country's beef industry into potential disaster.

At the heart of the regulatory response was a cultural difference in the approach to scientific uncertainty. The British approach traditionally excludes abstract uncertainties or knowledge limitations and applies a pragmatic, instrumentalist approach. The continental European tradition is founded in a culture that tends to integrate natural and human sciences more directly. Hence, precautionary regulatory intervention is often taken in response to a plausible risk, even though pathways of exposure cannot be demonstrated[21].

Differences in agricultural policy between the European Union and the Unites States underpin their divergent approach to GM crop risks. Regulatory differences have been analyzed in terms of the different cultural and economic meanings of agriculture[22]. US farms have more often been seen as analogous to factories, separate from wilderness and nature conservation areas. In Europe, however, farmland is widely regarded as an integral component of the environment — an aesthetic landscape, wildlife habitat, and part of the local heritage. Importantly, farms are a traceable guarantee of food quality. So EU

> **Genetic modification drives to the heart of concerns about 'mucking around with nature'.**

policy has moved towards less-intensive production and is more cautious of biotechnology. The United States, on the other hand, has seen a drive by companies to expand high-productivity agriculture.

In the BSE case, UK consumers could choose whether to purchase British beef based on the information available to them. However, trust in scientific and government institutions was severely impacted by the failure to inform people of the risks at an early stage. In the case of GM crops, confidence in the scientific understanding of the risks and distrust in the profit motives of the seed companies at the expense of the environment has similarly had a strong impact on acceptance. The similarities of public response to BSE and GM emphasize the need to understand linkages between responses to unrelated risks — indeed, responses can be predicted between risks.

There has long been awareness and concern about the different cultural definitions of 'hazard' and 'risk' that play-out through regulatory regimes. This is particularly evident across European member states, and it also varies between sectors such as pharmaceuticals and food (where risk assessment is the dominant approach) and environmental regulation (where hazard identification and assessment is prioritized)[23]. The GM case study in Chapter 11 highlights how the European Union's regulatory approval process for the commercial release of a GM trait — which is based on the presumption of hazard — is prohibitively expensive compared with the United States.

Political and regulatory differences in focus between hazard and risk have been attributed to strategic game-playing by stakeholders who are well-aware of the semantic difference between the terms. So, it is argued, risk responses have as much, if not more, to do with political interests and strategic positioning as the objective assessment of the risk, with all of its uncertainties[24]. Such institutional variability is one important factor influencing public mistrust in management and control regimes.

Context and Responsibility

Personal agency and institutional trust are deeply rooted and connected factors that determine how people respond to risk[25]. Trust and agency interact at different spatial and temporal scales, and we often see the most powerful responses at the local level.

Studies of the responses to natural hazards (flooding, sea level rise and radon) in different locations in the United Kingdom[26], on air quality[27], and on thresholds of response to climate change[28], have determined that even when people appear to understand the hazards and the risks to themselves and have the personal resources and capacity to respond, they may choose not to if they consider that the responsibility to reduce the risk lies elsewhere. The same has been evident in responses to flood risk in other countries. In high-risk areas where people take responsibility and acquire clean-up experience, risk awareness tends to remain high compared to those who have chosen to deny their vulnerability and responsibility[29]. Active investment of personal resources, even if no more than time, tends to support ongoing responsibility.

> **Choice and responsibility are sources of stress for people when information about risks appears confused and conflicted.**

Choice and responsibility are sources of stress for people when information about risks appears confused and conflicted. The initial response to the MMR (measles, mumps and rubella) vaccination in Britain in the late 1990s provides one example of this. A preliminary study of a small group of children — which could prove no causal link between the vaccination and autism, but which left open the possibility — generated media coverage that sparked a huge controversy. The immediate response focused on, indeed proactively played upon, the parental fear of autism; this led to a dramatic drop in the uptake of MMR, with some areas of the country falling below the health protection target (see case study for details). As communications from the government's Department of Health did not specifically negate the relevance of the study, the wide-scale response — which was fed through parental networks — was able to have damaging impact.

Socio-economic differences were strongly evident in the responses. Higher socio-economic groups that were better able to access a wider range of information sources, or could choose to pay for the alternative single vaccinations, were more likely to avoid MMR. It became evident that embedded social responsibility — through a long process of normalization of childhood vaccination — was very much secondary to individual maternal responsibility in relation to a child's health, when mothers in particular were faced with uncertainty and disruption to acquired trust in immunization[30].

Responsible Innovation, Context and Engagement

The notion of responsibility in innovation has grown in importance over the past decade and notably in European policy circles. The possibilities and opportunities of emerging technologies are of course accompanied by uncertainty and indeed sheer ignorance. These uncertainties are not purely around the possible harms, but also in the kind of futures societies wish for. Innovation takes place over multiple scales (increasingly global) and the range of actors (from individuals to corporations to states) are often acting in different cultural and economic contexts, which impact directly on notions of what is the 'right' and 'responsible' thing to do.

Governance of responsible innovation is being discussed in terms of a new adaptive framework, implying a move away from top-down, risk-based regulation to a system in which

CASE STUDY

MMR, BOWEL DISEASE, AUTISM AND MEASLES

David Salisbury (former Director of Immunisation, Department of Health)

In 1993, Dr Andrew Wakefield reported his observation that natural measles virus infection was implicated in the cause of Crohn's Disease[1]. Common sense suggested that this was highly unlikely: Crohn's Disease had been increasing in industrialized countries at the same time that measles had been decreasing through vaccination. Wakefield then went on to propose that attenuated measles vaccine virus was actually the cause of Crohn's Disease.

Both of these theories were soon demonstrated to be wrong. Other researchers pointed out that he had failed to carry out the manufacturer's recommended positive and negative controls for immunogold histology staining, and better epidemiological studies showed no association between measles vaccination and Crohn's Disease[2,3]. Despite this, Wakefield persevered with his belief that measles virus caused bowel disease.

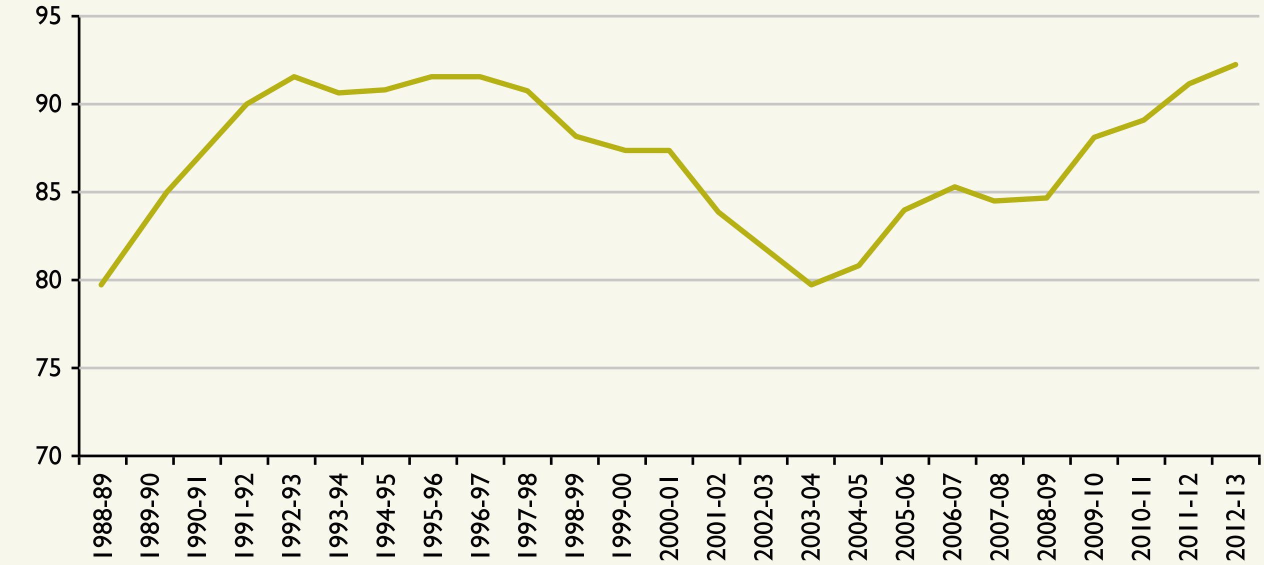
In 1998, he published a case study purporting to associate onset of autism and bowel disease with receipt of combined measles, mumps and rubella (MMR) vaccine[4]. Twelve cases were reported, many of whose parents were involved in litigation against the manufacturers of MMR vaccine. Despite no evidence for benefit, he strongly advocated the cessation of MMR vaccination in favour of single measles, mumps and rubella vaccination. Even though Wakefield's own team showed that there was no measles vaccine virus in bowel specimens from inflammatory bowel disease cases[5] or autistic children[6], he continued to promote his views against MMR despite multiple studies that failed to confirm that it was a risk factor in autism[7–14].

Although each of Wakefield's pronouncements was greeted with scepticism among relevant experts or expert review groups, they were given unprecedented coverage by uncritical or inexpert media, partly due to Wakefield's use of a public relations expert. Some health professionals colluded with anxious parents, who thought that avoiding the MMR vaccine would somehow protect their children from autism, and tried to offer six injections of separate vaccines (to equal the recommended two MMR doses). Private clinics sprang up offering expensive imported single vaccines that may not have been licensed, or indeed were known to cause mumps-meningitis and had been removed from the UK programme.

The results from repeated media stories linking MMR vaccine with autism and other adverse outcomes led to progressive loss of confidence in the safety of MMR vaccine among health professionals and parents[15–17]. As a consequence, MMR vaccine coverage fell from over 90% in 1994 to around 80% nationally in 2003–4, but with much lower figures in some parts of the country, especially in London and South Wales[18,19]. Since 2005, however, MMR coverage has progressively increased as anti-MMR stories faded from the media, and as local campaigns improved vaccination uptake (see Figure 1)[20].

Measles had been eliminated from England and Wales between 1994 and 2001 (ref. 21) but by 2006 there were resurgences of localized measles outbreaks (although no national level outbreaks occurred). Despite the apparently reassuring increases in MMR coverage, exceeding 90% by 2011, there was still a high risk of measles resurgences, owing to the cohorts of under-vaccinated children born during the years when MMR coverage was lowest. As these cohorts began to attend school, they started to come into contact with many

FIGURE 1 **MMR coverage at 24 months. (Source: NHS Immunisation Statistics)**



more children, raising the risk of measles transmission. In 2012, measles cases rose to levels that had not been seen in England and Wales since 1989, reaching a peak of 1912 confirmed cases (see Figure 2). Multiple outbreaks were detected, especially in the North East, the North West and in South Wales. Cases continued to rise up to the first quarter of 2013.

The highest numbers of cases were in children and young people who had been born during the years of lowest MMR vaccine coverage, when anti-MMR rhetoric was at its height (see Figure 3). A national MMR vaccine catch-up campaign was therefore rolled out, targeted at those who had had no MMR vaccine (those aged ten to sixteen years were the highest priority), followed by those who had only had a single dose of MMR. By the midpoint of the 2013 campaign, coverage in the ten- to sixteen-year-old group was estimated to have reached more than 95%. Since the completion of the campaign, measles cases have reverted to extremely low levels.

On 20 September 2003, Mark Henderson wrote in *The Times*: "Health scares such as this protect no one, whatever the sanctimonious claims of the zealots behind them. The MMR panic is more likely to cause deaths from measles than it is to save a single child from autism". How true that has turned out to be. In 2010, the General Medical Council removed Dr Wakefield's name from the UK Medical Register on the grounds that he had "acted dishonestly and irresponsibly in conducting his research", and that "his behaviour constituted multiple separate instances of serious professional misconduct"[22].

The loss of public and health professionals' confidence in the safety of MMR incurred a heavy cost to child health. But it has also been accompanied by huge costs to health research resources, which were diverted to negate false claims, as well as the additional time and money spent preventing, containing or treating measles cases. Clearly there are lessons for all involved in how scientific claims are reported; how media balance should reflect certainty and uncertainty, rather than simply giving equal coverage to both sides; how risks are communicated and interpreted by the public; and how research should be managed and published.

FIGURE 2 **Figure 2. Measles cases England & Wales 2008 to 2014. (Source: Health Protection Report Vol 8 Nos.8 –28 February 2014)**

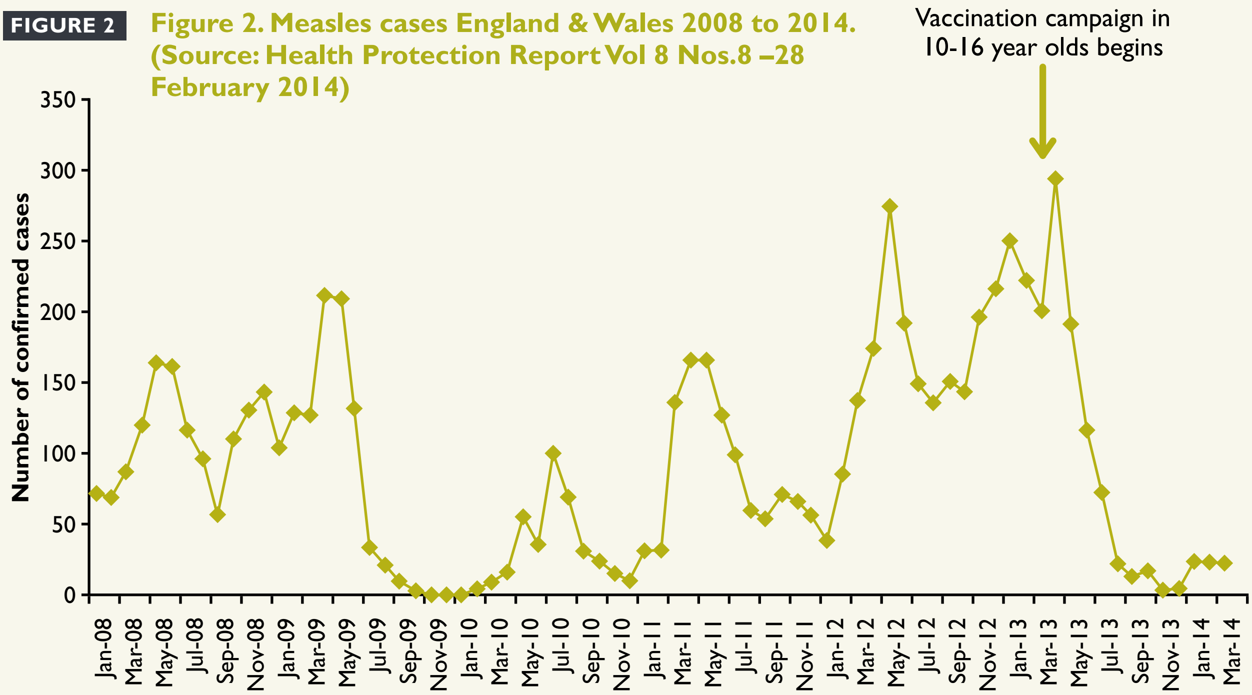
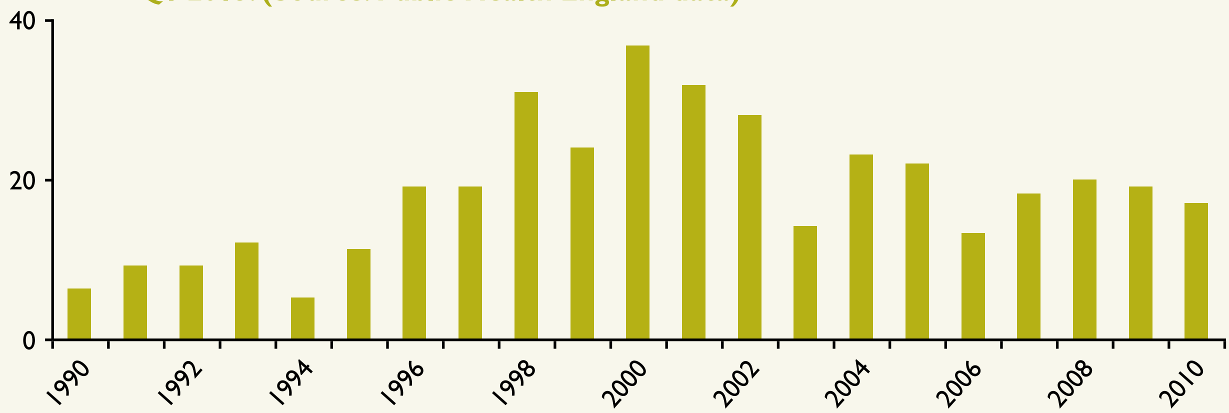


FIGURE 3 **Figure 3. Distribution of confirmed measles cases in England by year of birth, Q1 2013. (Source: Public Health England data)**



people and institutions behave such that innovation achieves desired outcomes[31]. This framework privileges anticipation, reflection, deliberation and response[32], placing an onus on innovators to reflect and listen to societal concerns and governance systems that develop social intelligence around the direction and control of technology[33].

The UK Royal Commission on Environmental Pollution[34] introduced the concept of continual 'social intelligence' gathering as a preferred approach to understanding how societal views and responses to new technologies are developing, viewing one-off public engagement as often being limited by time and, importantly, context. The recommendation resonated with the international experience of participatory technology assessment — such as Real-Time Technology Assessment (RTTA)[35], for example, an approach practised for over ten years by the Centre for Nanotechnology in Society at Arizona State University — and the various attempts by technology-assessment organizations in Europe to open up assessment to more inclusive approaches. The Danish Board of Technology, for example, sought to combine its more formal role of assessing technologies with proactive efforts to foster public debates, particularly using consensus conferences. It is disappointing that RTTA and similar approaches have not gained real decision-making traction.

Other chapters in this report highlight the important, indeed essential, role for communication and engagement in risk decision-making. In Chapter 5, Tim O'Riordan's plea to hold a 'wider conversation' is tinged with concern for the demands that opening-up decisions on innovation and risk inherently implies. These demands are not simply in the effective discussion of the science, and the need for honesty about the uncertainties. Indeed, all of our evidence confirms that through discussion-based engagement, members of the public can readily engage with science and appreciate that certainty about outcomes is not possible.

Conclusion – Responding to Culture and Motive

This chapter has sought to show that social, economic, cultural and political contexts are fundamentally important to how people and institutions respond to risk. How institutions behave in the public interest has a significant impact. As Sykes and Macnaghten note: "opening a dialogue is never a public good in itself: its value depends on the political culture in which it is enacted"[36]. This was strongly evident in the case of the waste-strategy development in Hampshire and East Sussex, two geographically-close local authorities in the United Kingdom. In each area, the same waste management company attempted public engagement around the detailed planning of energy-from-waste plants. In Hampshire, there was strong political support, and the need for the technology had been subject to extensive public engagement — but in East Sussex the opposite was true. This background meant that it was more difficult for the company to engage with the public in East Sussex. Public engagement is never merely a suite of methods that can be rolled out from place-to-place, regardless of context[37].

The metaphor of the 'field of play' has been applied to

Public engagement is never merely a suite of methods that can be rolled out from place-to-place, regardless of context.

the idea of mediated risk communication[38]. Developed in response to the over-simplified view of the role of the media as perpetrators of the social amplification of risks, the model sees audiences as active rather than passive receivers of messages. Government and state agencies, opposition parties, campaigning groups, corporations, scientific and expert communities as well as the media engage in a continual contest for public position and advantage. Communication and engagement has to be design-based and user-centered; that is based on an understanding of existing (and hence inherently changing) knowledge and beliefs. This requires detailed analysis over time of how different publics talk about and respond to highly specific and context-dependent risk issues.

This is far easier to say than to do (as discussed in Chapters 5, 7 and 11). Although a 'new governance agenda' (see Chapter 11) is evident, closing the gap between listening to views and concerns, and developing publicly-trusted policy responses around innovation, remains a serious challenge not only nationally but particularly in a trans-national context. This is because the opening up of decisions on innovation challenges preferred and embedded positions of expertise, power and authority.

Ultimately, innovation may not be tolerated at a particular point in time for perfectly logical reasons that have far less to do with concerns about the potential risks than with disquiet about institutional motives and behaviour, and perceived threats to the things that people value. There is an onus on decision-makers to proactively enhance their understanding of the power of context and to appreciate the common dimensions of responses, even between apparently unrelated risks. There is an essential need to gather social intelligence over time rather than merely supporting one-off public engagement exercises, particularly where these have more to do with trying to persuade the public of the benefits and the safety of technology. Effective innovation will require a partnership between decision-makers and the public that is characterized by listening, open and ongoing discussions, and trust. Of course, such characteristics take time and resources to develop and perfect. But expending such effort is likely to be more efficient and effective in supporting innovation.

Nick Beckstead (University of Oxford) and Toby Ord (University of Oxford)

CHAPTER 10: MANAGING EXISTENTIAL RISK FROM EMERGING TECHNOLOGIES

Despite the political and organizational challenges, policymakers need to take account of low-probability, high-impact risks that could threaten the premature extinction of humanity.

Historically, the risks that have arisen from emerging technologies have been small when compared with their benefits. The potential exceptions are unprecedented risks that could threaten large parts of the globe, or even our very survival[1].

Technology has significantly improved lives in the United Kingdom and the rest of the world. Over the past 150 years, we have become much more prosperous. During this time, the UK average income rose by more than a factor of seven in real terms, much of this driven by improving technology. This increased prosperity has taken millions of people out of absolute poverty and has given everyone many more freedoms in their lives. The past 150 years also saw historically unprecedented improvements in health, with life expectancy in the United Kingdom steadily increasing by two to three years each decade. From a starting point of about 40 years, it has doubled to 80 years[2].

These improvements are not entirely due to technological advances, of course, but a large fraction of them are. We have seen the cost of goods fall dramatically due to mass production, domestic time freed up via labour saving machines at home, and people connected by automobiles, railroads, airplanes, telephones, television, and the Internet. Health has improved through widespread improvements in sanitation, vaccines, antibiotics, blood transfusions, pharmaceuticals, and surgical techniques.

These benefits significantly outweigh many kinds of risks that emerging technologies bring, such as those that could threaten workers in industry, local communities, consumers, or the environment. After all, the dramatic improvements in prosperity and health already include all the economic and health costs of accidents and inadvertent consequences during technological development and deployment, and the balance is still overwhelmingly positive.

This is not to say that governance does or should ignore mundane risks from new technologies in the future. Good governance may have substantially decreased the risks that we faced over the previous two centuries, and if through careful policy choices we can reduce future risks without much negative impact on these emerging technologies, then we certainly should do so.

However, we may not yet have seen the effects of the most important risks from technological innovation. Over the next few decades, certain technological advances may pose significant and unprecedented global risks. Advances in the biosciences and biotechnology may make it possible to create bioweapons more dangerous than any disease humanity has faced so far; geoengineering technologies could give individual countries the ability to unilaterally alter the global climate (see case study); rapid advances in artificial intelligence could give a single country a decisive strategic advantage. These scenarios are extreme, but they are recognized as potential low-probability high-impact events by relevant experts. To safely navigate these risks, and harness the potentially great benefits of these new technologies, we must continue to develop our understanding of them and ensure that the institutions responsible for monitoring them and developing policy responses are fit for purpose.

Technology has significantly improved lives in the United Kingdom and the rest of the world.

This chapter explores the high-consequence risks that we can already anticipate; explains market and political challenges to adequately managing these risks; and discusses what we can do today to ensure that we achieve the potential of these technologies while keeping catastrophic threats to an acceptably low level. We need to be on our guard to ensure we are equipped to deal with these risks, have the regulatory vocabulary to manage them appropriately, and continue to develop the adaptive institutions necessary for mounting reasonable responses.

Anthropogenic existential risks vs. natural existential risks

An *existential risk* is defined as a risk that threatens the premature extinction of humanity, or the permanent and drastic destruction of its potential for desirable future development. These risks could originate in nature (as in a large asteroid impact, gamma-ray burst, supernova, supervolcano eruption, or pandemic) or through human action (as in a nuclear war, or in other cases we discuss below). This chapter focuses on anthropogenic existential risks because — as we will now argue — the probability of these risks appears significantly greater.

Historical evidence shows that species like ours are not destroyed by natural catastrophes very often. Humans have existed for 200,000 years. Our closest ancestor, *Homo erectus*, survived for about 1.8 million years. The median mammalian species lasts for about 2.2 million years[3]. Assuming that the distribution of natural existential catastrophes has not changed, we would have been unlikely to survive as long as we have if the chance of natural extinction in a given century were greater than 1 in 500 or 1 in 5,000 (since $(1 - 1/500)^{2,000}$ and $(1 - 1/5,000)^{18,000}$ are both less than 2%). Consistent with this general argument, all natural existential risks are believed to have very small probabilities of destroying humanity in the coming century[4].

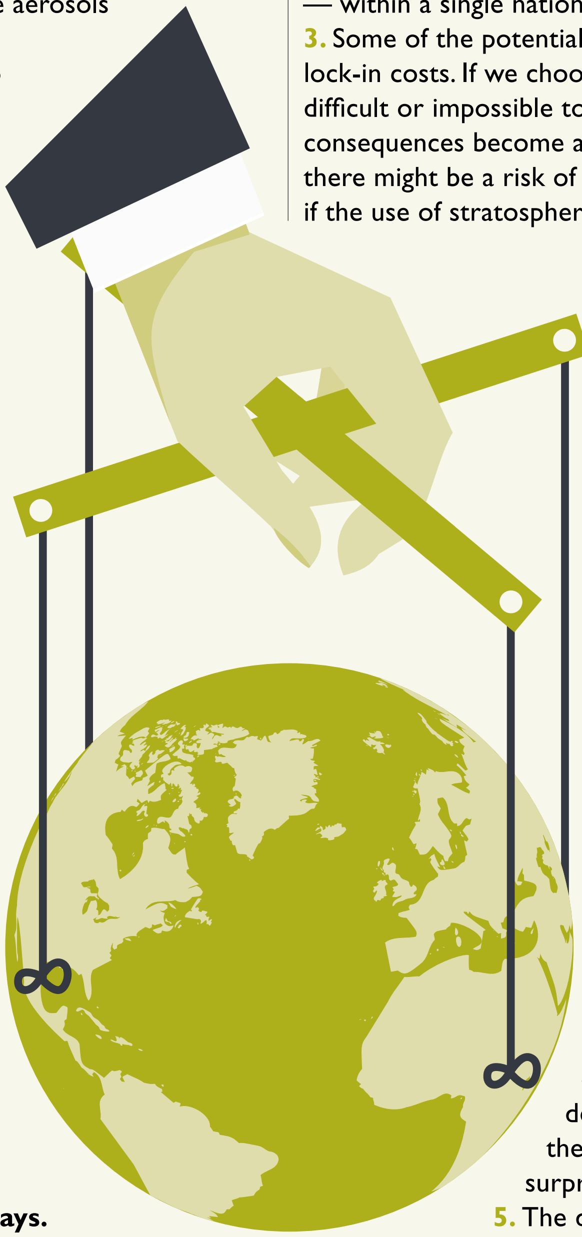
In contrast, the tentative historical evidence we do have points in the opposite direction for anthropogenic risks. The development of nuclear fission, and the atomic bomb, was the first time in history that a technology created the possibility of destroying most or all of the world's population. Fortunately we have not yet seen a global nuclear catastrophe, but we have come extremely close.

CASE STUDY

POLICY, DECISION-MAKING AND EXISTENTIAL RISK

Huw Price and Seán Ó hÉigeartaigh (University of Cambridge)

Geoengineering is the deliberate use of technology to alter planet-scale characteristics of the Earth, such as its climatic system. Geoengineering techniques have been proposed as a defence against global warming. For example, sulphate aerosols have a global cooling effect: by pumping sulphate aerosols into the high atmosphere, it may be possible to decrease global temperatures. Alternatively, seeding suitable ocean areas with comparatively small amounts of iron might increase plankton growth sufficiently to sequester significant quantities of atmospheric carbon dioxide. These technologies are already within reach, or nearly so (although their efficacy is still difficult to predict). As global warming worsens, the case for using one or more of them to ameliorate the causes or avert the effects of climate change may strengthen. Yet the long-term consequences of these techniques are poorly understood, and there may be a risk of global catastrophe if they were to be deployed, for example through unexpected effects on the global climate or the marine ecosystem.



This example illustrates the policy dimensions of existential risk in several ways.

1. It involves potentially beneficial technologies that may come with a small (though difficult to assess) risk of catastrophic side effects.

2. These risks are associated with the fact that the technology is global in impact. If we choose to employ it, we are putting all our eggs in one basket. This is especially obvious in the case of geoengineering, because the technology is intended to have planet-level effects. But it is also true of other potential sources of existential risk, such as synthetic biology or artificial intelligence, in the sense that it is unlikely that these technologies could be deployed merely locally — within a single nation, for example.

3. Some of the potential risks are associated with lock-in costs. If we choose one path now, it may be difficult or impossible to retreat later if unintended consequences become apparent — for example, there might be a risk of catastrophic sudden warming if the use of stratospheric aerosols was suddenly discontinued.

4. Once the technology is available, making a choice on its use is unavoidable — even a decision to do nothing is still a decision. Whatever we decide, our choice will have long-term consequences. However, geoengineering technology differs from some other potential sources of existential risk in that not using it is a feasible option, perhaps even the default option (at least for the time being). In other cases, various short-term benefits and associated commercial factors are likely to provide strong incentives to develop the technologies in question, and the task of managing extreme risks is to find opportunities to steer that development in order to reduce the probability of catastrophic surprises.

5. The decision to deploy geoengineering technology could, in principle, be made by a single nation or even a wealthy individual. In this respect, too, geoengineering illustrates one of the characteristic features of extreme technological risks: they are associated with the fact that powerful technologies put more power into fewer hands.

US President John F. Kennedy later confessed that during the Cuban missile crisis, the chances of a nuclear war with Russia seemed to him at the time to be "somewhere between one out of three and even". In light of this evidence, it is intuitively rather unclear that we could survive 500 or 5,000 centuries without facing a technologically-driven global catastrophe such as a nuclear war. We argue that in the coming decades, the world can expect to see several powerful new technologies that — by accident or design — may pose equal or greater risks for humanity.

1. Engineered Pathogens

Pandemics such as Spanish flu and HIV have killed tens of millions of people. Smallpox alone was responsible for more than 300 million deaths in the first half of the twentieth century. As the ongoing Ebola epidemic reminds us, disease outbreaks remain a potent threat today. However, pressures from natural selection limit the destructive potential of pathogens because a sufficiently virulent, transmissible pathogen would eliminate the host population. As others have argued, and we reiterate below, bioengineering could be used to overcome natural limits on virulence and transmissibility, allowing pandemics of unprecedented scale and severity.

For an example of an increase in fatality rates, consider mousepox, a disease that is normally non-lethal in mice. In 2001, Australian researchers modified mousepox, accidentally increasing its fatality rate to 60%, even in mice with immunity to the original version[5]. By 2003, researchers led by Mark Buller found a way to increase the fatality rate to 100%, although the team also found therapies that could protect mice from the engineered version[6].

For an example of an increase in transmissibility, consider the 'gain of function' experiments on influenza that have enabled airborne transmission of modified strains of H5N1 between ferrets[7]. Proponents of such experiments argue that further efforts building on their research "have contributed to our understanding of host adaptation by influenza viruses, the development of vaccines and therapeutics, and improved [disease] surveillance"[8]. However, opponents argue that enhancing the transmissibility of H5N1 does little to aid in vaccine development; that long lag times between capturing and sequencing natural flu samples limits the value of this work for surveillance; and that epistasis — in which interactions between genes modulate their overall effects — limits our ability to infer the likely consequences of other genetic mutations in influenza from what we have observed in gain-of-function research so far[9].

Many concerns have been expressed about the catastrophic and existential risks associated with engineered pathogens. For example, George Church, a pioneer in the field of synthetic biology, has said:

"While the likelihood of misuse of oligos to gain access to nearly extinct human viruses (e.g. polio) or novel pathogens (like IL4-poxvirus) is small, the consequences loom larger than chemical and nuclear weapons, since biohazards are inexpensive, can spread rapidly world-wide and evolve on their own."[10]

Similarly, Richard Posner[11], Nathan Myhrvold[12], and Martin Rees[13] have argued that in the future, an engineered pathogen with the appropriate combination of virulence, transmissibility and delay of onset in symptoms would pose an existential threat to humanity. Unfortunately, developments in this field will be much more challenging to control than nuclear weapons because the knowledge and equipment needed to engineer viruses is modest in comparison with what is required to create a nuclear weapon[14]. It is possible that once the field has matured over the next few decades, a single undetected terrorist group would be able to develop and deploy engineered pathogens. By the time the field is mature and its knowledge and tools are distributed across the world, it may be very challenging to defend against such a risk.

This argues for the continuing development of active policy-oriented research, an intelligence service to ensure that we know what misuse some technologies are being put to, and a mature and adaptive regulatory structure in order to ensure that civilian use of materials can be appropriately developed to maximize benefit and minimize risk.

We raise these potential risks to highlight some worst-case scenarios that deserve further consideration. Advances in these fields are likely to have significant positive consequences in medicine, energy, and agriculture. They may even play an important role in reducing the risk of pandemics, which currently pose a greater threat than the risks described here.

2. Artificial Intelligence

Artificial intelligence (AI) is the science and engineering of intelligent machines. Narrow AI systems — such as Deep Blue, stock trading algorithms, or IBM's Watson — work only in specific domains. In contrast, some researchers are working on AI with general capabilities, which aim to think and plan across all the domains that humans can. This general sort of AI only exists in very primitive forms today[15].

Many people have argued that long-term developments in artificial intelligence could have catastrophic consequences for humanity in the coming century[16], while others are more skeptical[17]. AI researchers have differing views about when AI systems with advanced general capabilities might be developed, whether such development poses significant risks, and how seriously radical scenarios should be taken. As we'll see, there are even differing views about how to characterize the distribution of opinion in the field.

In 2012, Müller and Bostrom surveyed the 100 most-cited AI researchers to ask them when advanced AI systems

Reduction of the risk of an existential catastrophe is a global public good.

might be developed, and what the likely consequences would be. The survey defined a "high-level machine intelligence" (HLMI) as a machine "that can carry out most human professions at least as well as a typical human", and asked the researchers about which year they would assign a 10%, 50% or 90% subjective probability to such AI being developed. They also asked whether the overall consequences for humanity would be "extremely good", "on balance good", "more or less neutral", "on balance bad", or "extremely bad (existential catastrophe)".

The researchers received 29 responses: the median respondent assigned a 10% chance of HLMI by 2024, a 50% chance of HLMI by 2050, and a 90% chance of HLMI by 2070. For the impact on humanity, the median respondent assigned 20% to "extremely good", 40% to "on balance good", 19% to "more or less neutral", 13% to "on balance bad", and 8% to "extremely bad (existential catastrophe)"[18].

In our view, it would be a mistake to take these researchers' probability estimates at face value, for several reasons. First, the AI researchers' true expertise is in developing AI systems, not forecasting the consequences for society from radical developments in the field. Second, predictions about the future of AI have a mixed historical track record[19]. Third, these 'subjective probabilities' represent individuals' personal degrees of confidence, and cannot be taken to be any kind of precise estimate of an objective chance. Fourth, only 29 out of 100 researchers responded to the survey, which therefore may not be representative of the field as a whole.

The difficulty in assessing risks from AI is brought out further by a report from the Association for the Advancement of Artificial Intelligence (AAAI), which came to a different conclusion. In February 2009, about 20 leading researchers in AI met to discuss the social impacts of advances in their field. One of three sub-groups focused on potentially radical long-term implications of progress in artificial intelligence. They discussed the possibility of rapid increases in the capabilities of intelligent systems, as well as the possibility of humans losing control of machine intelligences that they had created. The overall perspective and recommendations were summarized as follows:

- "The first focus group explored concerns expressed by lay people — and as popularized in science fiction for decades — about the long-term outcomes of AI research. Panelists reviewed and assessed popular expectations and concerns. The focus group noted a tendency for the general public, science-fiction writers, and futurists to dwell on radical long-term outcomes of AI research, while overlooking the broad spectrum of opportunities and challenges with developing and fielding applications that leverage different aspects of machine intelligence."
- "There was overall skepticism about the prospect of an intelligence explosion as well as of a "coming singularity," and also about the large-scale loss of control of intelligent systems. Nevertheless, there was a shared sense that additional research would be valuable on methods for understanding and verifying the range of behaviors of complex computational systems to minimize unexpected outcomes."
- "The group suggested outreach and communication to people and organizations about the low likelihood of the radical outcomes, sharing the rationale for the overall comfort of scientists in this realm, and for the need to educate people outside the AI research community about the promise of AI for enhancing the quality of human life in numerous ways, coupled with a re-focusing of attention on actionable, shorter-term challenges."[20]

> **Over the next few decades, certain technological advances may pose significant and unprecedented global risks.**

This panel gathered prominent people in the field to discuss the social implications of advances in AI in response to concerns from the public and other researchers. They reported on their views about the concerns, recommended plausible avenues for deeper investigation, and highlighted the possible upsides of progress in addition to discussing the downsides. These were valuable contributions.

However, the event had shortcomings as well. First, there is reason to doubt that the AAAI panel succeeded in accurately reporting the field's level of concern about future developments in AI. Recent commentary on these issues from AI researchers has struck a different tone. For instance, the survey discussed above seems to indicate more widespread concern. Moreover, Stuart Russell — a leader in the field and author of the most-used textbook in AI — has begun publicly discussing AI as a potential existential risk[21].

In addition, the AAAI panel did not significantly engage with concerned researchers and members of the public, who had no representatives at the conference, and the AAAI panel did not explain their reasons for being sceptical of concerns about the long-term implications of AI, contrary to standard recommendations for 'inclusion' or 'engagement' in the field of responsible innovation[22]. In place of arguments, they offered language suggesting that these concerns were primarily held by "non-experts" and belonged in the realm of science fiction. It's questionable whether there is genuine expertise in predicting the long-term future of AI at all[23], and unclear how much better AI researchers would be than other informed people. But this kind of dismissal is especially questionable in light of the fact that many AI researchers in the survey mentioned above thought the risk of "extremely bad" outcomes for humanity from long-term progress in AI had probabilities that were far from negligible. At present, there is no indication that the concerns of the public and researchers in other fields have been assuaged by the AAAI panel's interim report or any subsequent outreach effort.

What then, if anything, can we infer from these two different pieces of work? The survey suggests that some AI researchers believe that the development of advanced AI systems poses non-negligible risks of extremely bad outcomes for humanity, whilst the AAAI panel was skeptical of radical outcomes. Under these circumstances, it is impossible to rule out the possibility of a genuine risk, making a case for deeper investigation of the potential problem and the possible responses and including long-term risks from AI in horizon-scanning efforts by government.

Challenges of managing existential risks from emerging technology

Existential risks from emerging technologies pose distinctive challenges for regulation, for the following reasons:

1. The stakes involved in an existential catastrophe are extremely large, so even an extremely small risk can carry an unacceptably large expected cost[24]. Therefore, we should seek a high degree of certainty that all reasonable steps have been taken to minimize existential risks with a sufficient baseline of scientific plausibility.
2. All of the technologies discussed above are likely to be difficult to control (much harder than nuclear weapons). Small states or even non-state actors may eventually be able to cause major global problems.
3. The development of these technologies may be unexpectedly rapid, catching the political world off guard. This highlights the importance of carefully considering existential risks in the context of horizon-scanning efforts, foresight programs, risk and uncertainty assessments, and policy-oriented research.
4. Unlike risks with smaller stakes, we cannot rely on learning to manage existential risks through trial and error. Instead, it is important for government to investigate potential existential risks and develop appropriate responses even when the potential threat and options for mitigating it are highly uncertain or speculative.

As we seek to maintain and develop the adaptive institutions necessary to manage existential risks from emerging technologies, there are some political challenges that are worth considering:

1. Reduction of the risk of an existential catastrophe is a global public good, because everyone benefits[25]. Markets typically undersupply global public goods, and large-scale cooperation is often required to overcome this. Even a large country acting in the interests of its citizens may have incentives to underinvest in ameliorating existential risk. For some threats the situation may be even worse, since even a single non-compliant country could pose severe problems.
2. The measures we take to prepare for existential risks from emerging technology will inevitably be speculative, making it hard to achieve consensus about how to respond.
3. Actions we might take to ameliorate these risks are likely to involve regulation. The costs of such regulation would likely be concentrated on the regulators and the industries, whereas the benefits would be widely dispersed and largely invisible — a classic recipe for regulatory failure.
4. Many of the benefits of minimizing existential risks accrue to future generations, and their interests are inherently difficult to incorporate into political decision-making.

> The stakes involved in an existential catastrophe are extremely large, so even an extremely small risk can carry an unacceptably large expected cost.

Conclusion

In the coming decades, we may face existential risks from a number of sources including the development of engineered pathogens, advanced AI, or geoengineering. In response, we must consider these potential risks in the context of horizon-scanning efforts, foresight programs, risk and uncertainty assessments, and policy-oriented research. This may involve significant political and coordination challenges, but given the high stakes we must take reasonable steps to ensure that we fully realize the potential gains from these technologies while keeping any existential risks to an absolute minimum.

Julia Slingo (Met Office Chief Scientist), Rowan Douglas (Chairman, Willis Research Network), Trevor Maynard (Head of Exposure Management and Reinsurance, Lloyd's of London)

HIGH LEVEL CASE STUDY: NATURAL DISASTERS AND THE INSURANCE INDUSTRY

THE SCIENTIST'S PERSPECTIVE

Julia Slingo (Met Office Chief Scientist)

Protecting life, livelihoods and property is a fundamental responsibility of national governments. Weather-related hazards, including coastal and inland flooding, are high priorities in the UK government's National Risk Register of Civil Emergencies[1]. The atmospheric, ocean and land-surface observations and forecasts provided by the Met Office play a central role in helping to mitigate these risks.

Our world is increasingly and intricately interdependent, relying on global telecommunications, efficient transport systems, and the resilient and reliable provision of food, energy and water. All of these systems are vulnerable to adverse weather and climate. The additional pressure of climate change creates a new set of circumstances and poses new challenges about how secure we will be in the future. More than ever, the weather and climate have considerable direct and indirect impacts on us — our livelihoods, property, well-being and prosperity — and increasingly we rely on weather forecasts and climate predictions to plan our lives.

Uncertainty is an inherent property of the fluid motions of the atmosphere and oceans, which determine the weather and climate at the regional and local level. This was recognized in 1963 by Ed Lorenz in his seminal paper *Deterministic Nonperiodic Flow*[2], in which he introduces the concept of the atmosphere as a chaotic system subject to small perturbations that grow through non-linear processes to influence the larger scale: as Lorenz said, "the flap of a seagull's wings may forever change the course of the weather".

It is important to understand that a chaotic system is not the same as a random system. Chaos is manifested through the physical processes that allow energy to cascade from one scale to another and influence the final state of the system. The evolution of a chaotic system depends on the current state of the system, whereas a random system has no knowledge of the current state and assumes that each subsequent state is independent.

The concept of the weather and climate as chaotic systems has had a profound impact on the way in which forecasting has evolved over recent decades. No longer do we produce a single, deterministic forecast, but instead we perform an ensemble of forecasts that seek to capture the plausible range of future states of the weather and climate that might arise naturally from 'the flap of the seagull's wings'. This enables the forecaster to assess the probability of certain outcomes and to couch the forecast in terms of likelihoods of hazardous weather. In some circumstances the weather is highly predictable, and in other circumstances there is a wide degree of spread and hence a high level of uncertainty.

There are two major sources of uncertainty in the prediction process. The first involves the certainty with which we know the current state of the atmosphere (and ocean), known as *initial condition uncertainty*. Despite remarkable progress in Earth observation this uncertainty will always be present, because instruments have inaccuracies and we cannot monitor every part of the system at every scale. Tiny perturbations are therefore introduced in the initial state of the forecast, which then grow and cause the forecasts to diverge.

The second source of uncertainty comes from the model itself — *model uncertainty* — and recognizes that there are unresolved 'sub-grid scale' processes that will affect the evolution of the system. These include turbulent processes in the atmospheric boundary layer, the initiation and evolution of cumulus convection, the formation of clouds and the production of precipitation. The sub-grid scale variability in these processes is represented by random perturbations at the resolved scale, and increasingly draws on information from detailed observations and fine-scale models that seek to characterize the spatial and temporal characteristics of this sub-grid scale variability.

Uncertainty in climate prediction follows the same principles that are used in weather forecasting, incorporating both initial condition and model uncertainty. In climate, however, initial condition uncertainty is only important out to a few years ahead; beyond that, model uncertainty dominates. Indeed, both model uncertainty and the uncertainty in future emission scenarios dominate the range of possible climate change outcomes towards the end of the century. In this situation, model uncertainty goes beyond the unresolved, sub-gridscale processes, and includes the uncertainty in key physical parameters in the climate system, such as the response of the carbon cycle to a warming world and how readily cloud droplets are converted to rain drops through cloud microphysics.

The reliability of ensemble forecasting depends on whether the forecast probabilities match the observed frequencies of predicted outcomes. In weather forecasting, a reliable ensemble is one in which the ensemble spread is representative of the uncertainty in the mean. In the context of climate prediction, a reliable ensemble tends to be one in which the ensemble forecasts have the same climatological variance as the truth. This means that probabilistic forecasting systems require substantial re-forecasting of past cases to characterize the reliability of the system. In climate change, of course, the past is not an analogue for the future, and therefore gauging reliability depends much more on scientific assessment.

One recent development in weather forecasting and climate prediction is the translation of these probabilities in terms of risk. The UK's National Severe Weather Warning Service warns the public and emergency responders of severe or hazardous weather (rain, snow, wind, fog, or heat) that has the potential to cause danger to life or widespread disruption. Since 2011, the severity of the warning (yellow, amber or red) depends on a combination of both the likelihood of the event happening, and the impact that the conditions may have at a specific location (flooding, transport disruption, wind damage, airport closures, or health effects), rather than any pre-defined meteorological thresholds. Although the uncertainty in the weather (and climate) variables is quantified using probabilistic forecast systems, uncertainty in the downstream models tends not to be included in determining these risks. For that to happen, much more research needs to be done in delivering an end-to-end assessment of uncertainties, and therefore of risk.

THE INDUSTRY PERSPECTIVE

Rowan Douglas (Chairman, Willis Research Network)

As a focal point for risk, it is unsurprising that the global insurance sector has grappled with the challenges of understanding and managing extremes. Indeed, the past quarter of a century provides an informative journey of how the sector has achieved far greater resilience to catastrophic risks through the interplay of reforms in the scientific evaluation, prudential regulation and capital management of natural disaster risk.

Following a period of unprecedented losses from the mid-1980s, culminating with Hurricane Andrew (which hit the United States in 1992), the insurance industry faced a near-existential crisis. Confidence in the global risk-sharing mechanism was in structural disarray as firms across private, public and mutual sectors became insolvent or impaired. After approximately 300 years of successful operation, the insurance sector's *modus operandi* of relying on historical experience to evaluate risk was unsustainable.

As a consequence, traditional sources of insurance capital dried up and insurance capacity retreated: coverage became unavailable, unaffordable or severely restricted. But insurance is a necessity — it is a prerequisite for many forms of economic activity — so there was no shortage of demand for the situation to be resolved. Over the next five years, three seemingly unrelated forces converged to create the conditions for a transformation in how the insurance sector confronted extreme risk.

The first was the intervention of new 'smart' capital. The shortage of capacity had sharply increased prices and there was money to be made from underwriting risk, but this new capital demanded a new approach to risk evaluation, and to managing risk within more tolerable parameters at an individual policy and portfolio level.

The second was a quantitative revolution that embraced the developments in mainstream software and computing, as well as specialist expertise in emerging software firms known as catastrophe risk modelling companies. These firms began to develop robust methodologies to understand the potential locations and forces of threats such as extreme windstorms or earthquakes; the locations, characteristics and vulnerabilities of exposed buildings; and potential financial losses.

The third force was a regulatory trend. An insurance contract is a promise to pay money when a defined loss event occurs, but if there is no money to pay a claim the written promise is worthless. Until the mid-1990s, nobody had asked what level of tolerance an insurance contract should be designed to meet, for the simple reason that in general they had worked well up to that point. Should contracts operate to the 1-in-100 year risk, or 1-in-1000? Over a period of approximately five years, an emerging convention developed among regulators that insurance contracts should tolerate the 1-in-200 year level of maximum probable annual loss — that is, to perform at a 99.5% level of confidence. This level meant that insurance companies should have enough capital to meet all their policyholder obligations.

There was initially some confusion about what these terms meant, let alone how to assess risks at these extreme levels. It presaged a revolution in the industry, which not everyone was able to adapt to. Slowly but surely, the techniques and methodologies that were required to respond to these new demands began to be developed, applied, tested and refined, and quite quickly the results began to show.

In 2005, Hurricanes Katrina, Rita and Wilma (KRW) hit the US Atlantic and Gulf Coasts, causing unparalleled levels of losses at over US$50 billion. While the insurance and reinsurance market was put under severe stress, with major question marks over the accuracy of the modelling these specific events, there were very few insolvencies. Over the 13 years since Hurricane Andrew, the industry had allocated a greater proportion of capital against potential natural disaster loss events, which may have lain beyond previous underwriting experience. Ultimately there was sufficient capital in the system. If KRW had hit in 1995 before such reforms had taken effect, the impact on the sector and affected populations seeking support would have been catastrophic.

By 2011, the global industry suffered the worst year of natural catastrophe losses on record — in excess of US$120 billion — from seismic events such as the Great East Japan (Tohoku) and Christchurch earthquakes, and from weather losses such as the Thailand floods and a severe US tornado season. Yet despite this, and the wider global financial crisis, the re/insurance sector carried on almost unaffected. While there was still much to learn, it had begun to properly account for risk via the medium of the modelled world.

Finally, in the aftermath of Super Storm Sandy's impact on the New York region in 2012, the confidence in the modelling and assessment of natural disaster risk liberated over US$50 billion of new capital to respond to US disaster risk. Over a period of a quarter of a century, a new relationship between science, capital and public policy had delivered a paradigm shift in risk management and highlighted to many the dangers of overconfidence in past experience.

The international agenda for 2015 includes the renewal of the United Nations' (UN) Hyogo Framework for Action on disaster risk reduction in March, the UN's updated Sustainable Development Goals, and the UN Framework

Convention on Climate Change Conference of Parties in Paris in December. In this context, there is a growing recognition that the insurance industry's experience may provide essential ingredients for dealing with the overall challenges of natural disaster and climate risk, and also shed light on how we confront other risks of resilience and sustainable growth.

Under the auspices of the UN Secretary General's Office, a consortium including scientists, regulators, human rights experts, credit rating agencies and financial institutions have propelled an initiative that will integrate natural disaster risk and resilience into the financial system. What was once an existential risk to the insurance sector has now become a material risk across the wider economy, and should now be appropriately encoded into decision making. The outcome will influence how we build and operate our cities, arrange our companies and protect our populations. In the coming decades, millions of lives and livelihoods and billions of dollars of assets are at stake.

The initiative proposes that securities (including listed equities and bonds) and bank debt (including mortgage portfolios) should be exposed to the following stress tests to assess their exposure to natural disaster risk:

- 1-in-100 year maximum probable annual loss to natural disaster risk (as a survivability/solvency test).
- 1-in-20 year maximum probable annual loss to natural disaster risk (as an operational risk / profits test).
- The Annual Average Loss (AAL) to natural disaster risk.

The application of these metrics by insurance companies has been instrumental in the effective transformation of the industry's performance. In essence, risk discounts the value of assets and resilience increases the value of assets in the eyes of buyers and investors.

There is a growing recognition that many of the systemic changes that are necessary to confront our major challenges cannot be progressed until the costs of 'business as usual' are accounted for proportionately. Current levels of natural disaster risk seem to be a good place to start. Once properly informed, the invisible hand of the market has the power to transform urban landscapes, corporate operations and public policy to underpin resilience and sustainable growth.

This all rests on improvements in science that have enabled natural hazards to be understood as foreseeable, quantifiable and (in non-seismic risks) often forecasted events. But this scientific knowledge must be transformed by financial and legal mechanisms to have optimum impact on systemic risk-management and the protection of populations. This requires a common language and modelling framework to enable the communication and interoperability needed to manage risk.

This recent statement by the UN Office of the High Commissioner for Human Rights illustrates how the language of science, engineering and risk management is now informing the development and operation of social protections against excess losses:

"All states have positive human rights obligations to protect human rights. Natural hazards are not disasters, in and of themselves. They become disasters depending on the elements of exposure, vulnerability and resilience, all factors that can be addressed by human (including state) action. A failure (by governments and others) to take reasonable preventive action to reduce exposure and vulnerability and to enhance resilience, as well as to provide effective mitigation, is therefore a human rights question."

THE INSURANCE MARKET'S PERSPECTIVE

Trevor Maynard (Head of Exposure Management and Reinsurance, Lloyd's of London)

Lloyd's of London is a specialist insurance and reinsurance marketplace consisting of multiple competing entities (known as syndicates) with a mutualized central fund at its heart. To ensure that the fund is as safe as possible, the Corporation of Lloyd's sets capital requirements for these syndicates and has a suite of minimum standards covering every aspect of doing business, from claims management to catastrophe modelling. As such, the Corporation regulates the Lloyd's market with a small 'r'; the true financial regulator is the Prudential Regulation Authority, as it is for all other insurers in the United Kingdom.

Natural disasters are an important issue for Lloyd's; it actively seeks to take catastrophe risks from businesses, and also other insurers (called reinsurance). When disasters strike, the Lloyd's market will often pay a significant proportion of the insurance claims and so the risks need to be well understood and managed. This short case study will consider the management of natural disasters before, during, after and long after they occur.

Before the disaster, the Lloyd's market must estimate how much risk it has taken onto its balance sheet in order to ensure that premium rates and additional capital are sufficient to pay the claims that might arise. Policyholder security is paramount and we seek to hold assets well in excess of regulatory minima. However, no insurer's resources are infinite and some events could exhaust our funds. There is a trade off, though: the more funds that are held, the more expensive the insurance becomes, because shareholders need rewarding for the capital they make available to support the business. This is the first key regulatory decision that must be made in the face of uncertainty: what level of confidence should policyholders have a right to expect?

The Lloyd's approach largely follows the current regulatory approach in the United Kingdom. In simple terms, we estimate the size of claims that could only be exceeded with 0.5% probability over the coming year, and then deduct the premiums that we have received from customers — these premiums are the first line of defence when paying out insurance claims. The residual amount, known as the value at risk, is the minimum regulatory capital that we must hold as additional assets. We hold at least enough capital to survive a disastrous year that we might statistically expect to see only once in every 200 years. We then uplift this minimum capital further to provide a buffer.

Finally, we model any claims that are larger than the combined funds of any syndicate to see how the central fund would be affected. Then we ensure that this fund is large enough to survive all events with a probability greater than 0.5%, and add more buffer assets. This combination of mathematically-modelled amounts buffered with additional prudence helps us to handle the inevitable uncertainties in the models.

Lloyd's sells policies to many different businesses, including aviation, shipping, energy, property and liability business. Natural disasters directly affect many of these sectors, but claims can come from other causes such as litigation or terrorism. The capital calculation described above has to consider all those risks, while the modelling approaches vary depending on the type of business.

The modelling of natural disasters in particular has become more sophisticated over the past two decades. Losses were previously estimated using illustrative scenarios, but this approach suffers from many flaws. The scenarios may miss important exposures, may not be aligned with a specific probability of failure, and may overlook certain risks (such as contingent covers) completely. Today, we use catastrophe models that take simulated events such as hurricanes and earthquakes and estimate the damage caused to a portfolio of properties based on their age and building characteristics. Multiple disciplines come together to create these models, including actuaries, engineers and scientists. Regulators allow these models to be used, but must be convinced that they are built using sound principles and on reasonable and justifiable assumptions.

Over the years, these models have incorporated many features of natural catastrophes. These include issues such as 'post-loss amplification', where shortages of raw building materials and services (such as plumbers and engineers) can inflate rebuilding costs. Another feature is 'contract leakage', where judicial decisions grant payments to policyholders outside of the insurers' usual interpretation or intentions of a policy's terms and conditions. Regulators are keen to ensure that all material features are included in the models so that they are 'complete'.

During a disaster, insurers will observe the catastrophe and start to gear up their claims operations. Loss adjusters will get ready to assess the level of claims. Regulators will want initial estimates of the potential losses, to decide whether the affected firms have any potential solvency issues. Initial estimates are usually made using the same models that set the capital — there is significant uncertainty in these estimates, but they give a reasonable guide to the financial cost of the event.

Shortly after a disaster, insurers must set up reserves to pay the expected claims. At this stage many claims will not have been notified, so the losses must be estimated. And because there is always uncertainty about the impact of the event, Lloyd's typically takes a scenario approach to assess the damage. We usually ask for each syndicate to provide its own estimate of loss, but we also specify at least two scenarios with consistent assumptions that they must all use. This ensures a set of results that can be aggregated to form a consistent whole-market estimate.

Some time after the disaster, the underwriters have to consider how to incorporate the new information into their prices and into the next generation of models. In the case of earthquake insurance, for example, the buffer capital has to cover very large events. Prices (or 'premium rates') have to cover the long-run average claims, plus expenses, and also provide a return on the capital held in excess of reserves. Therefore the premiums must exceed the average losses in order to be risk-based.

The insurance industry understands clearly that much uncertainty remains. Many models are based on a few centuries of data, much of it inferred from proxy sources rather than being directly observed. We can quantify some of this uncertainty, though, by incorporating statistical distributions of the key parameters in to the models.

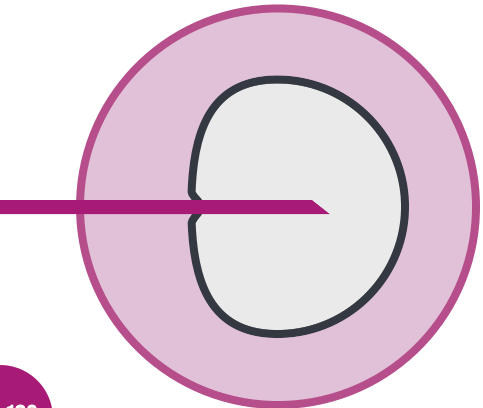
Notwithstanding their limitations, models have significantly aided the insurance industry's decision-making about inherently uncertain events. They incorporate and naturally illustrate the range of possible outcomes in a way that would not be highlighted by single deterministic scenarios.

Model-based methods provide a probability-weighted approach for decisions and are now embedded within the regulation of insurance in the United Kingdom. If new EU 'Solvency II' regulation comes into force, this approach will be adopted across the European Union. Indeed, we already see similar approaches around the world: earthquake insurance in Canada, for example, is required to meet a 1-in-500 year test.

> **The modelling of natural disasters has become more sophisticated over the past two decades.**

SECTION 5: MOVING THINGS FORWARD – GOVERNANCE AND DECISION-MAKING

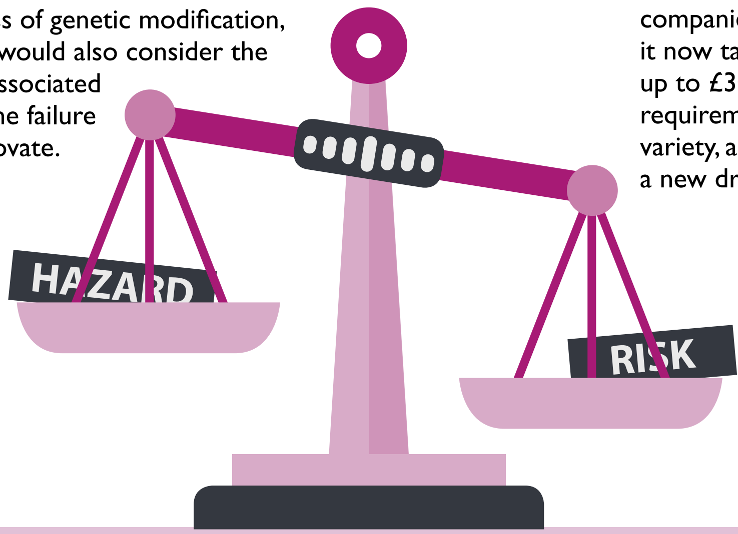
Towards the end of the twentieth century, the governance of technology has shifted from top-down regulation to include greater participation by non-governmental actors.



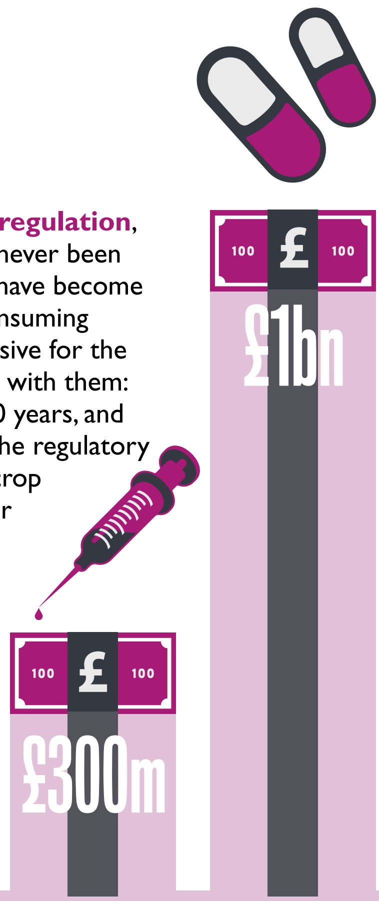
Between 2011 and 2014, the Human Fertilisation and Embryology Authority led an extended consultation process on the use of mitochondrial replacement procedures to eliminate faulty genetic material.

The HFEA consultation consisted of: Deliberative workshops; a public representative survey; open consultation meetings; a patient focus group; an open consultation questionnaire.

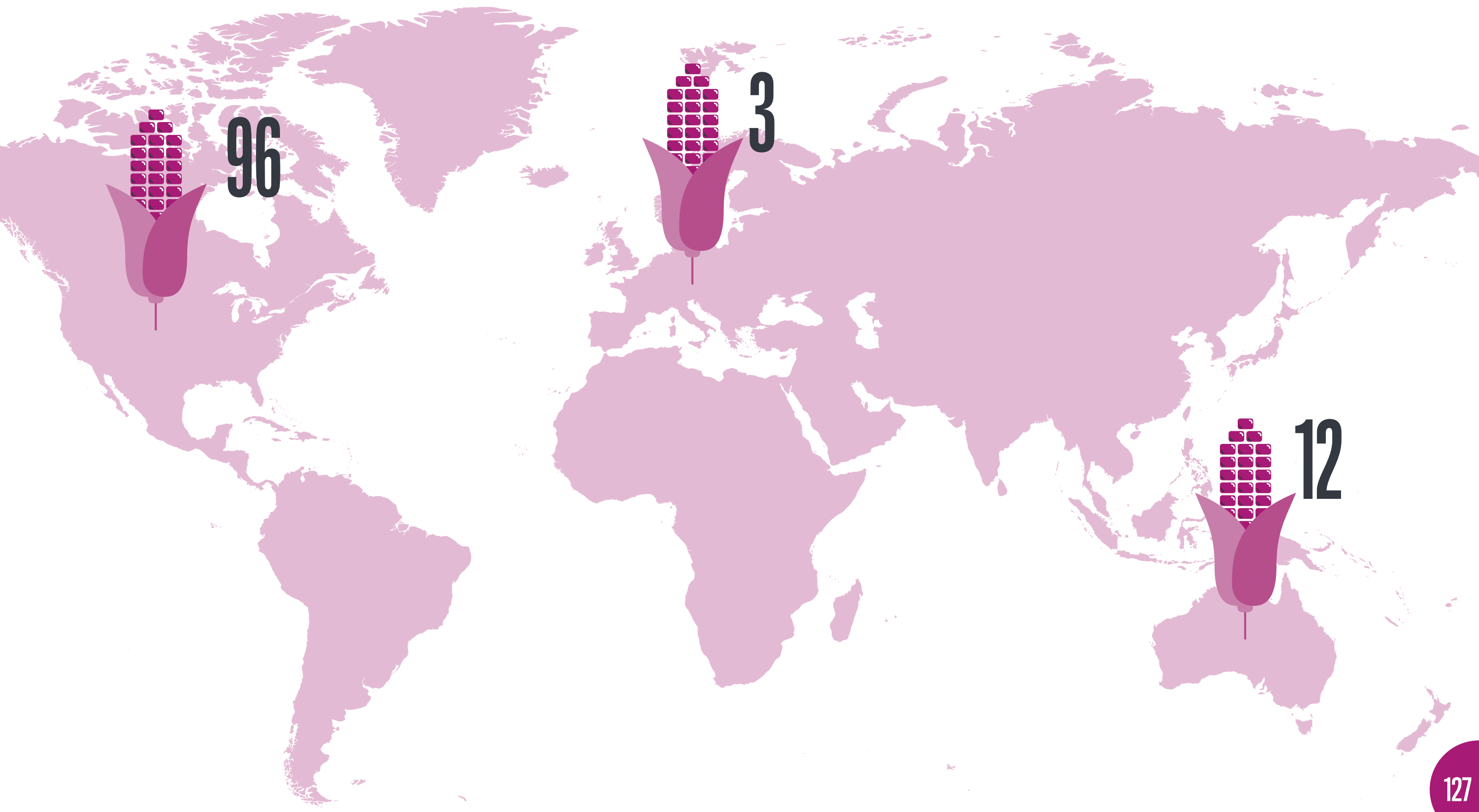
A revised strategy for innovation in GM crops would have a more risk-rather than hazard-based structure than the current process. It would take into account the evidence that there is no inherent environmental or nutritional hazard in the process of genetic modification, and it would also consider the risks associated with the failure to innovate.

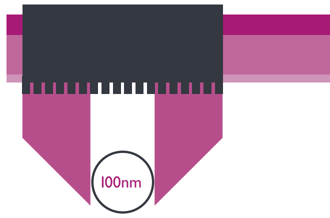


Thanks to more rigorous regulation, the products around us have never been safer. But regulatory systems have become more complex, more time consuming and considerably more expensive for the companies that need to work with them: it now takes approximately 10 years, and up to £300 million, to cover the regulatory requirements for a new GM crop variety, and up to £1 billion for a new drug.



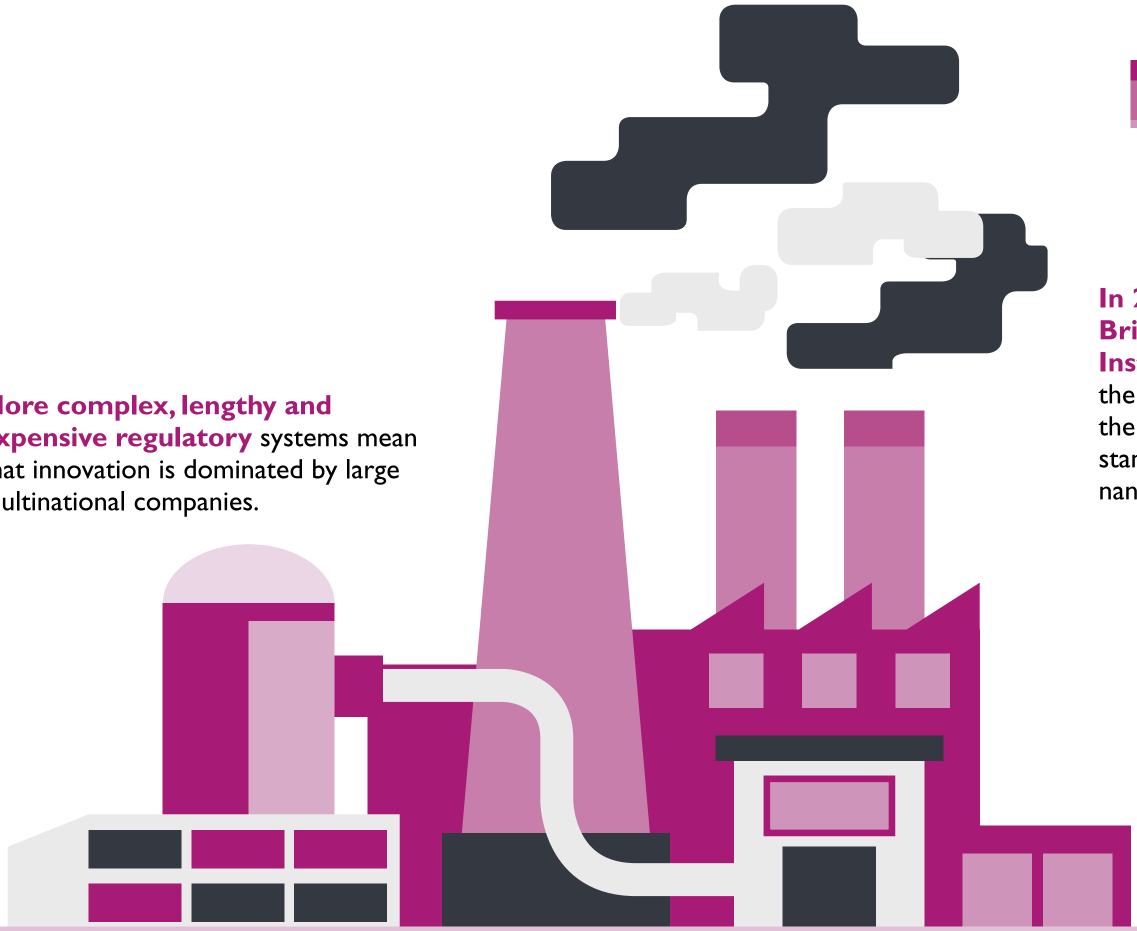
Only three GM crops have been approved for commercial cultivation in Europe since 1990; in the United States, there have been 96 commercial GM approvals since 1990; Australia has approved 12 GM crops since 2002.



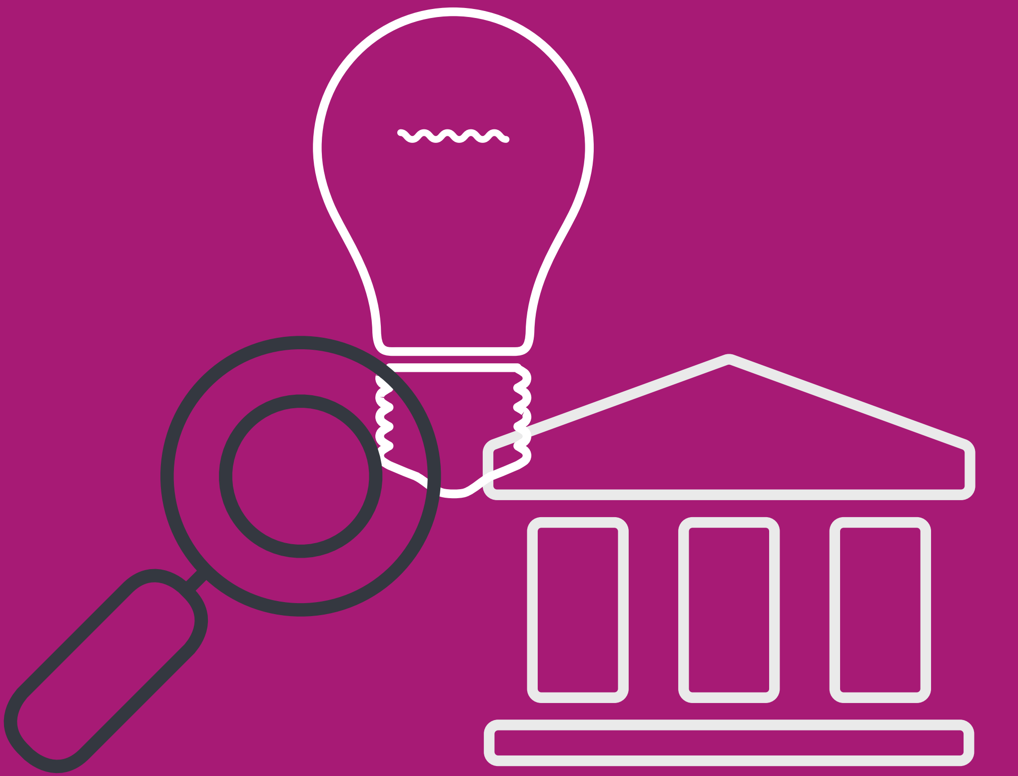


In 2004, the British Standards Institution pioneered the development of the first international standards committee on nanotechnologies.

More complex, lengthy and expensive regulatory systems mean that innovation is dominated by large multinational companies.



Joyce Tait
(University of Edinburgh)



CHAPTER 11: BRINGING IT ALL TOGETHER

The complexity of innovation governance systems — from the focus on risk-related policies and public engagement, to the rigidity of product regulatory frameworks — helps us to avoid potentially hazardous developments, but it also stifles potentially useful innovation.

Risk and innovation are contested topics in most fields of human endeavour. As the preceding chapters have shown, wherever one looks there is great variation, between and within nations and societies, in the ways we perceive the risks and benefits from innovations and in the ways we govern them. However, the prevailing expectation in most societies is that there will be a continuing trend in the development of innovations that will improve our lives through economic, health-related or environmental benefits[1]. And the risk governance processes we choose to put in place for innovative technologies will determine not just which products and processes are developed, but also what scale of company can participate in their development and ultimately the competitive advantage of nations and regions[2].

Given the importance of innovation to us all, we need a good understanding of how public and stakeholder pressures interact with risk regulatory systems and of how both stakeholders and regulators then guide innovation, encouraging some developments and closing off others. Specialist expertise is required in a range of contexts: to provide the evidence needed to make competent decisions on risk regulation, to conduct fair and equitable stakeholder engagement, or to develop an innovative product or process. But there is also an important requirement for a balanced generalist overview to understand how these specialisms and influences interact with one another in ways that can either be detrimental to, or support, particular innovations. In making decisions on risk regulation for advanced innovative technologies, regulators have often ignored the impacts of their decisions on innovative capacity and have, until very recently, given little consideration to how 'smarter' regulatory approaches could deliver safety and efficacy more cheaply and rapidly than current regimes. This is particularly the case for companies developing chemicals, pharmaceuticals, health care products based on regenerative medicine, pesticides, genetically modified (GM) crops and products based on nanotechnology and synthetic biology.

This chapter considers how issues of risk, trust, politics, benefits, engagement and regulation have combined to create the environment in which today's innovators must operate. The two decades spanning the transition from the twentieth to the twenty-first centuries saw the emergence and implementation of a new governance agenda that has had very considerable political influence. It has radically altered the innovation environment, particularly in areas of technology development that are likely to be publicly contested, with mixed outcomes and in many cases suboptimal delivery of public benefits from new scientific discoveries[3].

Regulation and the new governance agenda

Towards the end of the twentieth century, building on research in the social sciences, the concept of governance (the process of governing) began to shift in response to pressures from: the emergence of unexpected problems with technologies previously considered safe; a decline in public trust of government bodies and industry; the rapid pace of scientific development and technological change; the difficulties policymakers had in keeping up with this pace of change; and commercial pressures arising from globalization[4]. Two distinct academic disciplinary perspectives contributed to the development of this new governance agenda with little overlap among academic participants or literature cited, but with a common focus on the development of more participative, democratic decision making processes.

The first, led by academic policy researchers, envisaged a change in the role of the state from top-down regulation to a new governance style based on greater participation by non-governmental actors. The state changed from being the main implementer and controller of policy outcomes to facilitating and coordinating interaction between the various interests involved[5], giving rise to metaphors such as the 'hollowing out of the state'[6] or 'steering not rowing'[7]. The presumption was that government, having set the parameters in terms of the policy goals, then delegated to others how those goals were to be achieved. These ideas were developed in a general policy context and the literature makes little reference to risk and innovation, but they were influential across all policy areas and created a receptive policy space for the ideas emerging from the second academic perspective.

The second strand of academic thinking that contributed to the new governance agenda arose in science and technology studies (STS) and focused very strongly on issues of risk and innovation. It challenged the authority of science, particularly its presumed impartiality and its role as provider of public benefits. This strand of STS thinking was concerned about the undemocratic nature of this dominance of science on government decision making and sought to change the political landscape, again towards greater public participation in regulatory decision making[8]. Two related factors in STS thinking were particularly important in delivering the political influence they sought: (i) questioning the authority of scientific expertise and the validity of scientific

The prevailing expectation in most societies is that there will be a continuing trend in the development of innovations that will improve our lives.

evidence used to support policy and regulatory decisions by government[9]; and (ii) focusing much of their discourse on uncertainty and risk with the precautionary principle (or approach) being seen as the policy answer to this challenge.

Alongside this new bottom-up governance agenda, in technology-related areas there is still a need for regulation based on top-down command and control, backed up by sanctions and penalties to regulate the safety to human health and the environment of innovative products and of the processes used to develop them. As the governance agenda was bringing in a softer, more participative approach, existing regulatory regimes were changing in the opposite direction. Each time a new form of risk has been found in a class of products, a new layer or branch has been added to the regulatory system to ensure that future products will be safe from that type of defect. For example, following the discovery of birth defects caused by thalidomide, all new drugs were required to be tested for teratogenicity. In pesticide development, the damage to wildlife caused by organochlorine insecticides led to the rejection from development pipelines of any new pesticide that was likely to be persistent in the environment. As a result, the products in use today have never been safer. However, the regulatory systems themselves have become more complex, more time consuming and considerably more costly for the companies that need to work with them (it now takes approximately 10 years, and up to £300 million, to cover the regulatory requirements for a new GM crop variety and up to £1 billion for a new drug).

The shift to a new governance approach towards the end of the twentieth century can thus be seen as the addition of a new form of oversight for industry sectors that were already bearing a heavy and increasing regulatory burden. Indeed, there has been an increase in the complexity of the operating environment for innovators to accommodate the new focus on engagement and dialogue and to come to terms with the difficulties regulators have experienced in operationalizing the precautionary principle[10]. These issues are part of the background to the case study on GM crops in this chapter, and would be relevant to the alternative risk management strategy that it outlines. A possible example of such an approach, bringing together evidence-based regulation along with a continuing emphasis on openness and engagement, is given in the case study in Chapter 6 on changes to pig inspection.

The products in use today have never been safer. However, the regulatory systems themselves have become more complex, more time consuming and considerably more costly.

Participatory processes

Emerging from the new perspectives on risk governance and the emphasis on participative democracy, stakeholder engagement has become an essential requirement for

TABLE 1

The implications and outcomes related to engagement on the basis of interests and ideology (minds and hearts)[15].

Interest-based engagement (minds)	Uncommitted members of the public	Ideology-based engagement (hearts)
Restricted to specific developments		Spreads across related and sometimes unrelated developments
Location specific, locally organized		Organized nationally or internationally
Conflict can usually be resolved by: • providing information • giving compensation • negotiation		Conflict is very difficult to resolve: • information is treated as propaganda • compensation is seen as bribery • negotiation is seen as betrayal
Giving concessions leads to mutual accommodation		Giving concessions leads to escalation of demands
Negative events lead to adjustments in products and processes		Responses to negative events are disproportionate

scientists undertaking innovation-related research and for companies developing the resulting products and processes. The emphasis on uncertainty and precaution among STS academics led, in the first decade of this century, to the promotion of 'upstream engagement' as a key component of the new governance agenda. The think-tank Demos, in a policy publication advocating upstream engagement[11], made clear its political ambitions: "the task is to make visible the invisible, to expose to public scrutiny the assumptions, values and visions that drive science", and "… reshape … the very foundations on which the scientific enterprise rests".

Psychologists tell us that where issues are remote from society (as in upstream engagement or the development of truly novel technologies), citizens are more likely to engage with an issue on the basis of values or ideology rather than local personal interest[12]. In such cases, conflict and polarization of views are more likely to arise and resolution of any conflict will be more difficult to achieve[13] (see Table

CASE STUDY

A CASE HISTORY ON GM CROPS

David Baulcombe (University of Cambridge)

The first generation of genetically modified (GM) crops has delivered diverse and well-documented benefits. They have helped to stabilize soil and increase the efficiency of water use. They have also reduced pesticide toxicity for farmworkers and beneficial insects, and increased the profitability of agriculture in regions as diverse as India (GM cotton) and Hawaii (GM papaya).

The potential for benefit from GM is further enhanced by research in universities, institutes and companies, which have produced an extensive range of additional GM traits. These traits could improve the sustainability of crop production, or they could improve the quality of the crop products for nutrition or industry. In the near future there are exciting new genome editing methodologies that will further reinforce the transformative potential of GM in global agriculture. The detailed description of these potential benefits is described in a report produced for the UK government's Council for Science and Technology[1].

A European logjam on GM

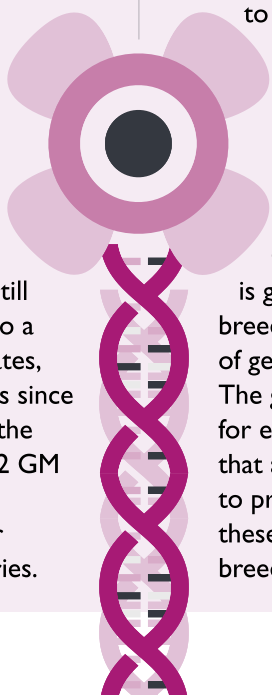
However, the full benefits of these GM traits are yet to be realized, especially in European Union, because complicated regulatory and approval processes have deterred commercial interest and excluded non-commercial applications. Only three GM crops have been approved for commercial cultivation in Europe since 1990 (ref. 2). An application for a GM maize (Dupont Pioneer's TC1507) was made in 2000, but is still in limbo even though the line is very similar to a previously-approved variety. In the United States, there have been 96 commercial GM approvals since 1990 and a healthy stream of applications to the regulatory process. Australia has approved 12 GM crops since 2002 (ref. 1).

Europe has a global leadership role and our logjam suppresses innovation in other countries. These countries may model their GM approval process on that of Europe, or they may prohibit GM crops because they are concerned that their cultivation would restrict their opportunity to export non-GM crops to Europe[3].

Risk and hazard in the European Union's regulatory process

The current EU regulation of GM crops has two stages. First the European Food Safety Authority (EFSA) assesses an application and expresses an opinion based on scientific evidence on whether a crop under evaluation is safe. If EFSA delivers a favourable safety opinion, the European Commission will then prepare a draft decision to authorise commercial cultivation, which is considered and voted on by an official EU committee of representatives from the Member States.

This process is expensive and time consuming, however, because it is based on the presumption of hazard. The process also has to be implemented in full for each application, irrespective of whether the GM trait is associated with any risk. The United States has a more streamlined regulatory process for the commercial release of a GM crop, but even there it can cost US$7 million to US$14 million (in 2007 prices)[4] — an amount that is prohibitive for small- and medium-sized enterprises. In Europe the costs could be greater, and innovation is correspondingly less likely.



The inappropriateness of the current EU approval process is illustrated by comparing GM with conventional plant breeding. There is great uncertainty associated with conventional breeding, because there is an unanticipated degree of genetic variation between closely related plants. The genomes of maize plants in a breeders cross, for example, may each have several hundred genes that are absent from the other parent[5]. It is difficult to predict the consequence of interactions between these genes in the hybrids produced by a conventional breeding programme. Further complications arise in

1). In essence, the more developed a particular application towards its end purpose, the more deliberative and meaningful the conversation is likely to be. When citizens are unfamiliar with the issues at stake, engagement processes — whether upstream or downstream — can thus become a process of framing these unfamiliar developments, either favourably or unfavourably, in the public mind, potentially giving considerable power to those who conduct the engagement[14].

conventional breeding because there may be epigenetic effects on gene expression in a hybrid plant that persist for many generations[6] after the initial hybridization event.

GM may also involve similar genetic and epigenetic uncertainties, but to a much more limited extent because there will normally be only one or a few transgenes in each line. One response to this comparison would be to introduce additional regulation for conventionally bred crops. However, the past experience of thousands of years of breeding — including modern breeding for the past hundred years — illustrates the absurdity of that conclusion. A more rational response would be to use conventional breeding as a benchmark: additional assessment would be appropriate if there is plausible additional risk associated with the GM trait relative to a conventionally bred variety.

The inappropriate differentiation of GM and conventional crops is illustrated by several recent examples in which the crop carries a transgene that could have been transferred by conventional breeding[7], albeit through a process that would take longer than with GM. The GM crops with the new gene would be subject to the EFSA/EU approval process, whereas the conventionally bred variety with the same gene would not, although the risks to health or the environment would be similar with both types of plant.

An alternative risk management strategy in crop improvement

A revised strategy for innovation in EU crops would have a more risk- rather than hazard-based structure than the current process. It would take into account the evidence that there is no inherent environmental or nutritional hazard in the process of genetic modification, and it would also consider the risks associated with the failure to innovate. It is unlikely that small revisions to the current process are likely to achieve an outcome that promotes innovation towards a sustainable agriculture of crops — instead, a new process should be derived based on the principles of risk assessment as applied in other industries. Where risks are difficult to quantify, it would be appropriate to implement GM-specific procedures only if the risk is assessed as being greater than with an equivalent variety produced by conventional breeding.

Psychologists tell us that where issues are remote from society, citizens are more likely to engage with an issue on the basis of values or ideology rather than local personal interest.

These points are raised in the Annual Report of the Government Chief Scientific Adviser 2014. Innovation: Managing Risk, Not Avoiding It under the heading 'Anticipating the Challenges', where it is noted that the categories of innovation likely to lead to the most heated discussion are (i) where the wider benefits of an innovation are accepted but where highly local costs and impacts are imposed, and (ii) where the debate is largely about values. Table 1 illustrates some of the characteristics of dialogue under these contrasting circumstances, demonstrating why value- or ideology-based conflicts are most difficult of all to resolve (as continues to be the case for GM and related technologies).

Despite such problems, the initial assumption of scientists and science funders was that upstream engagement would, if managed properly, improve public acceptance of new technologies and would not bring an end to any area of research[16]. However, as noted above, Demos[17] expected upstream engagement to have profound implications for the future of science and to reshape the way that science relates to public decision making. Although upstream engagement has been widely undertaken, for example by UK research councils[18, 19], Demos' ambitions have not yet been achieved. Also, there is not yet any evidence that better public acceptance of new innovative technologies will result from such engagement and in practice there have been reductions in funding for some areas of science and innovation, particularly in nanotechnology[20] and plant biotechnology, arising from political influences and policy makers' concerns about negative public opinion rather than evidence of potential or actual harm. As noted in case study on GM crops, such considerations have also influenced the extent to which GM crops are being cultivated in Europe[21].

Another presumption has been that, through the new governance approach, policy-makers would simultaneously engage with a wider range of stakeholders and also base their decisions on better quality evidence. A common tactic among the diverse groups and networks of stakeholders

CASE STUDY

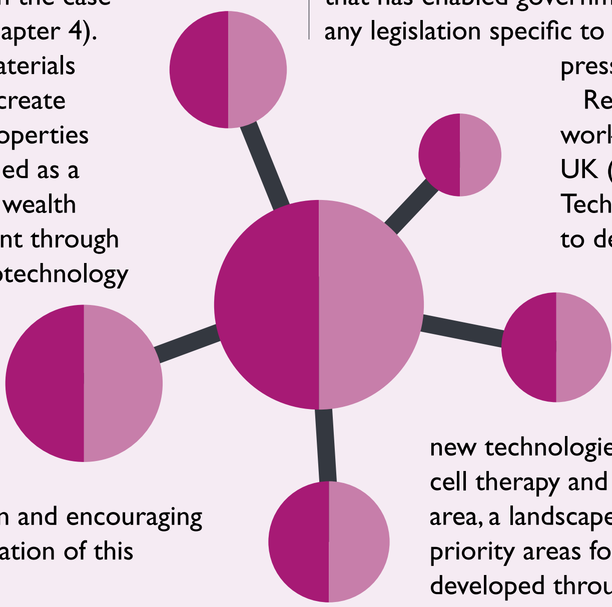
STANDARDS: SUPPORTING EMERGING TECHNOLOGIES AS AN ACCELERATOR OF INNOVATION

Scott Steedman (Director of Standards, British Standards Institution)

Positioned alongside regulation, voluntary consensus standards that have been developed with full stakeholder engagement and open public consultation can provide an invaluable tool to share information and to build trust in new and emerging technologies. Although the use of standards as an accelerator of innovation is well understood in other major economies (notably in Germany, where standards play a strong part in the activities of the Fraunhofer institutes), in the United Kingdom there is a poor understanding of the potential for standards to act as alternatives to regulation. This important tool is therefore frequently ignored in UK innovation strategy and planning.

Standards provide a powerful alternative to regulation in many areas, but can be particularly effective in supporting new and emerging technologies where public trust needs to be maintained. One particular case study, which shows the effectiveness of standards building up over time, is the emergence of nanotechnology (as outlined in the case study by Kamal Hossain in Chapter 4).

The ability to manipulate materials at very small length scales to create products with higher-value properties and functions was first identified as a potential source of significant wealth creation by the UK government through its creation of the LINK Nanotechnology Programme in the 1980s. This was followed by the Taylor Report on nanotechnology[1] in 2002, which recommended that the government should invest in stimulating innovation and encouraging successful commercial exploitation of this technology.



At the same time, public concern was growing over the potentially unknown and unquantified risks associated with nanomaterials, particularly in relation to the possible hazards they posed to humans and the environment. Environmental pressure groups demanded that the technology should be subject to stronger regulation.

In 2004 the British Standards Institution (BSI)[2], in its role as the UK National Standards Body, pioneered the development of the first international standards committee on nanotechnologies, as well as a UK standards committee to mirror this work. These bodies developed strategic plans that highlighted the three main priorities for standards development:

- Terminology and Nomenclature
- Measurement and Characterization
- Health, Safety, and Environment

Since then the expert committees have developed a number of standards, including vocabularies, occupational health and safety guides, toxicity testing standards, and characterization test methods. Laboratories testing against these standards can be accredited by the United Kingdom Accreditation Service (UKAS) to provide further confidence in the emerging technology. The development of these standards of best practice is one important factor that has enabled governments to avoid introducing any legislation specific to nanotechnologies, despite pressure to regulate the industry.

Recently, BSI has been working closely with Innovate UK (formerly the government's Technology Strategy Board) to demonstrate the value that timely standardization can bring to priority areas such as offshore renewable energy, assisted living (such as new technologies to support the elderly), cell therapy and synthetic biology. In each area, a landscape and roadmap that identifies priority areas for new standards was developed through a process of stakeholder engagement in a similar way to that used for nanomaterials ten years ago.

The success of this approach is increasingly widely recognized. Investment is now needed to extend the concept so that standards advice becomes permanently embedded within the Catapult technology and innovation centres, as well as research communities across the United Kingdom.

that engage with policy decisions on risk and innovation is to promote exclusively the evidence that supports their objectives or even to manufacture such evidence[22]. This is an inevitable part of political processes but, as noted above, upstream engagement tends to push dialogue towards issues of value and ideology and in such cases there is much less willingness on the part of protagonists to reconsider evidence on the basis of its scientific merit[23] (Table 1). Such challenges downgrade the value of research findings as evidence to support decision making and policymakers are finding that science and technology in some areas are becoming less governable as the evidence base for decisions is challenged and eroded.

Impact on innovation

Technology foresight has contributed to government support for the development of innovative technologies for over 30 years, but human capabilities in this area are notoriously flawed. Now, based on the new governance agenda we have included risk foresight (through the precautionary principle) and foresighting public needs and desires (through upstream engagement). In the case of advanced innovative technologies with product lead times considerably longer than five years, the uncertainty inherent in foresight becomes multiplied several-fold. The governance-based approach, promoted in a spirit of optimism as a means to achieve more democratic and more robust political processes and decisions, has distributed power more equitably across societal groups — but this has, in many cases, resulted merely in greater complexity and confusion, and longer delays in decision making.

There were sound reasons behind the changes in policy decision making outlined above. However, evidence is now beginning to accumulate that the complexity we have introduced into our governance systems through the upstream focus of risk-related policies and engagement, coupled with the increased complexity and rigidity of product regulatory systems, is stifling potentially useful innovation in addition to the desired impact of avoiding potentially hazardous developments.

> **Upstream engagement tends to push dialogue towards issues of value and ideology, with much less willingness on the part of protagonists to reconsider evidence on the basis of its scientific merit.**

> **Technology foresight has contributed to government support for the development of innovative technologies for over 30 years.**

For example, the more complex, lengthy and expensive our governance systems become, the more innovation becomes dominated by large multinational companies[24]. As observed in the GM crops case study, no small company with an innovative idea can hope to reach a market without doing so through a large multinational company, through selling the intellectual property, a straightforward buy-out or some other form of collaboration. Small companies therefore develop their business models with such outcomes in mind, leading to a focus on innovations that are likely to fit with the strategies of the large companies. These companies in turn will be most receptive to incremental innovations that will enable them to improve on their current products or processes by making them more efficient or more sustainable. Path-breaking, disruptive innovations that could potentially contribute to pressing societal needs will either meet with self-censorship by scientists and innovators or will fail to attract funding along their development pathway. The paradox here is that the domination of the agrochemical and pharmaceutical industry sectors by large multinational companies, so strongly criticized by environmental advocacy groups, is a direct result of the kind of regulatory system that they themselves have been instrumental in encouraging.

A comparison between the recent innovation experience of information and communication technologies (ICT), where there have been several waves of disruptive innovation over the past twenty years, and life sciences where innovation has been largely incremental despite enormous public investment in the basic science, illustrates this point. Likewise, failure by large multinational companies to develop products to meet evident human needs (new antibiotics to address the challenge of antibiotic resistance, or GM crops to control pests and diseases in non-commodity crops) relates to the incompatibility of such developments with current industry business models that are a direct result of the regulatory systems that apply in these sectors.

The new governance agenda and upstream engagement are probably here to stay, but we have yet to learn how to accommodate their combined pressures in a way that will circumvent their potentially corrosive impact on innovative developments that could meet important societal needs.

A more adaptive approach to the governance of risk and innovation

During the twentieth century, the focus of innovation moved from chemistry to information and communication technologies, and the bio-economy is now expected to be the growth engine of the twenty-first century. The innovation trajectories in each of these areas are (or will be) very different, but research on 'what works' in innovative business models, taking account of the complexity in the innovation environment arising from new governance approaches, has been very limited. Likewise, there has been little socio-economic research on the interactions between risk regulatory systems and innovation, as opposed to the very large amount of research on the new governance agenda.

It is becoming increasingly clear that our governance systems for advanced innovative technologies are not always fit for purpose. Product regulatory systems that have built up by a process of slow accretion over a period of years are now so onerous that even multinational companies are finding it difficult to develop new innovative products. The new governance agenda was intended to improve policy and regulatory decisions by making them more democratic. Instead it has led to a less democratic and less evidence-based system, in which risk regulation and restriction of specific areas of scientific and innovative activity are seen by some governments and policy makers, particularly in the European Union, as valid responses to societal pressures or the need for public reassurance, rather than a means of dealing with risks for which there is an evidence base[25].

Until recently, flaws in regulatory systems related to over-regulation of innovative products and processes have not been a matter of great concern for governments, except where there has been public pressure to address such problems, as in the case of the accelerated development of drugs to treat AIDS. This is in contrast to considerable government attention to the need for 'better regulation' in non-risk related areas. In a state of ignorance, or at least insouciance, the assumption has been that this hidden tax on innovation processes can be accommodated by companies while still delivering products at an affordable price. This chapter has focused on the areas where the current risk governance deficits are greatest and where the need for systemic change is most pressing, for example in areas linked to the bio-economy, but these challenges may spread in the near future to other advanced innovative technologies.

Such systemic factors can mitigate against effective decision making in at least two ways: (i) the system can become so amorphous and unstructured that there is no clear basis for decisions and also no clearly identified locus for decision making; or (ii) it can become so complex, rigid and constrained by legal and customary precedent that it is incapable of adapting to new threats or opportunities. The bio-economy is in danger of experiencing the first of these threats in the context of the new governance agenda and the

> **There has been little socio-economic research on the interactions between risk regulatory systems and innovation.**

second in the context of conventional risk regulation.

Therefore recommendations related to the adoption of a precautionary approach (see the 'NGO Perspective' in Section 2's fracking case study) should elicit a broad-based policy response that takes account of the interests and values of protagonists and the costs and benefits of alternative options, as outlined in Chapter 4's neonicotinoid pesticide case study. In a similar vein, the case study on bisphenol A in Chapter 3 points to the need for an increased focus on scientific evidence as a basis for regulatory decision making even, or perhaps particularly, where this is undertaken within the European Union's overall precautionary regulatory system.

Changing the behaviour of innovation or regulatory systems will require finding the right policy levers that will adapt or re-align the relevant system components, and new smarter approaches to regulation and governance are the most likely pressure points to deliver better innovation-related value for money from public investment in basic science.

The two case studies included in this chapter provide very interesting pointers to future directions that could be taken to meet these needs. Standards developed through dialogue between stakeholders and companies, to ensure the quality of products and processes and to govern health, safety and environmental impacts, have a much better record of being adaptive in the face of new technological developments than our current regulatory systems (see nanotechnology case study). This is not to suggest that standards could totally replace these regulatory systems, but much could be learned from the adaptive processes they have used so successfully.

The alternative risk management strategy proposed for novel crops by David Baulcombe (see GM crops case study) could be a starting point for re-thinking the European regulatory system in a way that would be sufficiently radical to enable re-shaping and reinvigorating of innovation for European crop production. Each approach has the potential to complement the other, and together they could enable us to deploy our insights more intelligently than we have done to date.

The above commentary should not be seen to counsel against the elements of the new governance approach or engagement, upstream or downstream. However, we need to learn how to overcome these systemic threats without jeopardizing the safety and effectiveness of the innovative products and processes that we will need to meet future societal challenges.

Lisa Jardine
(University College London)

CHAPTER 12: ULTIMATELY A DECISION HAS TO BE MADE

A wide-ranging consultation on mitochondrial-replacement procedures offers a successful example of engagement with the public on a controversial innovation.

At the end of the day, probably nothing is more illuminating and instructive for our understanding of risk in the context of scientific policy-making than to see how a specific example works out in practice.

A long career as a science communicator has taught me that the hardest thing to explain to a lay audience is that evidence-based science does not deal in certainties. To the non-scientist, science is engaged in delivering absolute truth based on incontrovertible facts. Propositions based on anything less than this are likely to be regarded as questionable. Above all, decisions based on 'likelihood' rather than 'fact' are perceived to involve unacceptable levels of risk: these are the decisions that give rise to 'shock horror' headlines in the tabloid press.

The reality is that a measure of uncertainty is a defining characteristic of the scientific method. The scientific solution to a problem is inevitably provisional. The scientist's goal is to arrive at the best fit between their findings so far and a hypothesis, or general principle. Fundamentally sceptical, scientists are always prepared to modify their outcomes in the face of additional data.

So there is inevitably a rupture between the certainty the lay person wants in answer to a question, and what the scientist is prepared to offer in response. A familiar example would be climate change, where climate change sceptics challenge scientists to 'prove once and for all' that global warning is man-made, and make much of the voices of those who dissent from the majority view. The scientists respond that the 'balance of probability' points strongly towards man's being the cause of climate change, and point out that 'the vast majority of climate scientists' ascribe to this view. They will always stop short, however, of claiming certainty.

I suspect that this is one of the things that originally attracted me to the practice of science: it eschews dogma. Evidence-based solutions to problems are offered tentatively and with circumspection, and are susceptible to revision in the light of further evidence.

For example, the paradigm-changing 1953 paper in the journal *Nature* by Francis Crick and James Watson, which proposed the double helix structure of DNA and transformed genetics, opens cautiously with the words: "We wish to *suggest* a structure for the salt of deoxyribose nucleic acid (DNA) ...". Towards its close, it gestures almost diffidently to the far-reaching implications of their 'suggestion': "*It has not escaped our notice* that the specific pairing we have postulated immediately *suggests* a possible copying mechanism for the genetic material" (my emphases)[1].

Public communication of science to a general audience is often a matter of helping the lay person to come to terms with this provisionality. In large part it consists in teaching those without a scientific background how to assess the claims made in areas that are complex and contested, often by translating them into more accessible terms.

Non-scientists have to be persuaded to accept a scientist's findings as reliable in spite of his or her reluctance to claim certainty, otherwise they are likely to find the costs of innovation based on a scientific discovery — and the risks involved — too high. The role of media commentators like myself on scientific issues in such cases is to be trusted explicators, presenting a specified scientific breakthrough in language accessible to all, to show both its benefits and disadvantages so that the public (which includes politicians) can make up their own mind responsibly.

Public communication of this kind is, however, a very different matter from engaging directly with the public and experts together, to progress and implement public policy. When I became Chair of the Human Fertilisation and Embryology Authority (HFEA) in January 2008, I quickly discovered that scientists' reluctance to claim certainty can prove problematic, not only when one is supporting innovation in assisted reproduction treatment, but even in sustaining the advances made to date. In spite of the successes of in vitro fertilization (IVF), are the risks that will always remain when we 'tamper' with nature simply too high[2]?

One of my personal goals when I took up the post was to develop clear and constructive lines of communication between the HFEA and those it regulated, and to build an educated conversation with the broader public. This quickly turned out to be a much harder aspiration than I had imagined. IVF stories make newspaper headlines, and both broadsheet and tabloid press tend to sensationalize their coverage for an eager readership. However thoughtfully the HFEA drafted its press releases, however careful I was in radio and TV interviews, both were all too often truncated or taken out of context, resulting in alarm rather than reassurance and education.

So when the HFEA was asked by the UK government's Department of Health to conduct a wide-ranging consultation on a controversial new process in 2011, we were determined to do so as far as possible so as to educate at the same time as gathering the information. A great deal of prior thought went into planning the stages of the consultation so as to produce properly informed

> **There is inevitably a rupture between the certainty the lay person wants in answer to a question, and what the scientist is prepared to offer in response.**

debate, which enabled the non-scientist to participate fully, and to avoid the kind of sensationalist responses all too familiar to us from press reports of previous new techniques[3].

An extended consultation

The HFEA is the UK's independent regulator of treatment using eggs and sperm, and of treatment and research involving human embryos. It sets standards for, and issues licences to, clinics and research establishments in the fertility sector. It provides authoritative information for the public, particularly those people seeking treatment, donor-conceived people and donors. It addresses policy issues relating to fertility regulation, which are sometimes ethically and clinically complex.

Between 2011 and 2014, the HFEA led a complex, extended consultation process, involving both experts (IVF practitioners and researchers) and the general public (including politicians and scientists outside the field), to enable ministers to decide whether a modification should be made to the legislation governing assisted reproduction (the 1990 Human Fertilisation and Embryology Act (amended)). This would allow a mitochondrial replacement procedure to eliminate faulty genetic material, which had been developed by researchers at Newcastle University and elsewhere, to be used in treatment. It involved the HFEA in consultations both with the expert scientific community and with the public at large, to determine (i) whether the procedure was effective and safe for treatment, and (ii) whether it was ethically acceptable to the public at large.

The HFEA commissioned and coordinated the consultations, and collated the results, before passing the results to government ministers. It (and therefore I as Chair) took no position on the matter, and has remained resolutely impartial throughout the process. I recall an interview on the BBC Radio 4 Today programme in which John Humphrys asked me what my opinion was on whether mitochondrial replacement ought to be made legal. My firm answer was that as Chair of the HFEA I had no opinion. "You must have, I refuse to believe that you don't have a view", was his response, "we hear you on Radio 4 every week, we know you have views." But I stuck to my guns. It was for ministers to make their own decision, based on the evidence assembled. The HFEA's responsibility was to present all the available material as clearly, accessibly and transparently as possible.

Over a period of three years we were gratified to watch the way in which large amounts of information — steadily, consistently and transparently presented — allowed our constituency groups to reach informed decisions. We found that the so-called 'general public' was willing and able to examine the evidence and reach a clear and confident decision, as long as the explanations we gave were well-structured and as far as possible avoided technical language.

Over the period of the consultation, both the expert groups and the general public moved from risk-averse

The HFEA's responsibility was to present all the available material as clearly, accessibly and transparently as possible.

anxiety to a clearly-expressed view that the benefits of mitochondrial replacement treatment, in allowing couples to avoid bearing children with devastating diseases, outweighed the possible risks and ethical misgivings. The views of special interest groups with fixed positions about any treatment involving human embryos came increasingly to look like outliers. They were not, of course, ignored, but were put in perspective by the increasingly steady assent of widely differing sectors of the community.

The HFEA's belief that, presented with all the available material, accompanied by thorough explanations and with ample opportunity for dialogue, consensus could be reached one way or the other was rewarded. The most clearly expressed reason given (by both scientific and lay constituencies) for allowing the new, as yet clinically untested procedure, was that there was a trusted regulator in place to monitor and oversee its clinical use on a case by case basis. Trust, in other words, mitigated aversion to innovation and risk.

I confess that I did not myself expect the consultation — however carefully conducted — to yield such a clearly supportive outcome. But at the end of the consultation process, the HFEA was able to advise the Secretary of State for Health, via the Department of Health, that there was public support for the clinical used of mitochondria replacement treatment. As an exercise in innovating in a controversial area while bringing the public along with it, it is worthwhile to look more closely at how that outcome was achieved.

A tale of two techniques

Mitochondria are present in almost all human cells. They generate the majority of a cell's energy supply. For any cell to work properly, the mitochondria need to be healthy. Unhealthy mitochondria can cause genetic disorders known as mitochondrial disease[4].

There are many different conditions that can be described as mitochondrial disease. They range from mild to severe or life threatening, and can have devastating effects for the families that carry them. There is no known cure for mitochondrial disease, and treatment options are limited.

Mitochondria replacement therapy currently proposes two methods for eliminating faulty DNA from the reproductive process: maternal spindle transfer and pronuclear transfer.

Maternal spindle transfer involves removing the spindle from the mother's egg before it is fertilized by the father's sperm. The maternal spindle is a structure within a woman's egg that contains the mother's half of a child's nuclear DNA. The father's half of the nuclear DNA comes from the sperm. The spindle is then placed into a donor egg with healthy mitochondria, from which the donor's spindle and, therefore, her nuclear DNA, has been removed. The egg — which no longer contains any of the mother's faulty mitochondria — is then fertilized by the father's sperm, and the resulting embryo is placed in the prospective mother at between 2 to 5 days of development.

Immediately after fertilization, an embryo has two pronuclei. These are the parts of the egg and sperm that hold the nuclear DNA. Pro-nuclear transfer involves removing the pronuclei from an embryo with unhealthy mitochondria immediately after fertilization. The pronuclei are then transferred into a donated early stage embryo. This donor embryo contains healthy mitochondria but has had its own original pro-nuclei removed[5].

Both procedures involve genetic material from three parties, and both involve genetic modification. The Human Fertilisation and Embryology Act (1990), the primary legislation that governs assisted reproduction and embryology procedures in the United Kingdom and whose statutory provisions the HFEA regulates, specifically prohibits placing any embryo in a woman if the nuclear or mitochondria DNA of any cell of the embryo has been altered. This prohibition made the use of mitochondria donation or replacement in treatment unlawful in the United Kingdom.

Following a review of the Human Fertilisation and Embryology Act (1990) in 2008, a power was introduced in the Act to enable the UK government to make regulations to allow the use in treatment of eggs and embryos which have had unhealthy mitochondria replaced by healthy mitochondria. The intention was that this technique would prevent the transfer of serious mitochondrial disease from mother to child and allow the mother to have her own genetically-related child. At that time, the government of the day gave an assurance that such regulations would not be made until any proposed technique was considered to be effective and safe for use in treatment.

By 2010, researchers at Newcastle University working on mitochondria replacement were making public their concern that the government should begin the process of drafting the regulations required to allow their laboratory research to be transferred to IVF clinics.

By this time, too, the press had sensationalized the mitochondria transfer techniques as producing 'three-parent babies'. Opponents voiced fears, loudly and publicly, that new government regulations were a 'slippery slope', opening the way to genetic manipulations and modifications of all kinds.

There was also considerable pressure on the HFEA from some scientific researchers. Regulation of IVF was, they maintained, bureaucratic and unnecessary. It was a serious impediment to innovation — had there been a regulator in 1978, it would have blocked a high risk move such as returning an embryo developed in vitro to the mother's womb, and there would have been no Louise Brown, no first baby born by in vitro fertilization at all. These reproaches were voiced vocally in the media, which I suspect anticipated violent antagonism to 'three-parent IVF' in any future public debate.

In 2011, the Secretary of State for Health and the Secretary of State for Business, Innovation and Skills asked the HFEA to convene an expert advisory group to carry out a scientific review "to collate and summarize the current state of expert understanding of the safety and efficacy of methods to avoid mitochondrial disease through assisted conception". The HFEA set up a panel of experts, chaired by Professor Neva Haites[6].

The panel concluded that the techniques of maternal spindle transfer and pronuclear transfer are potentially useful for a specific and defined group of patients whose offspring may have severe or lethal genetic disease due to mutations in mitochondrial DNA, and who have no other option if they are to have their own genetic child.

"As in every area of medicine, moving from research into clinical practice always involves a degree of uncertainty. The evidence currently available does not suggest that the techniques are unsafe," the report stated. "Nevertheless," it continued, "these techniques are relatively novel, especially applied to human embryos, and with relative few data to provide robust evidence on safety."

The panel therefore made a number of recommendations for further work it wished to see done before a decision was made to allow treatment using either of these techniques.

Following the release of the first report, in January 2012, the Wellcome Trust announced the establishment of a new Centre for Mitochondrial Research at Newcastle University, with significant funding, to undertake additional research recommended by the HFEA's expert group. Here, too, both scientific and public confidence was thereby strengthened.

In March 2013, the panel of experts reconvened and

The so-called 'general public' was willing and able to examine the evidence and reach a clear and confident decision.

again concluded that there was still nothing to indicate that the techniques were unsafe. The group also recommended long-term follow-up monitoring of any children born as a result of the use of these techniques in treatment.

The panel of experts' report concluded that there was no evidence that mitochondria replacement therapy was unsafe. It stopped short of expressing certainty that the new procedures were safe, as we might expect from a group of responsible scientists. Although in the short run this allowed the tabloid press to exaggerate the risks associated with the therapy, in the long run the scrupulous care with which the panel assessed a wide range of data and evidence helped build trust in the community at large. This was helped by the fact that the panel Chairs (Professor Neva Haites and Dr Andy Greenfield) were extremely effective communicators.

In its own statement, the HFEA said:

"The panel of experts convened by the HFEA to examine the safety and efficacy of mitochondria replacement carefully considered the interaction between nuclear and mitochondrial DNA and concluded that the evidence did not show cause for concern … As in every area of medicine, moving from research into clinical practice always involves a degree of uncertainty. Experts should be satisfied that the results of further safety checks are reassuring and long term follow-up studies are crucial. Even then patients will need to carefully weigh up the risk and benefits for them."

Here, once again, the HFEA scrupulously underlined the uncertainty that is part and parcel of scientific inquiry, while capturing the overall confidence, based on substantial amounts of data, that the panel expressed in the safety of mitochondria replacement, subject to regular checks and follow-up studies.

Dr Andy Greenfield, chair of the final reconvening of the panel of experts, said: "The scientific questions that we examined and the research that we examined — and it was voluminous — will never answer all of the critical questions. And, of course it won't answer the fundamental question, which is are these techniques safe and efficacious in humans."

Building a solid platform

Meanwhile, in January 2012, the Secretary of State for Health and the Secretary of State for Business, Innovation and Skills asked the HFEA, with the support of the Sciencewise Expert Resource Centre, to carry out public dialogue work on the ethics and public attitudes towards mitochondria replacement. This work was conducted between July and December 2012. It involved multiple strategies and modes of analysis, in order to include as wide a range of respondents as possible.

The public consultation consisted of five strands:

1. Deliberative workshops (held in Newcastle, Cardiff and London). These met twice in each location. Participants were recruited to represent a broad spectrum of age, gender, socio-economic status and family circumstances.

> **Taken together, the expert and public consultations provided a solid platform on which to build the HFEA's advice to ministers.**

Thirty people were recruited for each location. The aim of this strand of the consultation was to explore public attitudes in-depth, and to understand participant viewpoints as they become increasingly engaged with, and knowledgeable about, mitochondrial disease and mitochondria replacement techniques.

2. Public representative survey. Just under 1,000 face-to-face interviews were carried out with members of the public across 175 random locations. For each location, demographic quotas were set to ensure the sample was representative. The aim of the survey was to benchmark public opinion on: general attitudes towards medical research and genetic treatments; awareness of IVF and mitochondrial disease; views on the genetic treatment of mitochondrial disease; and attitudes to the regulation of genetic treatments.

3. Open consultation meetings. Two public meetings were held in November 2012, the first in London (53 attendees) and the second in Manchester (39 attendees). The meetings were open to anyone wishing to attend and were advertised on the HFEA consultation website, through HFEA networks, and promoted to stakeholders and the public in a number of ways. At each meeting, a panel of speakers shared their knowledge and views with audience members. Panellists were selected to reflect a range of different perspectives and areas of expertise, and to provoke discussion amongst participants.

4. Patient focus group. One focus group was held with six participants. The aim of the focus group was to create a forum where people effected by mitochondrial disease, either directly or indirectly, could give their in-depth views on mitochondria replacement techniques.

5. Open consultation questionnaire. A public consultation was held between September and December 2012. Respondents were invited to consider a range of information presented on the consultation website, and to respond to seven questions using the online questionnaire. Responses made via email or post were also accepted while the consultation was open. A total of 1,836 responses were received, the majority of which were received via the consultation website. Respondents include stakeholder organizations, individuals with personal experience of mitochondrial disease, as well as a large number of members of the public.

Each of these strands tapped into different groups, using different strategies. An enormous amount of time and energy was invested by HFEA staff in providing information to support the events, much of which can still be consulted on the HFEA website. It is noticeable that media coverage of the mitochondria replacement story throughout this period was unusually well-informed: the HFEA website encourages interested parties to use any text or illustration they like, to inform their own work, and several journalists incorporated graphic as well as textual material.

The public consultation also benefited from the fact that, fortuitously, the Nuffield Council on Bioethics conducted a six-month inquiry into the ethical issues raised by "new techniques that aim to prevent the transmission of maternally-inherited mitochondrial DNA disorders" during the same period, concluding that "if these novel techniques are adequately proven to be acceptably safe and effective as treatments, it would be ethical for families to use them"[7].

Taken together, the expert and public consultations provided a solid platform on which to build the HFEA's advice to ministers. After more than three years of engagement with scientists, ethicists and the broader public on mitochondria replacement, the HFEA reported to the Secretary of State for Health as follows:

"It is not the task of the HFEA to advise the Government as to whether it should permit mitochondria replacement in treatment. That decision would require a change in the law and is, quite properly, one which only Parliament can take. If the Government does wish to take steps to change the law, it must draft Regulations as provided by the Human Fertilisation and Embryology Act 1990 (as amended)."

"Our advice to Government is that there is general support for permitting mitochondria replacement in the UK, so long as it is safe enough to offer in a treatment setting and is done within a regulatory framework. Despite the strong ethical concerns that some respondents to the consultation expressed, the overall view is that ethical concerns are outweighed by the arguments in favour of permitting mitochondria replacement."[8]

I think this is a quite remarkable outcome for such a contentious piece of clinical innovation. I believe that the painstaking way in which the various consultations were conducted was in large measure responsible for the unexpectedly consensual and positive outcome.

In February 2014, the Department of Health opened a consultation on draft regulations for the use of mitochondria replacement techniques, which would eventually make such treatments lawful.

On 22 July 2014, the department published its response to the consultation on draft regulations, in which it expressed its satisfaction with the extensive process of the consultation overall, and announced its decision to go ahead with putting the regulations before Parliament:

"This consultation on proposed regulations has been the culmination of detailed consideration over a four year period, where the Government has aimed to ensure that full account is taken of all the available evidence on the science, ethics and safety of the techniques and that all voices are heard."

"The Government has decided to proceed with putting regulations before Parliament, subject to giving further consideration to the Expert Panel's recommendations, refining the draft regulations to take account of changes identified during the consultation, and discussion with the HFEA about an appropriate approval process. The Government will consider the timing of the regulations in the light of these actions. The regulations will be subject to full scrutiny by the public and Parliament through the affirmative procedure."[9]

Risk and uncertainty again

When I began writing this chapter, the regulations which would govern mitochondria replacement treatment were expected to be put before Parliament by the end of 2014. Given the success of the consultation process that had preceded the drafting of regulations, it was assumed at the HFEA that the necessary changes to the statute would have become law by the end of 2014. But that, it turned out, was not the end of the story.

On 1 September 2014 a debate took place in the House of Commons Chamber on mitochondrial replacement techniques and public safety, scheduled by the Backbench Business Committee. The motion was moved by the Conservative MP Fiona Bruce, and ran as follows:

"That this House takes note of the Human Fertilisation and Embryology Authority's most recent scientific review into the safety and efficacy of mitochondrial replacement techniques which highlights concerns for subsequent generations of children born through maternal spindle transfer and pronuclear transfer; welcomes the recent comments of scientists that, *prior to the introduction of such techniques, more research ought to be undertaken and a full assessment conducted of the potential risk to children born as a result*; and calls upon the Government, in light of these public safety concerns, to delay bringing forward regulations on mitochondrial replacement." (my emphasis)

There was, I confess, some dismay amongst those who had so carefully seen the matter through to this point, at the prospect of further delay being introduced. What was disappointing was that after all the careful consultation and explanation, there was the old issue of risk and uncertainty once again, raising its ugly head. Those supporting the motion made it clear that the issue was a real reluctance to introduce regulations before there was scientific evidence to show that mitochondria replacement techniques were safe and risk-free. This was the very thing we had been at such pains to educate the broader public to understand was something science, of its very nature, would always stop short of affirming absolutely, regardless of the amount of research conducted.

In the week leading up to the debate, the media was once again full of articles expressing alarm at the prospect of 'three-parent families', further suggesting that somehow the debate had rolled backwards, and that the good work done in consultation might have been undone. But it rapidly became apparent that those taking part in discussion were now markedly better informed, and had a clearer grasp on the science and the issues it raised, than three years earlier. And whenever a non-expert participated in the discussion, they were clearly drawing on the large amount of non-technical information available on responsible websites like that of the HFEA.

All the scientific reports were readily available on the HFEA website, so it was difficult for those urging delay to argue that not enough research had been carried out to guarantee the technique's safety. On the Today programme, on the day of the debate, Jeremy Farrar, Director of the Wellcome Trust, responded to the suggestion that the mitochondria replacement regulations were premature by stating firmly that the matter had had "unprecedented scientific scrutiny".

The debate itself was remarkably level-headed and well-informed. It confirmed the fact that discussion was now taking place based on real information, properly deliberated on and understood by all the protagonists, whether they supported the delaying motion or not. And what swayed the argument towards proceeding with regulations rather than delaying was the clear evidence that the public had fully participated in the process. As one contributor concluded:

"We conducted a structured dialogue to consult members of the public on what they thought. If they support them, then so should we, in all parts of the House."[10]

There is now, I think, little doubt that the new regulations will come into effect before the end of the present Parliament. And this example of full consultation will be on the record as evidence that — if carried out with sufficient care — we can conduct a genuine dialogue between science, government and the broader public, so that fears of risk and uncertainty are properly understood and allayed.

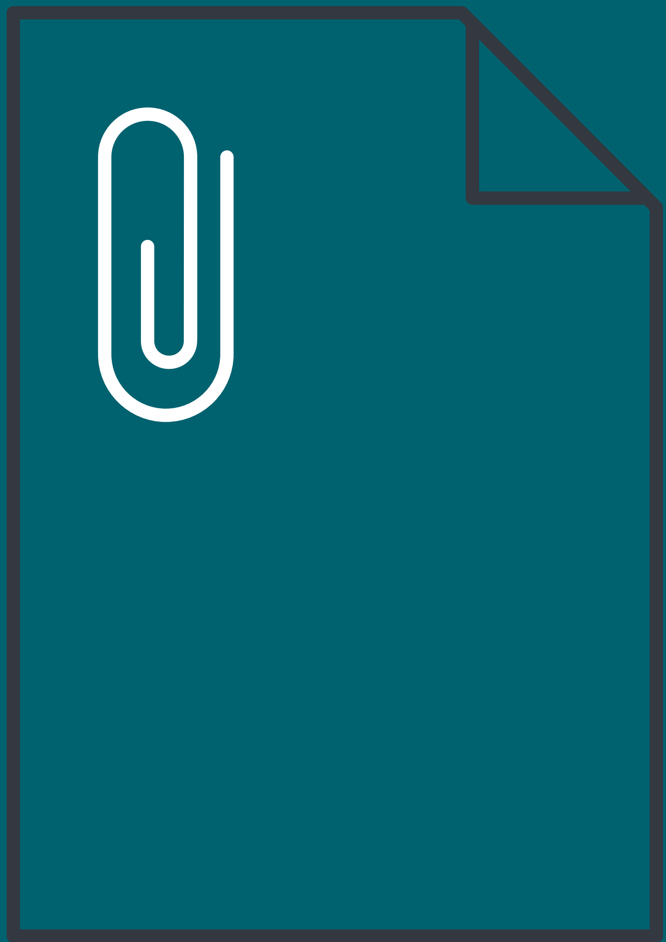
The last word

Proper engagement of the non-scientific public with complex science, in order to obtain its consent to innovation which inevitably carries with it uncertainty and risk, is not achieved lightly. I am proud to have been associated with a successful example of such a process, one which is likely to make the United Kingdom the first country to carry out an IVF procedure bringing hope to families otherwise unable to have a healthy child. I give the last word to one of the members of the expert panel on mitochondria replacement techniques, Professor Peter Braude:

"As a clinician I am aware that inherited mitochondrial disorders are horrible diseases that can devastate families. In the absence of any effective treatment, mitochondrial replacement therapies offer great hope to families afflicted by mitochondrial disorders.

Implementation of any new medical treatment is never wholly without risk, and genetic alteration of disease is an important step for society that should not be taken lightly. The panel has worked single-mindedly over a period of more than three years. It is a shining example of evidence-based regulation."

This example of full consultation will be on the record as evidence that we can conduct a genuine dialogue between science, government and the broader public.



ANNEX: INTERNATIONAL CONTRIBUTIONS

HOW TO BUILD REGULATORY FRAMEWORKS FOR NEW TECHNOLOGIES

Dominique Auverlot, Marie-Françoise Chevallier - Le Guyader, Françoise Roure, Jean-Luc Pujol, Aude Teillant, Clélia Godot[1]

Introduction

French citizens' vision of innovation and progress has deteriorated significantly: technical innovation is no longer synonymous with progress. As highlighted in the final report of *France ten years from now: Priorities for the Coming Decade*[2]: "the French keep trust in science but its applications are often considered with suspicion. Their distrust is not expressed as doubt about scientific contributions but with respect to the ability of public and private institutions to distinguish between real progress for our society and those that induce excessive risk. Our ambivalence about scientific and technical progress ultimately results mainly in broader distrust and doubt about our collective ability to use its results in the service of human progress."

Moreover, according to public surveys conducted as part of the exercise *France ten years from now*, French citizens are now particularly pessimistic: in October 2013, only 5% were confident about the future economy of the country. Thus, France ranks last among the 24 countries surveyed. This distrust extends to politics and institutions, to their regulatory frameworks and to the processes for managing risks coming from new technologies.

In this climate of distrust, the current procedures for citizen participation in public decisions promote "a more active citizen sovereignty," according to Pierre Rosanvallon, but they no longer allow for building standards recognized by society for the development of new technologies. Yet the industrial sector needs, now more than ever, a clear vision on the future regulatory framework in order to invest.

In short, as highlighted by the President of the National Commission for Public Debate (CNDP[3]) in an op-ed on July 25, 2014: "The challenge today is to invent a new model [of citizen participation in public decisions] that combines participation and efficiency". Applying this model for building a regulatory framework for new technologies, including risk management, is needed all the more.

This working paper will present first the current French procedures for citizen contributions to infrastructure projects that can be seen as successful; then, with a few examples, the difficulties encountered in public debates on new technologies. In a third section, we'll see that the deterioration of relations between science and society can probably explain these difficulties to some extent. Finally, it will outline some ways forward for establishing regulatory frameworks for new technologies based on public participation.

1. Public debate on infrastructure projects: a well-functioning response to public outcry

In 1992, following large public protests during several infrastructure projects (TGV Mediterranean, TGV Nord, motorways A14, A16, A1 bis, Nantes-Niort), an administrative report[4] stressed that citizens should be recognized as key players in public decision-making and that it should be a necessity to involve them continuously, well ahead of the decision, in particular at a regional scale.

Following its conclusions, laws adopted in 1995[5] and in 2002 created public debate procedures for local and regional development and infrastructure projects (roads, railways, power lines, and so on) and an independent administrative authority — the National Commission for Public Debate — to organize it. Some characteristics of the public debate procedure can be underlined:

• It lasts for four months (six in the case of additional expertise), and is conducted by a neutral third party — called a Particular Commission for Public Debate — which does not give any personal conclusion at the end of the debate. It has only to present the arguments exchanged during the debate for enlightening public decision-makers. It highlights in particular the pros and cons.

• The (public or private) project manager is required to give his decision about whether the project continues or not, and to provide possible changes resulting from the debate within three months after the publication of the report on the debate.

• The principle of equivalence: the same treatment is given to each participant in the public meeting, and more generally, in the public debate. Everyone, regardless of status, is encouraged in the same way to contribute to the debate.

• The 'upstream position' in the project design: the public debate is especially interesting when it occurs early enough in the operational schedule of the project, so that its design and its options may be questioned and changed if necessary at the end of the debate.

• An initial report, describing the project, its goals and its options, written by the project team (and verified by the Particular Commission for Public Debate), must be given to each participant (and is available on a dedicated website).

This procedure leads to a double improvement for the projects. Even before the debate, the project team has to re-examine its project and to present in a clear and pedagogical way its goals and the set of possible solutions for fulfilling them from a sustainable development perspective, knowing they will be submitted to public scrutiny. Following the debate, the project team is asked to reconsider its plan. It may well change it in the direction of the arguments set forth (by a majority or a minority of participants) or even abandon it. For instance, the debate on a new rail infrastructure from Roissy-Charles-de-Gaulle airport to the center of Paris has led to a complete reconsideration of the project originally planned.

The public debate for infrastructure projects has in fact three different functions. Firstly, it enables a debate about the various general concerns that are associated with the project, such as its economic benefits and its harm to the environment or biodiversity. Secondly, it enlightens representative democracy on the meaning of the decision that must be taken, by presenting all the arguments and suggestions expressed during the debate. Finally, it contributes fully to the design and development of the project (whose ideal is the co-production of a number of its elements).

Since the adoption of these laws, more than seventy public debates have been held. Without doubt, public debate has now become a kind of routine, and has served its purpose. Fifteen years after its initiation, we can say that it is a success[6]. Public debate, rooted in the large public protests that took place in the early 1990s, is indeed a good tool to help representative democracy to make decisions: it makes it possible for people to express their arguments and provides the CNDP with a snapshot of the public opinion on a particular topic to inform the decision maker.

Yet, is it possible today to apply the same procedure that has been proven successful for implementing new infrastructures to new technologies and their regulatory framework? The answer, as we shall see below, seems unfortunately to be negative.

2. Citizen-participation procedures that have not succeeded in establishing regulatory frameworks for new technologies

2.1. Public debates meet some difficulties when used for the development of new technologies

It is tempting to apply to debates on new technologies the same organization as the one that is used in public debates for infrastructure. In fact, this procedure was already used twice: first for a debate in 2009 about nanotechnologies, and more recently, at the end of 2013, for a debate on radioactive waste (more precisely on the plans for a deep disposal center for French radioactive waste). However, both of those debates unfortunately suffered from the radicalization of the protest, leading opponents to prevent the debate from being held. Some people would say that these events have been the result of actions carried out by a minority of the population (in the case of both nanotechnologies and nuclear power, this opposition arose prior to the debate) and that the organization of this public debate has offered them an opportunity to make their radical opposition (to the project and to the associated technology) heard at a national level. Still, that opposition remains real and prevents the public meetings from being held.

This threat may be also viewed as a result of a movement of distrust of institutions and their public decisions.

The debate on nanotechnologies[7]

In France, the public authorities, following a national stakeholder debate about environmental issues organized by the Ministry of Environment and known as the Grenelle de l'environnement (2007-2008), asked the National Commission for Public Debate to organize a consultation on how to promote responsible development of nanotechnologies. This debate was held from October 2009 to February 2010[8] and highlighted several items, although it was disrupted by radical opposition from some groups. First, public knowledge about nanotechnologies and their related societal challenges was very weak. Moreover, the vast majority of stakeholders expressed the need for more transparent and more open governance.

Public debate was a first step, which needed a response to be useful and called for sticking to a nanotechnology development policy that included consultation with various components of civil society in its operating mode. The many challenges raised by nanotechnologies — competitiveness, risk management, ethical issues and social acceptability — called for an innovative form of governance, in which governments and components of society interact dynamically to collectively determine the desired trajectory of development for nanotechnologies. This approach presupposes that some popular wisdom can be set aside, like the belief (largely shared by public decision makers) that information and scientific training are enough to ensure the support of the general public for technological developments. Actually, studies tend to show that laymen's opinions are based less on understanding and being informed of the special characteristics of nanotechnologies, than on the prejudices they have about technologies and the institutions that manage these. Here we can see the full importance of transparency in consultation and decision-making procedures for obtaining informed trust from citizens: transparency on how decisions are made (i.e. governance), R&D funding, ethics, the end objectives of development, risk management, and so on. Citizen involvement at a very early stage, based on procedures that must still be developed to a large extent, would allow nanotechnologies to develop in accordance with societal expectations. In this spirit, the European Commission launched on 13 May 2014 a "public consultation on transparency measures for nanomaterials on the market". If, in the short term, regulation can be regarded as a barrier to developing markets, there is no doubt that in the longer term it will be the main factor of companies' competitiveness in nanotechnologies by creating a more stable and secure environment for investment and consumption.

The debate on radioactive waste

The public debate on radioactive waste (more precisely on the plans for a deep disposal center for French radioactive waste, at Bure in eastern France) was held from 15 May to 15 December 2013. The fourteen public meetings that were initially planned have been all cancelled: the first two public meetings, in May and June, were prevented by opponents of the projects. The National Public Debate Commission then decided to continue the debate through proximity meetings (in town halls, markets and high schools); to organize debates on the Internet; and to hold a citizen conference. Thanks to those measures, the National Commission for Public Debate has been able to give its report, presenting the arguments for or against the project. In contrast, the classical form of public participation in public meetings has not been possible.

2.2. The debate about genetically modified organisms (GMOs): a badly begun process

GMOs

Genetically modified organisms (GMOs) have generated much debate since the late 1990s. Presented by some as a major technological innovation, giving significant economic benefits to those who use it; regarded by others as an uncontrolled process that can lead to severe damage to our ecosystem, and even to human beings; regarded finally as a new kind of agriculture with new dependencies, new shares of value added and new biodiversity. However, despite these various consultations, the issue of GMOs in France appears dominated by a governance problem under which the various players don't trust each other and use strategies that can be perceived as contrary to the rules imposed by parliament. This marks the failure of the attempt to regulate the development of a technology: crops grown without advertising, illegal uprooting, delays in transposition of European directives, and the use of GMOs in animal feed. However, there have been many attempts at debate:

• A citizen conference organized in 1998 by the French parliamentary office for evaluating scientific and technological choices (OPECST), held on the Danish model of 'consensus conferences'.

• A report published by the Commissariat Général du Plan, GMOs and agriculture: options for public policy (2001). This study, conducted by Bernard Chevassus-au-Louis, was particularly aimed at identifying "elements for a proactive strategy"[9].

• A conference held in 2002: this scientific study conducted at the request of the government established proposals for experimental field trials of genetically modified crops.

• A Parliamentary mission in 2005 entrusted to OPECST and directed by Yves Le Déaut on "the status of biotechnology in France and Europe".

In fact, the debate faced recurring difficulties, widening the distrust about GMOs themselves and about systems responsible for their governance. There were issues about:

• independence and objectivity of scientific experts (from politics, industry, etc.)
• lack of scientific knowledge
• lack of transparency in risk management systems
• lack of public information
• usefulness of GMOs in food
• lack of credibility of the measures taken.

GMO issues go beyond simple industrial and economic interests and can't be dissociated from the vision of the future of our agriculture in the context of globalization. Considering that a consensus between actors on this particular issue seems clearly impossible today in France, a public debate appears to be useless, mainly because of the radicalization of the opponents of GMOs: in fact, GMO issues are more and more often taken to court. Yet, at the same time, public information on GMOs is still necessary.

The painful experience of the French National Institute for Agricultural Research (INRA) on the grapevine

Fanleaf virus transmitted to grapevines by nematodes in the soil may kill the vines. To overcome this disease and to avoid polluting the soil with conventional treatments, INRA has developed since the mid-1990s genetically modified rootstocks to withstand the virus, rootstocks on which traditional grapevines may grow.

Since then, INRA has tried to conduct full-scale tests to verify the effectiveness of this process over time:

• A first test was begun in 1996, but the winemakers (on whose fields the test took place) gave up in 1999 for fear of a depreciation of the image of their products.

• A second test was conducted inside an INRA center in Colmar with a local monitoring committee for tracking the experiment and questioning researchers (leading to further research): the grapevines were uprooted in 2009 by individual opponents.

• A third test to follow up the previous one was interrupted by a new uprooting led by sixty people, including a winemaker.

This experiment showed both the interest in creating a local committee to monitor and to address all questions (even if it changed the research program — which is a positive result) and, at the same time, all the difficulties associated with current full-scale tests on GMOs in France within the existing legal framework.

2.3. The debate about shale gas, concluded even before it began!

The shale gas non-debate

The issue of shale gas — its potential and the possibility of exploiting it — arose in France in the first quarter of 2011, a year before the presidential and parliamentary elections. In parallel with a mission entrusted to senior officials, the French National Assembly asked two of its members to write a report on interest in and opportunities for exploiting unconventional hydrocarbons. They submitted their text on 8 June 2011. One month later, on 13 July 2011, a law was enacted that strictly limits exploratory drilling and production of unconventional hydrocarbons by prohibiting the use of hydraulic fracturing. The conclusion of the report written by senior officials was the following:

"The brutal and highly publicized eruption in France of the issue of shale gas — which has been underway for more than fifteen years in the United States, leading an upheaval in the country's energy balances — has not allowed the initiation of a serene technical and democratic debate at the desirable pace."

"The techniques used have all, when considered one by one, long been practiced (horizontal drilling, hydraulic fracturing, use of chemical additives etc.). It is the combination of these techniques that is innovative and allows the possibility of an economically viable operation. This combination, with the prospect of large-scale development in areas not accustomed to oil techniques, clearly raises concerns with regard to the risks involved."

"Since spring 2011, some European states have taken a significant part in the debate, with different results. Due to a more entrenched environmental sensitivity and to their urban concentrations, European countries are in a context that is not directly comparable to that of United States. The development of unconventional hydrocarbons in our continent will never reach the scale and speed of the combined experience of the United States over 20 years. Moreover, whatever the economic interest of the subsoil resources, it must be balanced with the inclusion of other assets regarding the territory, such as agriculture, natural heritage, tourism, etc."

It should be highlighted that the law was passed after a Parliamentary report and a Parliamentary debate, which is one of the best expressions of democracy. But this process took place before any scientific report could be written to clarify, from a scientific point of view, the different issues raised by the possibility of producing unconventional hydrocarbons.

Conclusion

It is clear that French society encounters problems when debating regulatory frameworks for new technologies in order to find the conditions under which such development could take place, or to decide about the research necessary to determine whether this development is desirable or not. The cancellation of a number of public meetings and the uprooting of some GMO tests emphasize the need to invent other forms of public participation. More generally, it leads us to consider that several barriers remain in debating such issues, some of which are specific to French society.

3. A deteriorating link between science and society

3.1. "The precautionary principle": a culprit too quickly identified

The precautionary principle was introduced into the Constitution after a vote of approval on the Environmental Charter by the French Parliament in Congress at Versailles in March 2005:

"Art. 5 – When the occurrence of any damage, albeit unpredictable in the current state of scientific knowledge,

> **It is clear that French society encounters problems when debating regulatory frameworks for new technologies.**

may seriously and irreversibly harm the environment, public authorities shall, with due respect for the precautionary principle and the areas within their jurisdiction, ensure the implementation of procedures for risk assessment and the adoption of temporary measures commensurate with the risk involved in order to deal with the occurrence of such damage".

Prior to the inclusion of the Environmental Charter in the Constitution, there was vigorous debate between those who wished to adopt some measures to avoid major damage to the environment, even in uncertain cases, and those who opposed them, arguing that they might inhibit economic initiative and technological innovation. Nearly ten years after its publication, two points need to be made:

- In legal terms, the precautionary principle has seldom been applied.

- Nevertheless, more and more public decisions take that principle as a reference. And, by the way, some of them seem to be taken under emotional stress, without relying on scientific knowledge. Therefore, it seems logical to remember that public decisions must be based on independent and multidisciplinary scientific expertise.

The issue at stake is not about being for or against GMOs or shale gas. It must be recalled that, under the current charter of the environment, 'risk assessments' must be implemented, temporary measures adopted and a research program has to be designed to resolve the possible uncertainties. The implementation of risk assessments should lead to an explicit formulation of the unresolved scientific issue — in a transparent way — and to the implementation of a research program to treat these issues rather than to continue discussing sterile arguments. But such assessments are often lacking.

In fact, innovation is not stifled in France by the precautionary principle but rather by a certain mindset in society and a growing distrust towards technological progress and scientists (see also the case study on risk and precaution). As a result, some technologies are de facto blocked, without any scientific debate on the unresolved questions. On the other hand, in some areas, some industries are tempted to continue their work without any transparency.

3.2. Public debate: a tool to be improved to address regulatory frameworks for new technologies

For more than two centuries — specifically since the French Revolution — French society has faced difficulties in inventing efficient relationships between popular sovereignty and the power of representative government. In his books, Pierre Rosanvallon shows how, through different times in its history, the French nation has tried to give a more accurate reality to the concept of popular sovereignty. Of course, the very essence of our democracy lies in the electoral vote: the fact remains, however, that "more active and more complex sovereignty" can lead to a government more faithful and attentive to the general will, without denying the tremendous ambiguity linked to that latter term. In a society increasingly disenchanted with politics, the question then arises of how to give shape to this "more active sovereignty".

In some areas, particularly the environment, comes the idea that the representative of the people must be informed, before making any decision, by a more direct link with citizens, a link that can take the form of a discussion among citizens.

This view could be supported by Habermas' early works, in particular the theory of communicative action, in which he considers the possible attainment of universality through discussion, or rather thanks to a real discussion among participants during which they should achieve impartiality through successive adjustments that require them gradually to adopt the perspective of all other participants. The decision on the rationality of a standard shall be suspended to obtain not only an agreement among the participants, but more precisely a unanimous consensus motivated by the recognition of the best arguments.

This 'discourse ethics' is based on a number of conditions that must be respected, including inter alia:

• The condition that everyone capable of speech and action is entitled to participate and to make a contribution, and everyone is equally entitled to introduce new topics or express attitudes, needs or desires.
• The condition that no relevant argument is suppressed or excluded by the participants.
• The condition that all the participants are motivated only by one concern: finding the best argument.
• The condition that the debate must be free from any restrictions that may prevent the manifestation of a better argument that can determine the outcome of the discussion.

It must, however, be noted, as Habermas often wrote, that the rules as stated in his discourse ethics can only be reached in a very approximate way, and that the rules followed by the participants in a public meeting of 1,000 to 1,500 people are very far from those set out.

Public meetings are therefore only an imperfect way forward. From the outset, the National Commission for Public Debate has dropped the goal of finding a consensus in its debates. More fundamentally, Rosanvallon emphasizes in his works the great difficulty of obtaining a given expression of the sovereign people: its expression (except in a referendum) is multiple and diverse, and it varies over time.

One of the former vice-presidents of the CNDP, Georges Mercadal, also points out that "it is not possible to claim that the meeting attendance, by the number and mode of recruitment, may be representative of the French population". He further states that "interventions [in public meetings] are overwhelmingly opposed to the projects" and that "projects are often of national interest, while the debate is confined to the areas of environmental impact". In these circumstances, public debate is an imperfect object that cannot be a representative assessment of the acceptance of the project and cannot be a substitute for representative democracy.

Georges Mercadal then proposed to "consider the public debate as a criticism of the project [coming from the society], presumably exhaustive because exercised by the most concerned people. The assessment remains the responsibility of the representative system, which must both consider that criticism and distance itself to preserve its judgment. This makes public debate the form of reflective dialogue … which may fill a gap often denounced in French democracy". In that sense, the main function of a public debate is to enlighten the representative democracy on the meaning of the decision it must take, by providing it with all the arguments and suggestions expressed during the debate. It also allows the public to participate to some extent in the decision (even if the co-construction of the decision seems very difficult, if not impossible).

The previous section, however, showed us that the current form of public debate, applied to new technologies, was facing a number of difficulties that could even result in making it impossible for a debate to be held. The staging of a national debate to decide the future of a technology constitutes a great opportunity for the most extreme opponents to gain the attention of the national media by preventing meetings from being held. A solution can possibly be found in retaining the benefits of public debate while trying to avoid its blockage by quite a few persons.

The current form of public debate, applied to new technologies, was facing a number of difficulties that could even result in making it impossible for a debate to be held.

3.3. The current difficulty faced by French society in developing standards around socio-technical issues

The distrust of experts

The distrust, mentioned above, still applies also to the experts and their institutions, nurtured by several cases that remain in our memories:

- The contaminated blood case, in which there was a delay in the implementation of safety measures.
- The radioactive clouds from the Chernobyl disaster that 'did not stop at the French border', their impact being measurable, contrary to statements made by some French senior officials at the time.

More recently, it appears clear that the debate on emerging technologies is often brought before the courts and has already led to several trials. Successive judgments of various courts about the installation of relay antennas or the uprooting of INRA grapevines demonstrate different kinds of expertise coming not only from scientists but also from civil society. For their decisions, elected officials, as well as judges, take into account all these forms of expertise. On the contrary, scientists are sometimes strongly challenged in these debates because their analysis tends to exclude any reference to values or perceptions that often guide the expertise emanating from associations and civil society. Public opinion is more and more concerned by conflicts of interest.

Since the 1990s, France has set up several agencies and dedicated expertise on risk. A wide range of sectors are included:

- A food safety agency (founded in 1999 following the 'mad cow' case and integrated in 2010 in ANSES, the French Agency for Food, Environmental and Occupational Health & Safety)
- Medicines and health products (ANSM, the French National Agency for Medicines and Health Products Safety)
- Nuclear safety (IRSN, the French national public expert in nuclear and radiological risks)
- Industrial environment (INERIS, established by the French Government in 1990 as the National Competence Centre for Industrial Safety and Environmental Protection).

The action of these agencies has helped to popularize the notion of expertise, to highlight the role of experts, and to provide reports that help build trust and generate constructive public debates and should be a possible way ahead.

The development of scientific illiteracy in a context of rising education

In a context of rising education levels in France (70% of a given age group now holds the baccalauréat), scientific expertise is in principle (and logically) questioned and challenged during public debates. A new paradox has however appeared: at the same time, the level of scientific

> **We are no longer in an information deficit model in which it was easy to blame the public for not being informed sufficiently to debate.**

culture remains low in a great number of countries (two out of five Americans do not believe in the theory of evolution; a large majority of members in the US Republican Party does not believe in the human source of climate change; most French citizens turn off the lights as their main step in the fight against climate change rather than turning down the heat).

Marie-Françoise Chevallier – Le Guyader reminds us that the notion of scientific illiteracy, which appeared in the United States in the mid-1980s, is seen by some as "a social and political danger affecting states whose development is based on science and technology". As she points out, this danger may induce a new view of public debates, with a negative answer as to their need! This challenge is even greater in several cases in which some lobbies — the merchants of doubt — are working to discredit scientific messages or to delay any decision (including those of the Intergovernmental Panel on Climate Change, IPCC), focusing heavily on the uncertainties linked to these decisions.

We are no longer in an information deficit model in which it was easy to blame the public for not being informed sufficiently to debate. We are facing a new paradigm: scientific information is available but, in some cases, its appropriation and full understanding by the public cannot really be attained. During the debate, everyone is legitimately concerned and gives his opinion, but an opinion is not a skill. A major issue related to the issue of trust is to recognize the specific skills of scientists and experts. Recent polls show the current ambiguity of French citizen, who likes scientists but who is less confident about their statements about sensitive subjects, as well as in their institutions. They tend to put more trust in associations and in NGOs.

The difficulty of French society holding real debates

Add to this the difficulty of French society to hold a real debate, without even making reference to the "discourse ethics" as stated by Habermas: public meetings more often correspond to a succession of presentations and questions from the audience rather than an exchange of arguments on a subject which should enable a 'co-built' solution. Under these conditions, Marie-Françoise Chevallier – Le Guyader emphasizes the current difficulty faced by French society in developing standards around socio-technical issues, the

RISK AND PRECAUTION

The precautionary principle is sometimes accused of creating an obstacle to innovation development, or even industrial activity. It is not so much its legal application that can pose problems for companies, as the erroneous invocation of the principle by groups opposed to technologies, new or otherwise, and its inappropriate application.

In 2013, La Fabrique de l'industrie set up a working group on this topic, comprising industrials, scientists and sustainable development experts. Interviews with numerous specialists revealed that the problem lies less in the precautionary principle itself than in an increasingly assertive demand for security from consumers and citizens, combined with their lack of trust in the institutions responsible for ensuring their protection. Some companies have successfully taken on this concern and responded in order to re-establish a more confident dialogue with their customers and neighbours. They have even managed to turn this capacity into a competitive advantage.

Misunderstood principle, often erroneously invoked

The precautionary principle fits in with a tradition already well established in some industries, such as air transport, drugs and the chemical industry. As a principle of law, in cases where it is difficult to establish the benefits and risks of a decision, it obliges public powers to take temporary measures proportionate to the suspected risks and to take action to better evaluate them. The regulator thus avoids the environment being endangered by parties against whom it would be difficult to seek redress in case of damage.

The precautionary principle was introduced into the French Constitution as a symbolic act to show that the President of the time was receptive to environmental concerns. To date, no laws have been declared unconstitutional on the basis of the precautionary principle, and case-law invocations have been prudent and limited. On the other hand, the precautionary principle is frequently evoked, often inappropriately, either by militant groups opposed to the use of a technology or product, or by politicians and civil servants keen to protect themselves against liability. It is not the precautionary principle in the legal sense of the term, but rather the concern expressed by citizens and consumers regarding certain technologies and the media coverage of this concern, that encourage politicians and the government to produce rules that result in constrictions and costs for industrials.

Is France more cautious than its partners?

These constraints are often viewed as greater in France than elsewhere. However, close analysis reveals that the situation varies depending on the subject. In domains like GM food and firearms, it is true that France is cautious in comparison to the United States. However, France comes across as more liberal in areas like tobacco, nuclear power and diesel particles. Germany, despite its reputed concern to maintain the competitiveness of its industry, has decided to pull out of nuclear power and opt for less controversial energy sources.

In France, studies show that society is split into groups with very different attitudes towards technological innovations and faith in progress. Surveys also show that these groups tend to diverge over time.

The frequently virulent statements made by concerned sections of the public mainly stem from a lack of trust in the institutions responsible for ensuring the security of people and the environment. This mistrust, which results from an accumulation of ill-managed crises, illustrates public powers' difficulty in organizing helpful dialogue and taking appropriate measures when uncertain situations arise.

Managing uncertainty

Managing major risks, particularly in situations of scientific uncertainty, poses considerable problems to public authorities.

• How can we establish the appropriate "considered action" for a situation, when we do not know its benefits and risks, or when those benefits and risks affect different sectors of the public?
• How can we put across messages that are scientifically rigorous, useable by public powers and comprehensible to non-specialists?
• How can we take on non-experts' concerns and make them part of the debate?

Group members
Thibaut Bidet-Mayer (assistant rapporteur)
Bernard Chevassus-au-Louis
Alain Coine
Geneviève Ferone
Pierre-Henri Gourgeon
Alain Grangé-Cabane (president)
Claudie Haigneré
Marie-Angèle Hermitte
Pierre-Benoît Joly
Jean de Kervasdoué
Jacques Kheliff
Brice Laurent (rapporteur)
Hélène Roques
Fabienne Saadane-Oaks
Thierry Weil
Claire Weill

External experts interviewed
Marie-Josée Forissier
Guy Sorman
Michel Serres
Jean-Pierre Clamadieu
William Dab
Jean-Christophe Ménioux
Marc Mortureux
Maryse Arditi

• How can we give entrepreneurs sufficient visibility so that they can invest and still be capable of reacting to new information?
• How can we guarantee European consumers decent protection, under international trade rules, without putting European producers at a disadvantage?

Answering these complex questions requires setting up the appropriate procedures, structures and instruments. It involves reviewing the way that public powers operate in contemporary societies in which uncertain situations are increasingly common and non-expert sectors of the public are increasingly keen to participate in decision-making. This calls for better organization of expertise on available knowledge and improved debate on what "considered action" involves, including participation from non-experts. The next step is to organize coherent, monitored, effective action that is responsive and capable of taking on board new information on risks.

Public authorities' current difficulty in adapting to this new context can lead them to making questionable or incoherent decisions, or even no decisions. Take for example the threat of an epidemic, prompting a vaccination campaign, during which time the threat dissipates as the disease evolves. Is it best to cancel the campaign, which no longer seems useful? Will people look back and criticize the government for having wasted money because it chose to buy vaccines at a time when the decision seemed appropriate? Will ill-intentioned commentators paint a retrospective view of the risk, exaggerating the probability of the scenario that ultimately occurred? Decision-makers will continue to be accused of either culpable negligence or excessive caution as long as people do not trust the institutions responsible for protecting them.

This lack of consensus on how to manage uncertain risks is maintained on the one side by "merchants of doubt", who play on the lack of certainty to refute the possibility of danger and stand up to objectively reasonable action, and on the other side by activists who contest dialogue arrangements and even sabotage debates, e.g. the cases of nanotechnologies and underground storage of radioactive waste. At times, the media add to the confusion and lack of trust by putting opposing opinions on the same level without indicating the often very different nature and weight of their arguments. The desire for a sensational storyline sometimes encourages alarmist messages.

To sum up, public powers are confronted with urgent demands from concerned members of the public, but they are ill equipped to adopt relevant, accepted measures. They generate a sometimes disordered accumulation of rules that constrict individuals or economic activity without always producing the anticipated security.

How some industrials tackle the demand for precaution

Public demand for precaution and the difficulties experienced by authorities in creating the appropriate measures result in a context that industrials need to deal with.

Most companies have long-standing expertise in managing the risks of their procedures and products. In addition, given that a proportion of the public remains concerned despite multiple protective regulations, some industrials have developed dialogue arrangements in order to take concerns on board, illustrate their ability to control risks, and restore stakeholder confidence.

The demand from society to reduce risks linked to production and consumption can also be a source of innovation and offer a competitive advantage to companies that respond better than their rivals. Strict regulations can even drive out less credible competitors.

To sum up, society's demand for security is growing, independently from any legal expression. Industrials can respond and benefit from it. Public powers need to show that they are capable of dealing with uncertain risks and re-establish a good level of trust, while making sure that the regulations they produce for application are effective and do not needlessly hinder economic activity or innovation.

About La Fabrique de l'industrie

La Fabrique de l'industrie is a think tank created in October 2011 by UIMM, the Cercle de l'Industrie and the GFI, with the aim of boosting and improving collective debate on industrial challenges. Its Chairmen are Louis Gallois and Denis Ranque. As a centre of thinking and debate, La Fabrique takes an in-depth, multi-disciplinary approach to the current situation and perspectives of industry in France and Europe, the attractiveness of its professions, its relationships with different stakeholders, and the opportunities and challenges brought about by globalization. It organizes exchanges of opinion and analyses to shed light on complex, subtly different situations. It readily works with any institution that can help it accomplish its missions. La Fabrique de l'industrie is a resource centre for all those involved in debates on industry: it gathers information, creates new spaces for dialogue, and produces critical reviews that decode the multiple points of view.

Access the entire output of La Fabrique de l'industrie on its website: www.la-fabrique.fr regulation of the development of new technologies being only one example.

4. Conclusion: Some ways forward

This section gives some possible solutions for a new model of citizen participation in establishing regulatory frameworks for new technologies. They involve public decisions at different scales: firstly in the long term, but also in the shorter term, and finally for on-going commercial negotiations.

The rejection of non-transparency

In the development of innovation and new technologies, the first possible solution — and unfortunately the easiest one — would be to say as little as possible and to avoid presenting and debating the risks. This solution may be tempting for some. But, for us, this is a losing strategy in the long run: the first incident associated with a given new technology would spark a media campaign that could stop its development. We shall therefore take for granted that the participation of civil society (public and all stakeholders) is necessary in the definition and treatment of a regulatory framework for new technologies.

Long-term solutions

(i) In the long run, it seems absolutely necessary to try to rehabilitate scientific culture and to learn to discuss and exchange views on — in other words, to debate — technical issues.

Another way forward is to strengthen the level of scientific culture and ethical approaches: the ability to explain major ethical questions and to create common rules in order to live together. Many such actions already exist in research and cultural institutions. However, these approaches must be embedded into the different communities by creating new audiences and facilitating multicultural dialogue and exchanges of expertise. For instance, in-depth discussions with lawyers are also needed to develop innovation.

(ii) According to surveys, two kinds of structures are considered trustworthy by French people:

- Multi-actor structures (grouping politicians, industrialists, experts, associations, policemen, firemen and general practitioners), which are considered particularly reliable.
- Independent authorities on food safety.

Using these bodies in public debates may be a way forward.

Some shorter-term solutions

In the shorter term, the public debate on a regulatory framework for the development of new technologies (or for a moratorium on them):

- can no longer be conceived as a one-time debate of four or six months, but rather as a continuous process which will last several years. In her policy brief about nanotechnologies, Aude Teillant points out that "it seems essential to set up permanent forums that are open to all stakeholders and whose objective is not to reach a consensus on a given issue but to express diverging points of view freely. Such a framework would help identify the scientific, ethical and social issues raised by these new technologies". In fact, some long-term structures for exchange and debate are needed to support the development of a new technology (or a moratorium).

- should rely on international scientific knowledge — as rigorous as possible — about the questions involved: it is absolutely essential to understand what science is able and is not able to say on a given topic. The IPCC is probably the best example. It is clear, however, that these results must not be the only basis on which the policy maker will take his decision: it is necessary to add, country by country, the outcome of debates with citizens. It should be stressed that if this scientific step seems absolutely necessary for the decision-making process, it should not be considered as sufficient: the participation of civil society is the following step, as essential as the scientific assessment. (In the best process, there would be interactions and issues coming from the public that would be dealt by scientific experts).

- would train leaders (political, industrial, social, etc.) about decision making in a social and political environment marked by the increasing complexity of the relationship between science, society and innovation environments and by public debate[10].

- would, before a public decision is taken, multiply (for instance under the authority of the CNDP) the forms of debate by holding meetings open to the public but also by asking other groups (public structures, associations) to organize their own debate on a given subject. There are, however, some necessary conditions for a good debate: its goal must be clearly defined, like the issues on which the government wishes further enlightenment; the public must not feel that the decision has already been made before its participation; in its commentaries on the final decision, the Government must clearly indicate how it has taken account of the main arguments presented in the debate.

- would find some legitimacy on the World Wide Web, where the experts' assumptions and assertions will be scrutinized and challenged. Since the start of the twenty-first century, a widely interconnected global society has emerged. Time and space will now never be managed as they used to be. 'ATAWAD' — connected at any time, anywhere, with any device — is the synthesis, and the symbol, of this trend. Digital natives themselves will probably feel outdated compared to the 'immersive technologies' natives who will be raised and educated between now and 2050.

In the shortest term, a novel scheme for high stakes/ high risk ongoing commercial negotiations

As experienced by the World Trade Organization in the field of GMOs, trade disputes concerning innovation in the field of agriculture and food will without any doubt be part of the potential obstacles for the conclusion of Transatlantic Trade and Investment Partnership agreements (TTIP between the EU and the USA, and CERA between the EU and Canada).

Under the negotiations scheme, the Sustainability Impact Assessment (SIA), a mandatory mechanism, must be applied to each domain of the agreements (energy, food, agriculture, ICTs, mining, pharmaceuticals, materials and so on) and agreed before the agreement is concluded. When the US Congress voted in favor of opening negotiations with the EU on the TTIP (with the European Commission, which has an exclusive competence, the European Parliament being only consulted for advice), it expressed the will that the agreement should be founded upon a common set of values supporting the whole edifice. For a SIA, we are aware of the fact that the so-called 'precautionary principle' will not be shared as the "common set of values" called for by the US Congress. This means that the opportunities for innovation in risky domains will be missed if the agreements (TTIP and CERA) go into a deadlock.

The stakes are about one trillion dollars in annual value added , according to the TTIP economic impact analysis prepared before the opening of the transatlantic negotiations. So what is left in terms of potential core values to be shared, in order to secure trust in innovations perceived as risky, and thereby characterized by a potential societal risk leading to a political rejection of the agreement?

The European Commission has been working on the concept of Responsible Research and Innovation, and published in 2013 a report exploring the different options for its adoption and implementation at the European Union level. The European Commissioner Michel Barnier adds the concept of responsible investment, which includes long-term systemic effects, and the ability to finance those investments for purposes of general interest (the safety of food and energy supplies, for instance).

So, with a reasonable expectation of success, we can forge the concept of responsible research, innovation and investment (R2I2), as the potential foundational shared value to be proposed as a trade-off for the SIA framework, in the event of difficulties (we are pretty confident those difficulties must not be denied but addressed properly as soon as reasonably possible, otherwise they will pop up at the worst moment of the negotiation agenda). Should the potential of this concept be understood in time, it would have a great positive impact.

OPTIMISM OF THE WILL: IN DEFENCE OF A MODERN STOICISM

Jesper Poulsen-Hansen (Co-Founder and Partner, Gemeinschaft consultancy)

From the fickle beginning of human existence we have found ways to explain and understand the uncertainty of our world. We have populated our collective imaginations with gods, sciences, superstitions, causalities, anxieties and rituals in order to impose a fleeting sense of stability on an otherwise volatile existence.

But why do we combat this uncertainty so ardently? The answer is fear. We fear the things we can't control or the things that we have difficulty understanding. This is also the main reason for our time's fixation with transparency, which again takes the shape of increased levels of surveillance and much new public-management logic. In short, we fear ambiguity and uncertainty, despite uncertainty being the prime mover of the progress of our species.

This has affected something of a shared pessimism when it comes to risk and innovations. We seem to associate uncertainty almost entirely with the bad things that could happen. But we seem to have forgotten that uncertainty is not only the source of dire news. It can also produce wonderful innovations and technological progress; indeed, historically it has.

Perhaps it is time to revisit the motto coined by the Italian political theorist and philosopher Antonio Gramsci: "pessimism of the intellect, optimism of the will". It was his way of describing these dual forces, which have always beleaguered mankind. Simply put, it means that we know things can go wrong but we have faith that it won't.

These dual forces of pessimism and optimism, intellect and will, are also the ground on which the relationship of risk and innovation is built. The pessimism suggested is not a bleak cynicism but rather a constructive scepticism. The optimism suggested (and much needed) is not a happy-go-lucky recklessness but rather a historically-founded faith in a modern humanism. What we need is a modern stoicism of the twenty-first century. Humanity is underrated!

REFERENCES

Chapter 1: Innovation, Risk and Government: Perspectives and principles from the social sciences

A full bibliography can be found at the end of the reference list for this chapter.

1. The authors would like to warmly thank Nick Crafts, David Newbery and John Vickers for their thoughtful comments and guidance. We have also benefited greatly from discussions with Tim Besley, Stefan Heck, Mark Schankerman and Cathy Zoi, and with the other contributing authors to this volume. We are grateful to the Grantham Research Institute on Climate Change & the Environment at the LSE for their support in producing this chapter. Any errors or omissions are our own.
2. See Perez (2010) and Stoneman (1995).
3. Hall & Rosenberg (2010) and Balconi et al. (2010).
4. In addition, *innovation applies to the understanding of innovation itself* — and a host of other social processes and policy problems. Hall & Rosenberg (2010) point out "the topic of innovation systems and institutions is still in its infancy empirically". Gallagher et al. (2012) point out that we need better measurement, modelling and theorising about innovation. This will allow better policy design, and a more powerful innovation system, in the future.
5. Department for Business, Innovation & Skills (2014).
6. Crafts & O'Rourke (2014).
7. Crafts & O'Rourke (2014).
8. Christensen (1997).
9. In some cases, such as those of displaced workers, those who lose may deserve supportive policies; in other cases, like that of firms in a competitive market, the threat of being a loser is often what spurs further innovation.
10. Sometimes strong stimulus for innovation comes from threat and war, but not all resulting innovations enhance human well-being.
11. Perez (2010).
12. Solow (1956); Swan (1956).
13. See, e.g., European Commission (2001), 5, 11. Innovations increase productivity by using existing resources in new or more productive ways.
14. Galasso & Schankerman (2014).
15. Hall & Rosenberg 2010 p5.
16. Other market failures that may be relevant to the incentives for innovation in certain sectors (e.g. the energy sector) include network infrastructure, coordination problems and inadequate information.
17. Griliches (1992); Hall et al. (2009); Griffith et al. (2004).
18. Galasso & Schankerman (2014).
19. Jaffe, et al. (2005).
20. For example, the political literacy and enculturation that results in stable institutions and a healthy society: see, e.g. Friedman (1962).
21. E.g. see Moretti (2004) Lange and Topel (2006).
22. Gallagher et al. (2012).
23. Stern (1989) provides a list of reasons why government interventions can fail (at p. 616).
24. Winston (2006).
25. This concept draws on work of Schumpeter (1934) and later 'evolutionary' theorists of innovation (e.g. Nelson and Winter 1982).
26. Freeman (1995); Lundvall (2010).
27. Crafts & Hughes (2013). For example, numerous authors conceive of the state playing a role within innovation systems beyond merely fixing market failures and "facilitating" private sector innovation: see, e.g., Johnson (1982); Chang (2008); Mazzucato (2013).
28. E.g. see Lundvall (2007); Dasgupta & David (1994).
29. See Knight (1921).
30. The Tick-Tock model is a chip technology roadmap, where every 12-18 months either a "tick" or "tock" is expected. A "tick" represents a shrinking of transistor size, and a "tock" represents a new microarchitecture taking advantage of that smaller size. This relative predictability is marketed to investors as an attractive feature of Intel's model. http://www.intel.com/content/www/us/en/silicon-innovations/intel-tick-tock-model-general.html.
31. Gallagher et al. (2012).
32. See Grossman and Helpman (1991); Lipsey et al. (2005); Ruttan (2006).
33. Cohen (2010).
34. Cohen (2010). Though of course, in the ICT sector, there are many large firms as well, such as Google, Apple, Microsoft and Facebook.
35. Cohen (2010); Schumpeter (1934).
36. Network linkages between firms and public sector agencies (e.g. universities) are also important and are discussed in the following section on firms and other institutions.
37. Schilling and Phelps (2007); Nooteboom (1999).
38. Coe and Helpman (1995).
39. LSE Growth Commission (2013).
40. Mazzucato (2013). Nicholas Stern was directly involved as Chief Economist in the 1990s building principles and strategies for the investments of the EBRD, on the board preparing for the UK's Green Investment Bank, as Chief Economist of the World Bank (2000-2003), and in the design and launch of the new BRICS-led development bank (announced on 15/7/2014).
41. Cohen (2010).
42. Cohen (2010).
43. Bloom and Van Reenen (2006).
44. i.e. innovators are unable to capture the full returns from their innovation.
45. Baumol (2002).
46. Galasso & Schankerman (2014).
47. When patents are annulled, small firm innovation increases by a remarkable 520% on average: Galasso & Schankerman (2014).
48. Foray and Lissoni (2010).
49. Many studies find that the co-location of start-ups and universities has little effect upon innovation or the strength of cross-sectoral relationships: see Foray & Lissoni (2010) pp. 303-305 and references there cited.
50. Foray & Lissoni (2010)
51. Azoulay et al. (2011); Editor (2009).
52. Azoulay et al. (2011).
53. E.g. see Etzkowitz, H. (2003).
54. See Foray & Lissoni (2010); Agrawal and Henderson (2002).
55. Dasgupta & David (1994)
56. Foray & Lissoni (2010); Philpott et al. (2011).
57. See Higgs (2013); Zimmer, M. (2009). GFP: from jellyfish to the Nobel prize and beyond. *Chemical Society Reviews*, 38(10), 2823-2832; and Azoulay et al. (2011).
58. Kahneman & Tversky (1979).
59. Chen and Miller (2007); Chen (2008).
60. IEA (2014), Data Services Table. See public energy R&D spending from 1970s to the present day. http://wds.iea.org/WDS/TableViewer/tableView.aspx.
61. This debate is framed as intrinsic motivation/extrinsic incentive in behavioural economics (e.g. see work by Swiss economist, Bruno Frey (1994 and 1997) on how intrinsic motivation can be crowded out by extrinsic incentives). Or for example, using financial incentives to improve teacher and student outcomes—one prerequisite for an effective innovation system—can actually harm educational outcomes. E.g. Fryer (2010 and 2011).
62. E.g. on soft vs. hard institutions see: Klein Woolthuis et al. (2005); Lundvall (2010).
63. See, e.g., Kahneman (2011); Thaler and Sunstein (2008); Mullainathan and Shafir (2013).
64. Johnson and Goldstein (2004).
65. E.g. see Behavioural Insight Team (2012) Paper on Fraud, Error and Debt; Wenzel (2004).
66. Camerer et al. (2003).
67. Haynes et al. (2012).
68. As countries "approach the frontier" of innovation, it "becomes more important to have high-quality education": Crafts & O'Rourke (2014).
69. See the above discussion on patents in section B(ii).
70. Smits and Kuhlmann (2004).
71. Azoulay, Graff Zivin and Manso (2011); Editor (2009). Further, we note that principal/agent issues would be relevant to how much freedom is needed to foster innovation and how such a system would be managed. At the same time, it would be beneficial to find the right balance between the micro-management of innovators and total freedom.
72. Griliches (1992); Hall et al. (2009); Griffith et al. (2004).
73. European Council for Nuclear Research, see http://home.web.cern.ch/.
74. Mazzucato 2013.
75. Abbate (1999); National Research Council [US] (1999); Mazzucato (2013).
76. Motoyama et al. (2011). The US Government currently spends $1.8 billion across 13 state agencies on the National Nanotechnology Initiative: Mazzucato (2013); http://

nanodashboard.nano.gov/.

77. See Mazzucato (2013) chs 6-7.
78. However, its finance and powers are currently quite limited (technically it is a revolving fund, as it has no borrowing powers).
79. See Lovei (1998).
80. Bazilian et al. (2013).
81. The world's first BRT system was built in 1974, in Curitiba, Brazil, but it was Bogota's successful design that brought BRTs back into the transport departments of cities worldwide.
82. C40/Arup (2014).
83. EPIA (2013).
84. See Heck and Rogers (2014).
85. Lundvall (2010).
86. Lundvall (2005) suggests the evidence of what works is scarce and much of it is conflicting.

Abbate, J., 1999, "Inventing the Internet", Cambridge, MA.: MIT Press.

Agrawal, A. and Henderson, R., 2002, "Putting patents in context: exploring knowledge transfer from MIT", Management Science 48(1): 44–60.

Azoulay, P., Graff Zivin, J.S. and Manso, G., 2011, "Incentives and creativity: evidence from the academic life sciences", The RAND Journal of Economics, 42(3): 527-554.

Balconi, M., Brusoni, S. and Orsenigo, L., 2010, "In defence of the linear model: An essay", Research Policy, 39(1): 1-13.

Baumol, W.J., 2002, "The free-market innovation machine: Analyzing the growth miracle of capitalism", Princeton University Press.

Bazilian, M., Onyeji, I., Liebreich, M., MacGill, I., Chase, J., Shah, J., Gielen, D., Arent, D., Landfear, D. and Zhengrong, S., 2013, "Re-considering the economics of photovoltaic power", Renewable Energy, 53: 329–338.

Behavioural Insights Team, 2012, "Applying behavioural insights to reduce fraud, error and debt", Cabinet Office, British Government.

Bloom, N. and Van Reenen, J., 2006. "Measuring and Explaining Management Practices across Firms and Countries". London: Centre for Economic Performance.

Camerer, C., Issacharoff, S., Loewenstein, G., O'donoghue, T. and Rabin, M. (2003). "Regulation for Conservatives: Behavioral Economics and the Case for Asymmetric Paternalism", University of Pennsylvania Law Review, 151(3): 1211-1254.

Chang, H.J., 2008, "Kicking Away the Ladder: The Myth of Free Trade and the Secret History of Capitalism". New York: Bloomsbury.

Chen, W.R. and Miller, K.D., 2007, "Situational and institutional determinants of firms' R&D search intensity", Strategic Management Journal, 28(4): 369-381.

Chen, W.R., 2008, "Determinants of Firms' Backward- and Forward-Looking R&D Search Behavior", Organization Science, 19(4): 609-622.

Christensen, C.M., 1997, "The innovator's dilemma: when new technologies cause great firms to fail", Harvard Business School Press.

Coe, D.T. and Helpman, E., 1995, "International R&D Spillovers". European Economic Review, 39(5): 859-887.

Cohen, W.M., 2010, "Fifty Years of Empirical Studies of Innovative Activity and Performance" in B. H. Hall and N. Rosenberg (eds.), Handbook of the Economics of Innovation, Vol. 1, UK: Elseiver, Chapter 4.

Crafts, N. and Hughes, A., 2013, "Industrial policy for the medium to long-term", Future of Manufacturing Project: Evidence Paper 37, Government Office of Science, British Government.

Crafts, N. and O'Rourke, K., 2014, "Twentieth Century Growth" in S. N. Durlauf and P. Aghion (eds.), Handbook of Economic Growth, Vol. 2, UK: Elsevier, Chapter 6.

C40/Arup, 2014. "Climate Action in Megacities: C40 Cities Baseline and Opportunities Volume 2.0".

Dasgupta, P. and David, P.A., 1994, "Toward a new economics of science", Research policy, 23(5): 487-521.

Department for Business, Innovation & Skills (2014), "UK Growth Dashboard" https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/271485/Growth_Dashboard_January_2014.pdf.

Editor, 2009, "Is the UK still committed to basic biology research?", Nature Cell Biology 11(363).

European Photovoltaic Industry Association (EPIA), 2013, "Retrospective measures at national level and their impact on the photovoltaic sector".

Etzkowitz, H., 2003, "Research groups as 'quasi-firms': the invention of the entrepreneurial university", Research policy 32(1): 109-121.

European Commission, 2001, "Building an Innovative Economy in Europe: A Review of 12 Studies of Innovation Policy and Practice in Today's Europe", Brussels: European Commission.

Foray, D. and Lissoni, F., 2010, "University Research and Public-Private Interaction", in B. H. Hall and N. Rosenberg (eds.), Handbook of the Economics of Innovation, Vol. 1, UK: Elseiver, Chapter 6.

Freeman, C., 1995, "The 'National System of Innovation' in Historical Perspective", Cambridge Journal of Economics, 19(1): 5-24.

Frey, B., 1994, "How Intrinsic Motivation Is Crowded Out and In", Rationality and Society 6(3): 334-352.

Frey, B., 1997: "On the relationship between intrinsic and extrinsic work motivation", International Journal of Industrial Organisation, Vol. 15: 427-439.

Friedman, M., 1962, Capitalism and Freedom, Chicago: University of Chicago Press.

Fryer, R.G., 2010, "Financial incentives and student achievement: Evidence from randomized trials", NBER Working Paper No. w15898.

Fryer, R.G., 2011, "Teacher incentives and student achievement: Evidence from New York City public schools", NBER Working Paper No. w16850.

Galasso, A. and M. Schankerman, 2014, "Patents and Cumulative Innovation: Causal Evidence from the Courts", NBER Working Paper No. 20269.

Gallagher, K.S., Grübler, A., Kuhl, L., Nemet, G. and Wilson, C., 2012, "The Energy Technology Innovation System", Annual Review of Environmental Resources 37: 137–62.

Griffith, R., Redding, S. and Van Reenen, J., 2004, "Mapping the two faces of R&D: productivity growth in a panel of OECD industries", Review of Economics and Statistics 86(4): 883-895.

Griliches, Z., 1992, "The search for R&D spillovers", NBER Working Paper No. w3768.

Grossman, G. and Helpman, E., 1991, Innovation and Growth in the Global Economy. Cambridge, MA: MIT Press.

Hall, B.H., Mairesse, J. and Mohnen, P., 2009, "Measuring the Returns to R&D", National Bureau of Economic Research, Paper No. w15622.

Hall, B.H. and Rosenberg, N., 2010, "Introduction to the Handbook", Chapter 1 in Hall, B.H. and Rosenberg, N. (eds.), Handbook of the Economics of Innovation, Vol. 1, UK: Elseiver.

Haynes, L., Goldacre, B. and Torgerson, D., 2012, "Test, learn, adapt: developing public policy with randomised controlled trials", Cabinet Office, Behavioural Insights Team.

Heck, S. and Rogers, M., 2014, "Resource Revolution: How to capture the biggest business opportunity in a century", New York: Houghton Mifflin Harcourt.

Higgs, P., 2013, "Peter Higgs Nobel Lecture", Stockholm University, Nobel Media.

International Energy Agency (IEA), 2014, "Data Services Table".

Jaffe, A., Newell, R. and Stavins, R., 2005, "A tale of two market failures: Technology and environmental policy", Ecological Economics 54(2): 164-174.

Johnson, C., 1982, "MITI and the Japanese Miracle: The Growth of Industrial Policy 1925–1975", Stanford: Stanford University Press.

Johnson, E.J. and Goldstein, D.G., 2004, "Defaults and donation decisions", Transplantation, 78(12): 1713-1716.

Kahneman, D., 2011, "Thinking, Fast and Slow", London: Penguin.

Kahneman, D. and Tversky, A., 1979, "Prospect Theory", Econometrica 47(2): 263–291.

Klein Woolthuis, R., Lankhuizen, M. and Gilsing, V., 2005, "A system failure framework for innovation policy design", Technovation 25: 609–619.

Knight, F., 1921, "Risk, uncertainty and profit", New York: Hart, Schaffner and Marx.

Lange, F. and Topel, R., 2006, "The social value of education and human capital", Chapter 8 in Hanushek, E.A., Machin, S.J. and Woessmann, L. (eds.), 2011, Handbook of the Economics of Education (Vol. 4), Elsevier.

Lipsey, R.G., Carlaw, K.I. and Bekhar, C.T., 2005, "Economic Transformations: General Purpose Technologies and Long Term Economic Growth", Oxford: Oxford University Press.

Lovei, M., 1998, "Phasing out Lead from Gasoline: Worldwide Experience and Policy Implications", World Bank Technical Paper No. 397.

Lundvall, B.Å., 2010, "National systems of innovation: Toward a theory of innovation and interactive learning", Vol. 2, Anthem Press.

Lundvall, B.Å., 2007, "National innovation systems—analytical concept and development tool", Industry and innovation, 14(1): 95-119.

Lundvall, B.Å., 2005, "National Innovation Systems – Analytical Concept and Development Tool", DRUID Tenth Anniversary Summer Conference, Copenhagen, Denmark, June 27-29.

LSE Growth Commission, 2013, "Investing for Prosperity – Skills, Infrastructure and Innovation", London School of Economics and Political Science (LSE), London.

Mazzucato, M., 2013, "The Entrepreneurial State", London: Anthem Press.

Moretti, E., 2004, "Estimating the social return to higher education: evidence from longitudinal and repeated cross-sectional data", Journal of Econometrics, 121(1): 175-212.

Motoyama, Y., Applebaum, R. and Parker, R., 2011, "The National Nanotechnology Initiative: Federal Support for Science and Technology, or Hidden Industrial Policy?" Technology in Society 33(1–2): 109-118.

Mullainathan, S. and Shafir, E., 2013, "Scarcity: Why having too little means so much", MacMillan.

National Research Council [US], 1999, "Funding a Revolution: Government Support for Computing Research", Washington, DC: National Academies Press.

Nelson, R. and Winter, S., 1982, "An Evolutionary Theory of Economic Change, Cambridge", MA: Harvard University Press.

Nooteboom, B., 1999, "Innovation and inter-firm linkages: new implications for policy", Research Policy, 28(8): 793-805.

Organisation for Economic Cooperation and Development (OECD), 2014, "Main Science and Technology Indicators" Database, available at: http://stats.oecd.org/Index.aspx?DataSetCode=MSTI_PUB (accessed 10 September 2014).

Perez, C., 2010, "Technological revolutions and techno-economic paradigms", Cambridge Journal of Economics, 34: 185–202.

Philpott, K., Dooley, L., O'Reilly, C. and Lupton, G., 2011, "The entrepreneurial university: Examining the underlying academic tensions", Technovation 31(4): 161-170.

Ruttan, V., 2006, "Is War Necessary for Economic Growth? Military Procurement and Technology Development", New York: Oxford University Press.

Schilling, M.A. and Phelps, C.C., 2007, "Interfirm collaboration networks: The impact of large-scale network structure on firm innovation", Management Science, 53(7): 1113-1126.

Schumpeter, J.A., 1934, "The theory of economic development: An inquiry into profits, capital, credit, interest, and the business cycle", Transaction Publishers.

Solow, R., 1956, "A Contribution to the Theory of Economic Growth", Quarterly Journal of Economics, 70: 65-94.

Smits, R. & Kuhlmann, S., 2004, "The rise of systemic instruments in innovation policy", International Journal of Foresight and Innovation Policy, 1(1): 4-32.

Stern, N., 1989, "The Economics of Development: A Survey", Economic Journal, 99: 597-685.

Stoneman, P., 1995, "Introduction", in Stoneman, P. (ed.), Handbook of the Economics of Innovation and Technological Change, Oxford: Blackwell.

Swan, T., 1956, "Economic Growth and Capital Accumulation", Economic Record, 32: 334-361.

Thaler, R.H. and C. Sunstein, "Nudge: Improving Decisions about Health, Wealth and Happiness", US: Caravan.

Wenzel, M., 2004, "An analysis of norm processes in tax compliance", Journal of Economic Psychology, 25(2): 213-228.

Winston, C., 2006, "Government Failure Versus Market Failure: Microeconomics Policy Research and Government Performance", AEI-Brookings Joint Center for Regulatory Studies, Washington, DC.

Zimmer, M., 2009, "GFP: from jellyfish to the Nobel Prize and beyond", Chemical Society Reviews 38(10): 2823-2832.

Chapter 1 Case Study: Fukushima

1. Pravettoni, R. *Number of Disasters per Year* (UNEP/GRID-Arendal, 2012). Available at http://www.grida.no/graphicslib/detail/number-of-disasters-per-year_1408.
2. Yokoyama, J. Fukushima Disaster and Reform. Environmental Policy and Law 43, 226-227 (2013).
3. Ruff, T.A. A Public Health Perspective on the Fukushima Nuclear Disaster. Asian Perspective 37, 523-549 (2013); Eisler, R. The Fukushima 2011 Disaster 73-89 (London and New York, CRC Press, 2013).
4. For further discussion of the points summarized in this paragraph, see Yokoyama 2013: 226-233.
5. Srinivasan, T. N. and Gopi Rethinaraj, T.S. Fukushima and Thereafter: Reassessment of Risks of Nuclear Power. Energy Policy 52, 733-735 (2013); Thomas, S. What will the Fukushima disaster change? Energy Policy 45, 12-17 (2012); Kersten, J., Uekoetter, F. and Vogt, M., Europe After Fukushima: German Perspectives on the Future of Nuclear Power. RCC Perspectives 1 (2012).
6. McCurry, J. Naoto Kan Resigns as Japan's Prime Minister. The Guardian 26 August 2011. Available at http://www.theguardian.com/world/2011/aug/26/naoto-kan-resigns-japan-pm

Chapter 2: Future Global Trends in Innovation

1. Goldin, I. and Mariathasan, M. (2014) *The Butterfly Defect: How Globalization Creates Systemic Risks, and What to Do about It*, Princeton: Princeton University Press, Chapter 7.
2. US National Science Foundation (2012) 'Science and Engineering Beyond Moore's Law'; see also author's discussions with the Future of Computing Programme in the Oxford Martin School, University of Oxford. Gordon Moore did not suggest that the trend would continue over decades, and would have been surprised by the longevity of his predictions.
3. Manyika, J. et al. (2013) 'Disruptive Technologies: Advances that Will Transform Life, Business, and the Global Economy', *McKinsey Global Institute*.
4. Ibid., p. 29.
5. UN (2013) 'Deputy UN Chief Calls for Urgent Action to Tackle Global Sanitation Crisis', *UN News Centre*.
6. Simons, B. (2012) 'Africa's True Mobile Revolution Has Yet to Start', Harvard Business Review Blog Network.
7. The Economist (2012) 'The Bank of SMS', quoting a survey conducted by the Gates Foundation, the World Bank and Gallup.
8. International Data Corporation (2010) 'ICT Outlook: Recovering into a New World'.
9. Markoff, J. (2012) 'Skilled Work, Without the Worker', *The New York Times*.
10. Manyika, J. et al. (2013).
11. Frey, C and Osborne, M. (2014) 'The Future of Employment: How susceptible are jobs to computerisation?' *Oxford Martin School Working Paper*.
12. Morse, E. et al. (2012) 'Energy 2020: North America, the New Middle East?' Citi GPS.
13. WTO (2008) 'World Trade Report 2008: Trade in a Globalizing World', p. 15.
14. UNCTAD (2012) 'Twenty years of India's Liberalization: Experiences and Lessons'.
15. See Oxford Martin School (2013) 'Now for the Long Term', Oxford Martin Commission for Future Generations.
16. The GAVI Alliance. 'Disbursement by Country', available at http://www.gavialliance.org/results/disbursements/ (last accessed 22 June 2014); The Global Fund, 'One Million Lives are Saved Every Year', available at http://onemillion.theglobalfund.org/pages/mission (last accessed 22 June 2014).
17. Ernst and Young (2011) 'Tracking Global Trends: How Six Key Developments are Shaping the Business World'.
18. ILO (2010) 'International Labour Migration: A Rights-Based Approach', p. 15.
19. UNFPA (2007) "Urbanization: A Majority in Cities", http://www.unfpa.org/pds/urbanization.htm (accessed 22 June 2014).
20. Goldin, I., Cameron, G. and Balarajan, M. (2011) *Exceptional People: How Migration Shaped Our World and Will Define Our Future*, Princeton: Princeton University Press, pp. 165-6.
21. Ortega, F. and Peri, G. (2009) 'The causes and effects of international migrations: evidence from OECD countries 1980-2005', *NBER Working Paper No. 14833*.
22. Citi Research (2013) 'Is Immigration the Antidote to Ageing Demographics in the Advanced Economies?'
23. Goldin, I. et al. (2011), p. 168.
24. Kerr, W. and Lincoln, W. (2010) 'The Supply Side of Innovation: H-1B Visa Reforms and U.S. Ethnic Invention', *Journal of Labor Economics* 28, no. 3.
25. UNESCO (2012) 'Youth and Skills: Putting Education to Work', *EFA Global Monitoring Report*, p. 8.
26. World Bank (2013) 'The State of Education', available at http://datatopics.worldbank.org/education/wStateEdu/StateEducation.aspx (last accessed 20 June 2014).
27. Ibid.
28. Gibney, E. (2013) 'A different world', *The Times Higher Education*.
29. OECD (2013) 'How many students study abroad and where do they go?' *Education at a Glance 2013: Highlights*.
30. Kasprowicz, P. and Rhyne, E. (2013) 'Looking Through the Demographic Window: Implications for Financial Inclusion', Centre for the Study of Financial Inclusion, Publication 18.
31. Wuestner, C. (2012) 'BMW Finds New Ways to Improve Productivity with Aging Workforce', *Bloomberg*.
32. Pricewaterhouse Coopers (2010) 'New Release: Shift in World Economic Power means a decade of seismic change'.
33. This section draws on Goldin, I. and Mariathasan, M. (2014) *The Butterfly Defect: How Globalization Creates Systemic Risks, and What to Do about It*, Princeton: Princeton University Press.
34. Ibid.
35. Dattels, P. and Kodres, L. (2009) 'Further Action Needed to Reinforce Signs of Market Recovery: IMF', *IMF Survey Magazine: IMF Research*.
36. Oxford Economics (2010) 'The Economic Impacts of Air Travel Restrictions Due to Volcanic Ash'.
37. Ibid., p. 2.
38. Davis, J. (2007) 'Hackers Take Down the Most Wired Country in Europe', *Wired Magazine* 15, no. 9.
39. Belson, K. (2008) "03 Blackout Is Recalled, Amid Lessons Learned', *The New York Times*.
40. Korea Net (2013) 'Overview', available at http://www.korea.net/AboutKorea/Economy/Overview (last accessed 22 June 2014).

41. Vanichkorn, S. and Banchongduang, S. (2011) 'Rehabilitation to cost B755bn', *Bankok Post.*
42. Fleck, F. (2003) 'How SARS Changed the World in Less than Six Months', *Bulletin of the World Health Organization* 81, no. 8, p. 626.
43. Ibid.
44. Goldin, I. and Winters, L. (eds.) (1992) *The Economics of Sustainable Development*, Cambridge, UK: Cambridge University Press.
45. Kilpatrick, A. (2011) 'Globalization, Land Use, and the Invasion of West Nile Virus', *Science* 334, no. 6054; Lounibos, L. (2001) 'Invasions by Insect: Vectors of Human Disease', *Annual Review of Entomology* 47.
46. The Economist (2012) 'The Euro Crisis: An Ever-Deeper Democratic Deficit'.

Chapter 2 Case Study: Communicating the risk of climate change

1. Moser, S. C. and Dilling, L., *Environment* **46**, 36 (2004).
2. Lowe, T. *et al. Public Understanding of Science* **15**, 451 (2006).
3. Ereaut, G. and Segnit, N. *Warm Words: How are we telling the climate story and can we tell it better?* (Institute for Public Policy Research, London, 2006).
4. Tversky, A. and Kahneman, D. *Cognitive Psychology* **5**, 207–233 (1973).
5. Slovic, P. *The Feeling of Risk: New Perspectives on Risk Perception* (Earthscan, London, 2010).
6. Lyons, J. *Documentary, Performance and Risk* (Routledge, London, forthcoming).

Chapter 2 Case Study: Risk and Innovation in Developing Countries: A new approach to governing GM crops

1. https://www.dur.ac.uk/ihrr/gmfuturos/
2. Baulcombe, D. et al. *Reaping the Benefits: Science and the Sustainable Intensification of Global Agriculture* (Royal Society, 2009). Available at https://royalsociety.org/policy/publications/2009/reaping-benefits/
3. Macnaghten, P., Carro-Ripalda, S. and Burity, J. (eds.) *A New Approach to Governing GM Crops: Global Lessons from the Rising Powers* (Durham University Working Paper, 2014). Available at https://www.dur.ac.uk/resources/ihrr/GMFuturosWorkingPaper.pdf
4. Macnaghten, P. and Carro-Ripalda, S. (eds.) *Governing GM crops: Lessons from the Global South for Agricultural Sustainability* (Routledge, 2015 forthcoming)
5. Hajer, M. *Authoritative Governance: Policy Making in the Age of Mediatization* (Oxford Univ. Press, 2009).
6. Hajer, M. Policy without polity: Policy analysis and the institutional void. *Policy Sciences* **36**, 175-195 (2003).
7. Stilgoe, J., Owen, R. and Macnaghten, P. Developing a framework for responsible innovation. *Research Policy* **42**, 1568–1580 (2013). Available at http://dx.doi.org/10.1016/j.respol.2013.05.008
8. Owen, R. *Responsible Innovation Framework: Scoping Study and Science – Policy Seminar* (ESRC Impact Report, RES-077-26-0001). Available at http://www.esrc.ac.uk/my-esrc/grants/RES-077-26-0001/outputs/read/fe4e127b-5d99-41e0-bae8-376640ba5575
9. *Framework for Responsible Innovation* (EPSRC, 2014). Available at http://www.epsrc.ac.uk/research/framework/

Chapter 3: A Recent Chronology of Public Risk Management in Government

1. Adams J (1995) *Risk*, UCL Press, London, 228pp.
2. Health and Safety Executive (2001) *Reducing Risks, Protecting People,* HSE Books, Suffolk; available at: http://www.hse.gov.uk/risk/theory/r2p2.pdf
3. United Kingdom Offshore Operators Association (1999) *Industry Guidelines on a Framework for Risk Related Decision Support*; UKOOA, London, UK
4. Royal Commission of Environmental Pollution (1998) 21st Report: Setting Environmental Standards, Cm 4053, HMSO, London.
5. Strategy Unit (2002) *Risk: Improving Government's capability to handle risk and uncertainty*, The Strategy Unit, London, 134pp available at: http://webarchive.nationalarchives.gov.uk/+/http:/www.cabinetoffice.gov.uk/media/cabinetoffice/strategy/assets/su%20risk%20summary.pdf
6. Pollard, S.J.T., Yearsley, R., Reynard, N., Meadowcroft, I.C., Duarte-Davidson, R. and Duerden, S. (2002) Current directions in the practice of environmental risk assessment in the United Kingdom, *Environ. Sci. Technol.* 36(4):530-538
7. Rothstein, H., Irving, P., Walden, T. and Yearsley, R. (2006) The risks of risk-based regulation: insights from the environmental policy domain, *Environment International* 32: 1056-1065.
8. Risk and Regulation Advisory Council (2009) *Response with responsibility. Policy-making for public risk in the 21st century*, Report URN 09/948, London, UK, 40pp. available at: http://www.mbsportal.bl.uk/secure/subjareas/mgmt/bis/128466file51459.pdf
9. Beddington, J. (2013) Addressing the challenges of the 21st century. *FST Journal* 2013: 21: 4-7.
10. Department of Environment, Transport and the Regions (1998) *Policy Appraisal and the Environment,* Her Majesty's Stationery Office, London.
11. Parliamentary Office of Science and Technology (1996) *Safety in Numbers? Risk Assessment in Environmental Protection*, POST, London available at: http://www.parliament.uk/business/publications/research/briefing-papers/POST-PN-81/safety-in-numbers
12. OXERA (2000) *Policy, risk and science: Securing and using scientific advice*. Research Report 295/2000, HSE Books, Sudbury available at: http://www.hse.gov.uk/research/crr_pdf/2000/crr00295.pdf
13. The Royal Society (1992) *Risk: analysis, perception and management*. Report of a Royal Society Study Group, The Royal Society, London, 201pp.
14. Slovic, P. (1993) Perceived risk, trust, and democracy, *Risk Analysis* 13: 675-682.
15. Fischer, F. (1993) The greening of risk assessment, in D. Smith (ed.) *Business and the environment,* London, PCP, pp.98-115.
16. Department of Environment, Transport and the Regions and the Environment Agency (2000) *Guidelines for environmental risk assessment and management, Revised Guidance*, DETR, EA and Institute of Environmental Health, The Stationery Office, London, 88pp.
17. The Cabinet Office (1999) *Modernizing Government*, Cm 4310, Her Majesty's Stationery Office, London.
18. Department of Trade and Industry (1998) *The Use of Scientific Advice in Policy Making*, London.
19. House of Lords, Select Committee on Economic Affairs (2006) *5th Report. Government policy of the management of risk, Volume 1*, HL 183-I, The Stationery Office, London, 40pp
20. House of Commons. Science and Technology Committee (2011) *Scientific advice and evidence in emergencies*. Third report of session 2010-2011, HC498, The Stationery Office, London, UK, 88pp.
21. Interdepartmental Liaison Group on Risk Assessment (1998) *Risk Assessment and Risk Management: Improving Policy and Practice within Government Departments*; HSE Books, Sudbury, Suffolk, available at: http://www.hse.gov.uk/aboutus/meetings/committees/ilgra/minrpt2.htm
22. House of Commons (2000) *The BSE enquiry, Volume 1: findings and conclusions*, The Stationery Office: London
23. Department of the Environment (1995) *A guide to risk assessment and risk management for environmental protection*, HMSO, London, 92pp
24. Interdepartmental Liaison Group on Risk Assessment (2002) *The precautionary principle: policy and application* accessed at http://www.hse.gov.uk/aboutus/meetings/committees/ilgra/index.htm
25. *Orange Book: Management of Risk – Principles and Concepts* (HM Treasury, London, 2004). Available at https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/220647/orange_book.pdf
26. Department for Environment, Food and Rural Affairs (2002) *Risk management strategy*, Department for Environment, Food and Rural Affairs, London.
27. Department for Environment, Food and Rural Affairs (2011) *Guidelines for environmental risk assessment and management. Green leaves III. Revised Departmental guidance*. Cranfield University and Department for Environment, Food and Rural Affairs, PB13670, London, UK, 79pp. available at: https://www.gov.uk/government/publications/guidelines-for-environmental-risk-assessment-and-management-green-leaves-iii
28. Her Majesty's Inspectorate of Pollution (1995) *Operator and Pollution Risk Appraisal*, HMIP, London, 22pp
29. Her Majesty's Inspectorate of Pollution (1995) *The application of risk assessment and risk management to integrated pollution control*, Centre for Integrated Environmental Risk Assessment, HMIP, London, 59pp.
30. Environment Agency (1997) *Operator and Pollution Risk Appraisal. Version 2*, Environment Agency, Bristol, 34pp
31. European Commission (2009) *Third Strategic Review of Better Regulation in the European Union, European Commission communication*, COM(2009)15, 28 January.
32. European Commission (1998) *IMPEL Report: Minimum criteria for inspections – frequency of inspections* IMPEL Network, Brussels.
33. OECD (2005) *Guiding Principles for Regulatory Quality and Performance*, Organisation for Economic Cooperation and Development,

Paris available at: http://www.oecd.org/fr/reformereg/34976533.pdf
34. Confederation of British Industry (1998) *Worth the risk: improving environmental regulation*, CBI, London, 23pp
35. Risk and Regulation Advisory Council (2009) *Tackling public risk: a practical guide for policy makers*. Risk & Regulation Advisory Council, London available at: http://webarchive.nationalarchives.gov.uk/20100104183913/http:/www.berr.gov.uk/deliverypartners/list/rrac/index.html
36. Hampton, P. (2005) *Reducing administrative burdens: effective inspection and enforcement*, HM Treasury, 147pp
37. National Audit Office and Better Regulation Executive (2007) *Hampton implementation reviews: Guidance for review teams*, NAO and BRE, London, 30pp
38. Dahlström, K., Howes, C., Leinster, P. and Skea, J. (2003) Environmental management systems and company performance: assessing the case for extending risk-based regulation *European Environment* 13(4): 187-203.
39. Gunningham, N. and Grabosky, P. (2009) *Smart regulation: designing environmental policy*, Clarendon Press
40. Gouldson, A. (2004) Cooperation and the capacity for control: regulatory styles and evolving influences of environmental regulation in the UK, *Environment and Planning C*, 22: 583-603.
41. Foot, J. (2009) *Citizen involvement in local governance: summary*, Joseph Rowntree Foundation, York, UK, 20pp.
42. Lyons, M. (2007) *Lyons Enquiry into Local Government. Place shaping: a shared ambition for the future of local government*, The Stationery Office, accessed at https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/229035/9780119898552.pdf
43. Sparrow, M.K (2008). *The character of harms. Operational challenges in control*. Cambridge University Press. Cambridge, UK, 264pp.
44. Pollard, S.J.T., Kemp, R.V., Crawford, M. Duarte-Davidson, R. Irwin, J.G. and Yearsley, R. (2004) Characterising environmental harm: developments in an approach to strategic risk assessment and risk management, *Risk Analysis* 24(6): 1551-1560
45. Klinke, A.; Renn, O. (2002) A new approach to risk evaluation and management: Risk based, precaution based, and discourse based strategies. *Risk Analysis*: 22: 1071-1094.
46. Cabinet Office (2010) *National risk register of civil emergencies*. Cabinet Office, London, UK; 2010. Available at: http://www.cabinetoffice.gov.uk/media/348986/nationalriskregister-2010.pdf.
47. Cabinet Office (2012) *National risk register of civil emergencies*. Cabinet Office, London, UK; 2012. Available at: https://www.gov.uk/government/publications/national-risk-register-of-civil-emergencies
48. World Economic Forum. *Global risks 2011 6th edition. An initiative of the risk response network*. A World Economic Forum Report, Switzerland, 56pp; 2011; available at http://riskreport.weforum.org/
49. Prpich, G., Evans, J., Irving, P., Dagonneau, J., Hutchinson, J., Rocks, S., Black, E. and Pollard, S.J.T. Character of environmental harms – overcoming implementation challenges with policy makers and regulators. *Environ. Sci. Technol.* 2011: 45; 9857-9865.
50. Ernst and Young (2010) *The Ernst & Young business risk report. The top 10 risks for business. A sector wide view of the risks facing business across the globe*, Ernst & Young Global Limited, London, 45pp.
51. Lloyds (2013) *Realistic disaster scenarios. Scenario specification v1.0 – 7th January 2013*, Lloyds, London, UK, 55pp.
52. Government Office for Science (2011) *Blackett review of high impact low probability risks*, Government Office for Science, Department for Business, Innovation and Skills, London, 45pp.
53. Economist Intelligence Unit (2011) *The long view. Getting new perspective on strategic risk*, The Economist Intelligence Unit Ltd., London, UK, 35pp.
54. International Risk Governance Council (2011). *Improving the management of emerging risks. Risks from new technologies, system interactions, and unforeseen or changing circumstances*. IRGC, Geneva, Switzerland, 43pp.

Chapter 3 Case Study: Consistency and Transparency in Evidence-Based Regulation: Risk and precaution in the regulation of bisphenol A

1. European Food Safety Authority *Public consultation on the draft opinion on bisphenol A (BPA) – Assessment of human health risks* (2014). Available at http://www.efsa.europa.eu/en/consultationsclosed/call/140117.htm
2. Committee on Toxicity of Chemicals in Food, Consumer Products and the Environment *COT responds to EFSA consultation on BPA* (2014). Available at http://www.food.gov.uk/news-updates/news/2014/5994/cot-response (for minutes of relevant meetings, see also http://cot.food.gov.uk/sites/default/files/cot/finlmin4feb14.pdf and http://cot.food.gov.uk/sites/default/files/cot/finlmin18314.pdf).
3. Food Standards Agency *Bisphenol-A (BPA)* (2014). Available at food.gov.uk/science/bpa/
4. European Commission *Communication from the Commission on the precautionary principle* (2000). Available at http://ec.europa.eu/dgs/health_consumer/library/pub/pub07_en.pdf
5. Food Standards Agency *Report on the transparent use of risk assessment in decision making* (2012). Available at http://www.food.gov.uk/science/sci-gov/decision-making

Section 1 High Level Case Study: Synthetic Biology

1. Royal Academy of Engineering *Synthetic Biology: scope, applications and implications* (2009). Available at http://www.raeng.org.uk/publications/reports/synthetic-biology-report
2. UK Synthetic Biology Roadmap Coordination Group *A Synthetic Biology Roadmap for the UK* (Technology Strategy Board, 2012). Available at http://www.rcuk.ac.uk/publications/reports/syntheticbiologyroadmap/
3. Scientific Committee on Health and Environmental Risks, Scientific Committee on Emerging and Newly Identified Health Risks and Scientific Committee on Consumer Safety *Opinion on Synthetic Biology I: Definition* (European Commission, 2014). Available at http://ec.europa.eu/health/scientific_committees/emerging/docs/scenihr_o_044.pdf
4. *Synthetic Biology Dialogue* (2010). Available at http://www.bbsrc.ac.uk/web/FILES/Reviews/1006-synthetic-biology-dialogue.pdf
5. International Genetically Engineered Machine competition: http://igem.org

Chapter 4: Making Choices In The Face Of Uncertainty: Strengthening Innovation Democracy

1. Economics BIS, No P. *Innovation and Research: Strategy for Growth*. London; 2011.
2. OECD. *The OECD Innovation Strategy: getting a head start on tomorrow*. Paris: OECD
3. Foresight_Horizon_Scanning_Centre. *Technology and Innovation Futures : UK Growth Opportunities for the 2020s*. London; 2012.
4. NESTA. *The Innovation Gap Why policy needs to reflect the reality of innovation in the UK*. London; 2006.
5. Murray R, Caulier-grice J, Mulgan G. *Social Venturing*. London
6. TSB. *Concept to Commercialisation: a srategy for business innovation, 2011-2015*. London; 2011:2011–2015.
7. Smith A, Fressoli M, Thomas H. Grassroots innovation movements: challenges and contributions. *J Clean Prod*. 2013:1–11. doi:10.1016/j.jclepro.2012.12.025.
8. Bound K, Thornton I. *Our Frugal Future: lessons from India's Innovation System*. London; 2012:1–94.
9. ERAB. *The new Renaissance: will it happen? Innovating Europe out of the crisis*. Brussels: Commission of the European Communities; 2012.
10. Malhotra A, Schulte J, Patel P, Petesch P. *Innovation: for Women's Empowerment and Gender Equality*. Washington DC; 2009.
11. CEC. *Reaping the benefits of globalization: European Competitiveness Report 2012*. Brussels; 2012.
12. Harris M, Albury D. *The Innovation Imperative: why radical innovation is needed to reinvent public services for the recession and beyond*. London; 2009.
13. Tenner E. *Why Things Bite Back: technology and the revenge of unintended consequences*. New York: Vintage; 1999.
14. BIS. Innovation is Great... Britain. Available at: http://i.telegraph.co.uk/multimedia/archive/02004/great-innovation_2004849i.jpg.
15. Malerba F, Brusoni S, eds. *Perspectives on Innovation*. Cambridge: Cambridge Univ Press; 2007.
16. CEC. *Gearing European Research towards Sustainability: RD4SD Exercise*. Brussels; 2009.
17. Lightman A, Sarewitz D, Desser C, eds. *Living with the Genie: essays on technology and the quest for human mastery*. Washington DC: Island Press; 2003.
18. Steward F. *Breaking the boundaries: transformative innovation for the global good*. London; 2008:12–3.
19. Scrase I, Stirling A, Geels F, Smith A, Zwanenberg P Van. *Transformative Innovation*. London; 2009:1–67.
20. WBCSD. *Vision 2050*. Geneva; 2010.
21. Stirling A. *Emancipating Transformations: from controlling "the transition" to culturing to culturing plural radical progress*. Brighton; 2014.

22. OECD. *Dynamising National Innovation Systems*. Paris: OECD Publishing; 2002. doi:10.1787/9789264194465-en.
23. OECD. *Governance of Innovation Systems – Volume 1: synthesis report*. Paris; 2005.
24. *Who Owns Science? The Manchester Manifesto*. Manchester; 2010.
25. Wyatt S, Henwood F, Lecturer S, Miller N, Senker P, eds. *Technology and In/equality: questioning the information society*.
26. STEPS. *Innovation, Sustainability, Development: a new manifesto*. Brighton; 2010.
27. IRGC. *Risk governance: towards an integrative approach*. Geneva; 2006. doi:10.1515/9783110285161.219.
28. OECD. *Main Science and Technology Indicators*.; 2013:1–30.
29. Alic JA. *Trillions for Military Technology: how the Pentagon innovates and why it costs so much*. New York: Palgrave MacMillan; 2007.
30. Parkinson S, Pace B, Webber P. *Offensive Insecurity: The role of science and technology in UK security strategies*. London: Scientists for Global Responsibility; 2013.
31. Kaldor M. *Human Security: Reflections on Globalization and Intervention*. Cambridge: Polity Press; 2007.
32. Alic J. *Energy Innovation From the Bottom Up*.; 2009.
33. Popp D, Newell RG. *Where Does Energy R&D Come From? Examining Crowding Out from Environmental friendly R&D*. Cambridge Mass; 2009.
34. WHO. *The 10 / 90 Report on Health Research*. Geneva: World Health Organisation; 2002.
35. Miller P, Wilsdon J, eds. *Better Humans: the politics of human enhancement and life extension*. London: Demos
36. Nuffield_Council. *Emerging biotechnologies: technology, choice and the public good*.; 2012.
37. *Neuroscience, society and policy*. London: The Royal Society; 2011:viii, 64 p.
38. Hall B, Rosenberg N, eds. *Economics of Innovation – Volume I*.; 2010.
39. Mazzucato M. *The Entrepreneurial State: debunking public vs private sector myths*. London: Anthem Press; 2013.
40. Owen R, Bessant J, Heintz M, eds. *Responsible Innovation: managing the responsible emergence of science and innovation in society*. Chichester: Wiley; 2013.
41. Jackson T. *Prosperity without growth ?*
42. Cable V. *Oral statement to Parliament: Innovate 2011*. London; 2011:1–3.
43. Scrase JI, Smith A, Kern F. *Dynamics and deliberations: comparing heuristics for low carbon innovation policy*. Brighton; 2010:1–42.
44. Scrase I, MacKerron G, eds. *Energy for the Future: A New Agenda*. London: Palgrave Macmillan; 2009.
45. Renn O. *Risk Governance: coping with uncertainty in a complex world*. London: Earthscan; 2008.
46. NESTA. Compendium of Evidence on Innovation Policy. 2011. Available at: http://www.innovation-policy.net/compendium/.
47. Broers A. *The Triumph of Technology*. Cambridge: Cambridge Univ. Press; 2005.
48. Dosi G. *Innovation, Organization and Economic Dynamics – Selected Essays*. Cheltenham: Edward Elgar; 2000.
49. Nelson R, Winter S. *An Evolutionary Theory of Economics Change*. Cambridge MASS: Harvard University Press; 1982.
50. Arthur WB. *The Nature of Technology: What It Is and How It Evolves*. London: Penguin; 2009.
51. Frenken K. The early development of the steam engine: an evolutionary interpretation using complexity theory. *Ind Corp Chang*. 2004;13(2):419–450. doi:10.1093/icc/dth017.
52. Saviotti PP, Frenken K. Export variety and the economic performance of countries. *J Evol Econ*. 2008;18(2):201–218. doi:10.1007/s00191-007-0081-5.
53. Frenken K, Saviotti PP, Trommetter M. Variety and niche creation in aircraft, helicopters, motorcycles and microcomputers. *Res Policy*. 1999;28(5):469–488.
54. Stirling A. A general framework for analysing diversity in science, technology and society. *J R Soc Interface*. 2007;4(15):707–19. doi:10.1098/rsif.2007.0213.
55. Page SE. *The Difference: how the power of diversity creates better groups, firms, schools and societies*. Princeton: Princeton University Press; 2007.
56. Stirling A. From Enlightenment to Enablement: Opening up Choices for Innovation. In: Lopez-Claros A, ed. *The Innovation for Development Report*. Basingstoke: Palgrave Macmillan; 2010:199–210.
57. EEA. *Late lessons from early warnings: science, precaution, innovation*.; 2013.
58. Gee D, Vaz SG, Agency EE. *Late lessons from early warnings: the precautionary principle 1896-2000*.; 2000:1–211.
59. RS, RAEng. *Shale gas extraction in the UK: a review of hydraulic fracturing*. London; 2012.
60. Royal_Society. *Nanoscience and nanotechnologies: opportunities and uncertainties*. London; 2004.
61. Kearnes M, Rip A. The Emerging Governance Landscape of Nanotechnology. In: Gammel S, Lösch A, Nordmann A, eds. Akademisch. Berlin; 2009:1–35.
62. Schiller PL, Bruun EC, Kenworthy JR. *An Introduction to Sustainable Transportation: policy, planning and implementation*. London: Earthscan; 2010.
63. North P. *A Human Security Doctrine for Europe: the Barcelona report of the tudy group on Europe's security capabilities – Presented to EU High Representative for Common Foreign and Security Policy Javier Solana*. Barcelona; 2004.
64. Stirling A. Pluralising progress: From integrative transitions to transformative diversity. *Environ Innov Soc Transitions*. 2011;1(1):82–88. doi:10.1016/j.eist.2011.03.005.
65. Stirling A. Keep it complex. *Nature*. 2010;468:1029–1031.
66. Stirling A. Limits to the Value of External Costs. *Energy Policy*. 1997;25(5):517–540.
67. Amendola A. Recent paradigms for risk informed decision making. 2001;40:17–30.
68. Haskel, Lord, Warner, Lord. *Setting priorities for publicly funded reseach – Volume I: Report*. London; 2010.
69. Antonelli C, Foray D, Hall BH, Steinmueller WE, eds. *New Frontiers in the Economics of Innovation and New Technology: essays in honour of Paul A. David*. Cheltenham: Edward Elgar; 2006.
70. Liebowitz SJ, Margolis SE. The Fable of the Keys. *J Law Econ*. 1990;(October).
71. David PA. Clio and the Economics of QWERTY. *Econ Hist*. 1985;75(2):332–337.
72. David PA. *Path Dependency and the Quest for Historical Economics: one more chorus of the ballad of QWERTY*. Oxford; 1997.
73. Amell TK, Kumar S. Cumulative trauma disorders and keyboarding work. 1999;25.
74. Noyes JAN. The QWERTY keyboard: a review. *Int J Man Mach Stud*. 1983;18:265–281.
75. Wilsdon J, Willis R, Demos. *See-through science : why public engagement needs to move upstream*. London: Demos; 2004:69 p. ; 20 cm.
76. Collingridge D. *Critical Decision Making: a new theory of social choice*. London: Frances Pinter; 1982.
77. Collingridge D. *The Social Control of Technology*. M. Keynes: Open University Pres; 1980.
78. Shaxson L, Harrison M, Morgan M. *Developing an evidence-based approach to environmental policy making : insights from Defra's Evidence & Innovation Strategy.* Brighton; 2009:1–33.
79. Wynne B. Public engagement as a means of restoring public trust in science—Hitting the notes, but missing the music? *Community Genet*. 2006;9:211–220.
80. Wynne B. Risk and Environment as Legitimatory Discourses of. *Curr Sociol*. 2002;50(May):459–477.
81. Wilsdon J, Wynne B, Stilgoe J. *The Public Value of Science: or how to ensure that science really matters*. London; 2005.
82. Pollock N, Williams R. The business of expectations: How promissory organizations shape technology and innovation. *Soc Stud Sci*. 2010;40(4):525–548. doi:10.1177/0306312710362275.
83. Van Lente H. Navigating foresight in a sea of expectations: lessons from the sociology of expectations. *Technol Anal Strateg Manag*. 2012;24(8):769–782. doi:10.1080/09537325.2012.715478.
84. David PA, Rothwell GS. "Standardisation, Diversity and Learning: strategies for the coevolution of technology and industrial capacity." 1996.
85. Chesbrough H, Vanhaverbeke W, West J, eds. *Open Innovation: researching a new paradigm*. Oxford: Oxford Univ Press; 2006.
86. Blind K. The Impact of Standardization and Standards on Innovation. 2013;(February):1–33.
87. Hughes T. *Networks of Power: electrification in western society 1880-1930*. Baltimore: Johns Hopkins University Press; 1983.
88. Chou C, Shy O. The crowding-out effects of long duration of patents. 2013;24(2):304–312.
89. Hilgartner S. Intellectual Property and the Politics of Emerging Technology: inventors, citizens, and powers to shape the future. *Chic Kent Law Rev*. 2009;81(1):197–224.
90. Porte TR La, ed. *Social Responses to Large Technical Systems: Control or Anticipation*. Dordrecht: Springer; 1991.
91. Kaplinsky R. Globalisation and Unequalisation: What Can Be Learned from Value Chain Analysis? *J Dev Stud*. 2000;37(2):117–146. doi:10.1080/713600071.
92. Winner L. *Autonomous Technology: technics out of control as a theme in political thought*. Camb MASS: MIT Press; 1977.
93. Sabatier P. Social Movements and Regulatory Agencies : Toward a More Adequate and Less

Pessimistic Theory of " Clientele Capture "*. 1975;6:301–342.
94. Walker W. Entrapment in large technology systems: institutional commitment and power relations. *Res Policy*. 2000;29(7-8):833–846. doi:10.1016/S0048-7333(00)00108-6.
95. Arthur WB. "Competing Technologies, Increasing Returns, and Lock-in by Historical Events." 1989.
96. Goldacre B. *Bad Science*. London: Harper; 2009.
97. Rowell A. *Green Backlash: Global Subversion of the Environment Movement*. London: Routledge; 1996.
98. Laufer WS. Social Accountability and Corporate Greenwashing. *J Bus Ethics*. 2003;43(Iso 2002):253–261.
99. Krimsky S. *Science in the Private Interest: has the lure of profits corrupted biomedical research*. Oxford: Rowman and Littlefield; 2003.
100. Newman P, Kenworthy J, eds. *Cities and Automobile Dependence, an International Sourcebook*. Aldershot: Gower; 1989.
101. Oreskes N, Conway- EM. *Merchants of doubt: how a handful of scientists obscured the truth on issues from tobacco smoke to global warming*. London: Bloomsbury; 2010.
102. Scrase I, MacKerron G. *Energy for the Future: A New Agenda*. Palgrave Macmillan; 2009.
103. OORWM. *Managing our radioactive wastes safely: CoRWM's recommendations to Government*. London; 2006.
104. Sally C Davies. *Infections and the rise of antimicrobial resistance – Annual Report of the Chief Medical Officer, Volume II*. London; 2011.
105. Stirling A. "Opening Up" and "Closing Down": Power, Participation, and Pluralism in the Social Appraisal of Technology. *Sci Technol Hum Values*. 2008;23(2):262–294.
106. Baulcombe D, Crute I, Davies B, et al. *Reaping the benefits: science and the sustainable intensification of global agriculture*. London: Royal Society; 2009:72p. : illus.
107. BIS. *The Future of Food and Farming: challenges and choices for global sustainability*. London; 2011.
108. IAASTD. *Agriculture at a Crossroads: international assessment of agricultural knowledge science and technology for development (IAASTD)*. Washington: Island Press; 2009.
109. Pretty J. *Agri-Culture: reconnecting people, land and nature*. London: Earthscan; 2002.
110. Wright O. Opponents of third world GM crops are "wicked", says Environment Secretary Owen. *Guardian*. 2013;(October):1–10.
111. HoC. *GM foods and application of the precautionary principle in Europe*. London; 2014:1–7.
112. Poltronieri P, Reca IB. Transgenic, Cisgenic and Novel Plant Products, Regulation and Safety Assessment. In: Poltronieri P, Hong Y, eds. *Applied Plant Genomics and Biotechnology*. Cambridge: Elsevier Woodhead; 2014.
113. Watts S. Genetic moderation is needed to debate our food future. *New Sci*. 2014;(July):8–10.
114. POST. *GM in Agricultural Development*.; 2012:1–4.
115. IRRI. *Scuba rice : breeding flood-tolerance into Asia ' s local mega rice varieties*. Manila; 2009:1–6.
116. Jansen K, Vellema S, eds. *Agribusiness and Society: corporate responses to environmentalism, market opportunities and public recognition*. London: Zed Books
117. Benbrook CM. Impacts of genetically engineered crops on pesticide use in the US – the first sixteen years. *Environ Sci Eur*. 2012;24:1–13.
118. Palombi L. *Gene Cartels: biotech patents in the age of free trade*. Cheltenham: Edward Elgar Publishing; 2009. doi:10.4337/9781848447431.
119. GMSRP. *GM Science Review Panel Minutes, 24 June 2003*. London; 2003:1–4.
120. FAO. *Save and Grow: a policymaker's guide to the sustainable intensification of smallholder crop production*. Rome: UN Food and Agriculture Organisation; 2011.
121. Leeuwisen C. *Communication for Rural Innovation Rethinking Agricultural Extension*. Oxford: Blackwell; 2004.
122. Lockie S, Carpenter D, eds. *Agriculture, Biodiversity and Markets: livelihoods and agroecology in comparative perspective*. London: Earthscan
123. Altieri MA, Nicholls CI. *Agroecology and the Search for a Truly Sustainable Agriculture*. Colonia Lomas de Virreyes: UNEP; 2005.
124. Uphoff N, ed. *Agroecological Innovations: increasing food productivity with participatory development*. London: Eartscan; 2002.
125. Lichtfouse E. *Climate Change, Intercropping, Pest Control and Beneficial Microorganisms*. Berlin: Springer; 2009.
126. Radcliffe EB, Hutchinson WD, Cancelado RE, eds. *Integrated pest management: concepts, tactics, strategies and case studies*. Cambridge: Cambridge Univ Press; 2009.
127. Sauerborn KMJ. *Agroecology*. Berlin: Springer; 2013.
128. Pretty J, ed. *The Earthscan Reader in Sustainable Agriculture*. London: Earthscan; 2005.
129. Gustavsson J, Cederberg C, Sonnesson U, Otterdijk R van, Meybeck A. *Global food losses and food waste: extent, causes and prevention*. Rome; 2011.
130. Lang T, Heasman M. *Food Wars: the global battle for mouths, minds and markets*. London: Earthscan; 2004.
131. Guyomard H, Moue C Le, Gohin A. Impacts of alternative agricultural income support schemes on multiple policy goals. *Eur Rev Agric Econ*. 2004;31(2):125–148.
132. Sen A. *Development as Freedom*. New York: Knopf; 2000.
133. Stirling A. *Direction, Distribution and Diversity! Pluralising Profess in Innovation, Sustainability and Development*. Brighton; 2010:1–45.
134. Crouch C. *Post Democracy*. London: Polity; 2004.
135. Stirling A. OPENING UP OR CLOSING DOWN? analysis, participation and power in the social appraisal of technology Andy Stirling, SPRU, University of Sussex paper for submission to. *Japan J Sci Technol Soc*. (October 2004):1–35.
136. Stilgoe J. The road ahead. Public Dialogue on Science and Technology. BIS, centre S expert resource, eds. 2009.
137. Stirling A. Pluralising progress: From integrative transitions to transformative diversity. *Environ Innov Soc Transitions*. 2011;1(1):82–88.
138. IPCC. *Renewable energy sources and climate change mitigation: special report of the Intergovernmental Panel on Climate Change*. Cambridge UK: Cambridge Univ Press; 2012. doi:10.5860/CHOICE.49-6309.
139. Nuttall WJ. *Nuclear Renaisance: Technologies and Policies for the Future of Nuclear Power*. Bristol: Institute of Physics Publishing; 2005.
140. Meadowcroft J, Langhelle O, eds. *Caching the Carbon: the politics and policy of carbon capture and storage*. Cheltenham: Edward Elgar; 2009.
141. Shepherd J, Caldeira K, Cox P, et al. *Geoengineering the climate: science, governance and uncertainty*. London: The Royal Society; 2009:82 p. ; 30 cm.
142. Fleming JR. *Fixing the Sky: the checkered history of weather and climate control*. New York: Columbia University Press; 2010.
143. Ridgwell A, Freeman C, Lampitt R. Geoengineering: taking control of our planet's climate. *Sci Sees Furth*. 2012:22–23.
144. Ruddiman WF. *Plows, Plagues and petroleum: how humans took control of climate*. Princeton: Princeton Univ Press; 2005.
145. IPCC WG1. *Fifth Assessment Report: Summary for Policymakers*. Geneva; 2013:1–36.
146. Cairns R, Stirling A. "Maintaining Planetary Systems" or "Concentrating Global Power?" High Stakes in Contending Framings of Climate Geoengineering. *Glob Environ Chang*. 2014.
147. Cairns RC. Climate geoengineering: issues of path-dependence and socio-technical lock-in. *WIREs Clim Chang*. 2014. doi:10.1002/wcc.296.
148. EREC. *Rethinking 2050: a 100% renewable energy vision for the EU*. Brussels; 2010.
149. ECF. *Roadmap 2050: a practical guide to a prosperous, low carbon Europe*. Brussels; 2010.
150. PWC. *100% renewable electricity: A roadmap to 2050 for Europe and North Africa*. London; 2010.
151. WWF. *The Energy Report: 100% renewable energy by 2050*. Gland; 2011.
152. *The Energy Review*. London; 2002.
153. GEA. *Global Energy Assessment Toward a Sustainable Future*. (Davis G, Goldemberg J, eds.). Cambridge UK: Cambridge Univ Press; 2012.
154. Jacobson MZ, Delucchi MA. A Plan to Power 100 Percent of the Planet with Renewables. *Sci Am*. 2009:1–5.
155. King D. David King: Why we have no alternative to nuclear power: if there were other sources of low carbon energy I would be in favour, but there aren't. *Independent*. July 2006:1–4.
156. MacKay DJC. *Sustainable Energy – without the hot air*. Cambridge: UIT; 2009.
157. Rockström J, Steffen W, Noone K, et al. A safe operating space for humanity. *Nature*. 2009;461(September).
158. Lakatos I, Musgrave A, eds. *Criticism and the Growth of Knowledge: Proceedings of the International Colloquium in the Philosophy of Science*. Aberdeen: Aberdeen University Press; 1970.
159. Popper K. *Conjectures and Refutations*. New York: Basic Books; 1962.
160. Stirling A. Let's Hear it For Scepticism. *Res Fortnight*. 2011.
161. Rip A. Controversies as Informal Technology Assessment. *Knowl Creat Diffus Util*. 1987;8(2):349–371.
162. Leach M, Scoones I, Wynne B. *Science and Citizens: globalization and the challenge of*

engagement. London: Zed Books; 2005.

163. Garud R, Karnøe P. Bricolage versus breakthrough: distributed and embedded agency in technology entrepreneurship. *Res Policy*. 2003;32(2):277–300.

164. Karnoe P, Jorgensen U. The Danish Wind Turbine Story – Technical Solutions to Political Visions? 1991.

165. Fressoli M, Arond E, Abrol D, Smith A, Ely A, Dias R. When grassroots innovation movements encounter mainstream institutions : implications for models of inclusive innovation. 2014;(July):37–41. doi:10.1080/2157930X.2014.921354.

166. Dryzek JS, Downes D, Hunold C, Schlosberg D. *Green States and Social Movements: environmentalism in the United States, United Kingdom, Germany and Norway*. Oxford: Oxford Univ Press; 2003.

167. Redclift M. *Sustainable Development: exploring the contradictions*. London: Routledge; 1987.

168. Ekins P. *A New World Order: Grassroots Movements for Global Change*.

169. Hess DJ. *Alternative Pathways in Science and Industry: activism, innovation and the environment in an era of globalisation*. Cambridge MS: MIT Press; 2007.

170. Adger WN, Jordan A, eds. *Governing sustainability*. Cambridge: Cambridge University Press; 2009.

171. Fanon F. *Toward the African Revolution*. New York: Grove Press; 1964.

172. Stirling A. *Emancipating Transformations : from controlling ' the transition ' to culturing plural radical progress*.; 2014:1–49.

173. Presidential T, Commission C, Assessment R, Management R. Risk Assessment and Risk Management In Regulatory Decision-Making. 1997.

174. HMT. *Managing risks to the public: appraisal guidance*. London; 2005.

175. Porter TM. *Trust in Numbers: the pursuit of objectivity in science and public life*. Princeton: Princeton University Press; 1995.

176. Hacking I. The Emergence of Probability: a philosophical study of early ideas about probability, induction and statistical inference. 2006.

177. Wolpert L. *The Unnatural Nature of Science: why science does (not) make common sense*. London: Faber and Faber; 1992.

178. WHO. *Removing Obstacles to Healthy Development*. Feneva; 1999.

179. Suter GW. *Ecological Risk Assessment*.; 2006.

180. R.E.Hester, Harrison R, eds. *Risk Assessment and Risk Management*. London: Royal Society of Chemistry; 1998.

181. GOS. *Blackett review of high impact low probability events*.

182. Lofstedt R. *Reclaiming health and safety for all : Reclaiming health and safety for all : An independent review of*. London; 2011:110.

183. Freemantle N. Does the UK National Health Service need a fourth hurdle for pharmaceutical reimbursement to encourage the more efficient prescribing of pharmaceuticals ? *Health Policy (New York)*. 1999;46:255–265.

184. Jasanoff S, ed. *States of Knowledge: the co-production of science and social order*. London: Routledge; 2004.

185. HSE. *Reducing risks, protecting people: HSE's decision making process*. London; 2001.

186. ONR. *Safety Assessment Principles for Nuclear Facilities*. London; 2006.

187. Bentkover JD, Covello VT, Mumpower J, eds. *Benefits Assessment: the state of the art*. Dordrecht: Reidel; 1986.

188. O'Brien M. *Making Better Environmental Decisions: an alternative to Risk Assessment*. Cambridge Mass: MIT Press; 2000.

189. Hacking I. *An Introduction to Probability and Inductive Logic*. Cambridge: Cambridge University Press; 2001.

190. Keynes JM, Lewis CI. A Treatise on Probability. *Philos Rev*. 1922;31(2):180. doi:10.2307/2178916.

191. Adams J. *Risk*. London: Routledge; 1995.

192. WHO. *Health and environment: communicating the risks*. Copenhagen; 2013.

193. Renn O, Dreyer M, SpringerLink. *Food safety governance: integrating science, precaution and public involvement*. Berlin: Springer; 2009.

194. Aven T, Renn O. *Risk Management and Governance: concepts, guidelines, applications*. Heidelberg: Springer; 2010.

195. IRGC. *Nanotechnology Risk Governance Recommendations for a global coordinated approach to the governance of potential risks*. Geneva; 2007.

196. RS. *Endocrine disrupting chemicals (EDCs)*. London; 2000.

197. Millstone E, Brunner E, Mayer S. Beyond "substantial equivalence." *Nature*. 1999;401(6753):525–6. doi:10.1038/44006.

198. Stirling AC, Scoones I. From Risk Assessment to Knowledge Mapping: Science , Precaution, and Participation in Disease Ecology. *Ecol Soc*. 2009;14(2).

199. Lewis CI, Keynes JM. A Treatise on Probability. *Philos Rev*. 1922;31(2):180. doi:10.2307/2178916.

200. Rowe WD. Understanding Uncertainty. 1994.

201. Wynne B. Uncertainty and Environmental Learning: reconceiving science and policy in the preventive paradigm. 1992.

202. Funtowicz SO, Ravetz JR. Scientific Uncertainty and Quality Evaluation in Technology Scenarios and R&D Programmes. 1989.

203. Goffman E. *Frame Analysis: an essay on the organisation of experience*.

204. Jasanoff S, Kim S-H. Containing the Atom: Sociotechnical Imaginaries and Nuclear Power in the United States and South Korea. *Minerva*. 2009;47(2):119–146. doi:10.1007/s11024-009-9124-4.

205. Thompson M, Warburton M. Decision Making Under Contradictory Certainties: how to save the Himalayas when you can't find what's wrong with them. 1985.

206. Stirling A. Risk at a turning point? *J Environ Med*. 1999;1(3):119–126. doi:10.1002/1099-1301(199907/09)1:3<119::AID-JEM20>3.0.CO;2-K.

207. Shrader-Frechette KS. *Risk and Rationality: philosophical foundations for populist reforms*. Berkeley: University of California Press; 1991.

208. Kelly JS. *Arrow Impossibility Theorems*. New York: Academic Press; 1978.

209. MacKay AF. *Arrow's Theorem: the paradox of social choice – a case study in the philosophy of economics*. New Haven: Yale University Press; 1980.

210. Sarewitz D. How science makes environmental controversies worse. *Environ Sci Policy*. 2004;7(5):385–403. doi:10.1016/j.envsci.2004.06.001.

211. Stirling A. Precaution, Foresight and Sustainability: reflection and reflexivity in the governance of science and technology chapter. In: Voss J-P, Kemp R, eds. *Reflexive Governance for Sustainable Development*. Cheltenham: Edward Elgar; 2006:225–272.

212. Loasby BJ. *"Choice, Complexity and Ignorance: am inquiry into economic theory and the practice of decision making."* Cambridge: Cambridge University Press; 1976.

213. Stirling A. Risk, Uncertainty and Precaution: Some Instrumental Implications from the Social Sciences. In: Berkhout F, Leach M, Scoones I, eds. *Negotiating Change: new perspectives from the social sciences*. Cheltenham: Edward Elgar; 2003.

214. Faber M, Proops JLR. *Evolution, Time, Production and the Environment*.

215. Zwanenberg P Van, Millstone E. how reassurances undermined precaution. 2000;(11):10–11.

216. Thornton J. *Pandora's Poison: chlorine, health and a new environment strategy*. Cambridge Mass: MIT Press; 2000.

217. Hoffmann MJ. *Ozone Depletion and Climate Change: Constructing a Global Response*. Albany: State University of New York Press; 2005.

218. Randall A. *Risk and Precaution*. Cambridge: Cambridge University Press; 2011.

219. Wynne B. Risk and environment as legitimatory discourses of technology: reflexivity inside out? *Curr Sociol*. 2002;50(3):459–477.

220. Taleb NN. *The Black Swan: The Impact of the Highly Improbable*. New York: Random House; 2007.

221. Brooks H, Cantley] [M. "The Typology of Surprises in Technology, Institutions and Development." 1986.

222. Rosenberg N. Uncertainty and Technological Change. 1996.

223. Stirling A, European Commission. Joint Research C, Institute for Prospective Technological S, Network E. *On science and precaution in the management of technological risk : an ESTO project report*. [Seville]: European Commission, Joint Research Centre; 2001:142 p. : ill. ; 30 cm.

224. Bertolotti M. *The History of the Laser*. London: Institute of Physics; 1999.

225. Szoka B, Marcus A, eds. *The Next Digital Decade: essays on the future of the internet*. Washington DC: TechFreedom; 2010.

226. Stirling A. Risk, uncertainty and power. *Seminar*. 2009;(May 2009):33–39.

227. ESRC. *Science, technology and globalisation*. Swindon

228. Ravetz JR. Usable Knowledge, Usable Ignorance: Incomplete Science with Policy Implications. *Sci Commun*. 1987;9(1):87–116. doi:10.1177/107554708700900104.

229. Jasanoff S. Technologies of Humility: citizen participation in governing science. *Minerva*. 2003;41:223–244.

230. O'Riordan T, Cameron J, Jordan A. *Reinterpreting the precautionary principle*. London: Cameron May; 2001:284 p. : ill. ; 24 cm.

231. Harding R, Fisher E. *Perspectives on the*

precautionary principle. Annandale, N.S.W.: Federation Press; 1999:xvi, 320 p. : ill. ; 25 cm.
232. Fisher E. Precaution, Precaution Everywhere: Developing a "Common Understanding" of the Precautionary Principle in the European Community. *Maastricht J Eur Comp L*. 2002;9:7–28.
233. UNEP. *Rio Declaration on Environment and Development*. Rio de Janeiro, Brazil; 1992.
234. Raffensperger C, Tickner JA. Protecting public health & the environment : implementing the precautionary principle / edited by Carolyn Raffensperger and Joel A. Tickner ; foreword by Wes Jackson. Raffensperger C, Tickner JA, eds. 1999.
235. Marchant G, Mossman KL, eds. *Arbitrary and Capricious: the precautionary principle in the European Union courts*. Washington DC: American Enterprise Institute; 2004.
236. Morris J, ed. *Rethinking Risk and the Precautionary Principle*. London: Butterworth Heinemann; 2000.
237. Goklany IM. *The Precautionary Principle: a critical appraisal of environmental risk assessment*. Washington DC: Cato Institute; 2001.
238. Sunstein CR. *Laws of Fear: beyond the precautionary principle*.
239. Martuzzi M, Tickner JA. *The precautionary principle: protecting public health, the environment and the future of our children*. Citeseer; 2004.
240. Taverne D. *The march of unreason: science, democracy, and the new fundamentalism*. Oxford: Oxford University Press; 2005.
241. Holm, S. and Harris, J. Precautionary principle stifles discovery. *Nature* 400, 398 (1999).
242. Stirling A. Deliberate futures: precaution and progress in social choice of sustainable technology. *Sustain Dev*. 2007;15(5):286–295. doi:10.1002/sd.347.
243. Dekkers M, Bock K, Rubsamen H, et al. *The Innovation Principle: stimulating economic recovery*. Vrussels; 2013.
244. Tait J. Upstream engagement and the governance of science: the shadow of the genetically modified crops experience in Europe. *EMBO Rep*. 2009;10:S18–S22.
245. Luj L, Todt O. Analyzing Precautionary Regulation : Do Precaution , Science , and Innovation Go Together ? *Risk Anal*. 2014. doi:10.1111/risa.12246.
246. Felt U, Wynne B, Callon M, et al. *Taking European knowledge society seriously : report of the Expert Group on Science and Governance to the Science, Economy and Society Directorate, Directorate-General for Research, European Commission*. (Felt U, Wynne B, eds.). Brussels: European Commission; 2008:166 p. ; 23 cm.
247. Hopkins MM, Nightingale P. Strategic risk management using complementary assets: Organizational capabilities and the commercialization of human genetic testing in the UK. *Res Policy*. 2006;35(3):355–374. doi:10.1016/j.respol.2005.12.003.
248. Marchant GE, Mossman KL. *Arbitrary and Capricious: the precautionary principle in the European Union courts*. Washington DC: American Enterprise Institute Press; 2004.
249. CEC. *Communication from the Commission on the Precautionary Principle*.; 2000:1–28.
250. Stirling A, ed. *On Science and Precaution in the Management of Technological Risk – Volume II: casestudies*. Sevilla: Institute for Prospective Technological Studies; 2001.
251. Levidow L, Marris C. Science and governance in Europe: lessons from the case of agricultural biotechnology. *Sci Public Policy*. 2001;28(5):345–360.
252. Dreyer M, Renn O, Ely A, Stirling A, Vos E, Wendler F. A General Framework for the Precautionary and Inclusive Governance of Food Safety. 2007.
253. Ravetz J. The post-normal science of precaution. *Futures*. 2004;36(3):347–357. doi:10.1016/S0016-3287(03)00160-5.
254. Stirling A, Gee D. Science, precaution, and practice. *Public Health Rep*. 2002;117(6):521–33.
255. McGlade J, Quist D, Gee D. social responsibility for new technologies. *Nature*. 2013;497(7449):317. doi:10.1038/497317a.
256. Stirling A. Governance of Neuroscience: challenges and responses. In: *Brain Waves: neuroscience, society and policy*. London: Royal Society; 2011:87–98.
257. Stirling A. Risk, precaution and science: towards a more constructive policy debate – Talking point on the precautionary principle. *EMBO Rep*. 2007;8(4):309–315.
258. Stirling A. Opening Up the Politics of Knowledge and Power in Bioscience. *PLoS Biol*. 2012;10(1):e1001233. doi:10.1371/journal.pbio.1001233.
259. Dovers SR. A framework for scaling and framing policy problems in sustainability. *Ecol Econ*. 1995;12:93–106.
260. Dovers S, Handmer JW. Ignorance, the Precautionary Principle, and Sustainability. *Ambio*. 2013;24(2):92–97.
261. Tickner JA, Wright S. The precautionary principle and democratizing expertise : a US perspective. 2003;30(3):213–218.
262. Fisher E, Jones J, Schomberg R von, eds. *Implementing the precautionary principle: perspectives and prospects*. Edward Elgar Publishing; 2002:155–65.
263. Lujan JL, Todt O. Precaution in public: the social perception of the role of science and values in policy making. *Public Underst Sci*. 2007;16(1):97–109. doi:10.1177/0963662506062467.
264. Rip A. Constructive Technology Assessment. In: Stirling A, ed. *On Science and Precaution in the Management of Technological Risk – Volume II: CaseStudies*. Sevilla: Institute for Prospective Technological Studies; 1999.
265. Lane D, Pumain D, Leeuw SE van der, West G, eds. *Complexity Perspectives in Innovation and Social Change*. Berlin: Springer; 2009.
266. Sadeleer N De. *Implementing the Precautionary Principle: approaches from the Nordic countries, the EU and the USA*. (Sadeleer N de, ed.).
267. Stegmaier BP, Visser VR, Kuhlmann S. Governance of the Discontinuation of Socio-Technical Systems — An Exploratory Study of the incandescent light bulb phase-out. In: *The Governance of Innovation and Socio-Technical Systems in Europe: New Trends, New Challenges – Panel on The governance of innovation and sociotechnical systems: design and displacements*. Vol 2012. Copenhagen; 2012.
268. Weitzman ML. On Diversity. *Q J Econ*. 1992;May.
269. Stirling A. Diversity and ignorance in electricity supply investment: Addressing the solution rather than the problem. *Energy Policy*. 1994.
270. Breznitz S. Educating for coping with change. In: Hamburg D, Frankenheuser M, eds. *Ancient humans in tomorrows electronic world*. Washington DC: Aspen Institute; 1986:32–41.
271. Norgaard RB. *Development Betrayed: the end of progress and a coevolutionary revisioning of the future*. London: Routledge; 1994.
272. Grabher G, Stark D. "Organizing Diversity: Evolutionary Theory, Network Analysis and postsocialism." *Reg Stud*. 1997.
273. James P. "Energy, Environment and Rationality." *Energy Environ*. 1990:114–123.
274. Folke C, Carpenter S, Elmqvist T, Gunderson L, Holling CS. Resilience and Sustainable Building Adaptive Capacity in a World of Transformations. *Ambio*. 2002;31(5):437–440.
275. Rosenberg N. *Inside the Black Box: technology and economics*. Cambridge: Cambridge University Prs; 1982.
276. Nowotny H. Democratising expertise and socially robust knowledge. *Sci Public Policy*. 2003;30(3):151–156.
277. Yoshizawa G, Stirling A, Suzuki T. Multicriteria Diversity Analysis: theory, method and an illustrative application. 2011:211–243.
278. Skea J. Valuing diversity in energy supply. *Energy Policy*. 2010;38(7):3608–3621. doi:10.1016/j.enpol.2010.02.038.
279. Stirling A. *Electronic Working Papers Series On the Economics and Analysis of Diversity*.
280. Geels FW, Smit WA. Lessons from Failed Technology Futures: Potholes in the Road to the Future. In: Brown N, Rappert B, Webster A, eds. *Contested Futures A sociology prospective techno-science*. Aldershot Burlington USA Singapore Sydney: Ashgate; 2000:129–156.
281. Stirling A. Energy Research & Social Science Transforming power : Social science and the politics of energy choices. *Energy Res Soc Sci*. 2014;1:83–95. doi:10.1016/j.erss.2014.02.001.
282. Stirling A. Multicriteria diversity analysis A novel heuristic framework for appraising energy portfolios. *Energy Policy*. 2009:1–13. doi:10.1016/j.enpol.2009.02.023.
283. Lawson N. *The View from Number 11: memoires of a Tory radical*. London: Bantam Press; 1992.
284. Stirling A. Multicriteria diversity analysis. *Energy Policy*. 2010;38(4):1622–1634. doi:10.1016/j.enpol.2009.02.023.
285. Felt U, Barben D, Irwin A, et al. *Science in Society: caring for our futures in turbulent times*. Strasbourg; 2013.
286. Brooks EC. Framework for responsible innovation. 2014:2014. Available at: http://www.epsrc.ac.uk/research/framework/ 1/1. Accessed June 29, 2014.
287. Steps Centre. Innovation, sustainability, development : a new manifesto. 2010.
288. BEPA. *Empowering people, driving change: social innovation in the European Union*. doi:10.2796/13155.
289. Stirling A, European Commission. Directorate-General for Research S, Society. *From Science and Society to Science in Society: Towards a Framework for "Co-operative Research."* Luxembourg: Office for Official Publications of the European Communities; 2006:74 p. ; 25 cm.
290. Sclove RE. *Reinventing technology Assessment: a 21st Century Model – using citizen participation, collaboration and expert analysis to inform and improve decision making on issues involving*

science and technology. Washington DC; 2010.

291. Stirling A. *European Commission FP7 Expert Advisory Group on Science in Society – Final report*. Brussels; 2009:1–15.
292. Fiorino DJ. Citizen Participation and Environmental Risk: a survey of institutional mechanisms. 1990.
293. Feyerabend P. *Against Method*. London: Verso; 1975.
294. Mohr A, Raman S, Gibbs B. *Which publics? When? Exploring the policy potential of involving different publics in dialogue around scienc and technology*. London; 2014.
295. Paper SW. Empowering Designs: towards more progressive appraisal of sustainability.
296. Porter ME, Linde C Van Der. Green and Competitive: Ending the Stalemate. *Harv Bus Rev*. 1995;September-.
297. Tornatzky LG, Fergus EO, Avellar JW, Fairweather GW, Fleischer M. *Innovation and Social Process: national experiment in implementing social technology*. (Tonratzky LG, Fergus EO, Avellar JW, Fairweather GW, Fleischer M, eds.). New York: Pergamon; 1980.
298. Wynne B. Public Participation in Science and Technology: Performing and Obscuring a Political–Conceptual Category Mistake. *East Asian Sci Technol Soc an Int J*. 2007;1(1):99–110. doi:10.1007/s12280-007-9004-7.
299. Bussu S, Davis H, Pollard A. *The best of Sciencewise reflections on public dialogue*. London; 2014.
300. Stirling A. *From Science and Society to Science in Society: towards a framework for co-operative research*. Brussels; 2006.
301. Beck U. *Risk Society: Towards a New Modernity*. London: SAGE; 1992.
302. Pellizzoni L. Trust, Responsibility and Environmental Policy. *Eur Soc*. 2005;7(4):567–594. doi:10.1080/14616690500194118.
303. Krefting L. Trustworthiness. 1991;45(3):214–222.

Chapter 4 Case Study: Neonicotinoid Insecticides and Insect Pollinators

1. Godfray, H. C. J. *et al. Proc. Roy. Soc. B: Biological Sciences* **281**, 20140558 (2014).

Chapter 4 Case Study: Nanomaterials

1. Royal Society and the Royal Academy of Engineering *Nanoscience and nanotechnologies: opportunities and uncertainties* (2004). Available at http://www.nanotec.org.uk/finalReport.htm
2. Scientific Committee on Consumer Safety *Opinion on Titanium Dioxide (nano form)* (European Commission, 2013). Available at http://ec.europa.eu/health/scientific_committees/consumer_safety/docs/sccs_o_136.pdf
3. European Commission Recommendation on the Definition of Nanomaterial. *Official Journal of the European Union*, L 275/38 (2011). Available at http://ec.europa.eu/research/industrial_technologies/pdf/policy/commission-recommendation-on-the-definition-of-nanomater-18102011_en.pdf
4. International Organization for Standardization *Nanotechnologies — Guidance on voluntary labelling for consumer products containing manufactured nano-objects* (ISO/TS 13830:2013). Available at http://www.iso.org/iso/catalogue_detail?csnumber=54315

Chapter 5: Holding a Wider Conversation

1. Menaker, D. (2000) *A Good Talk: the story and skill of conversation*. Basic Books, New York.
2. Organisation for Economic Cooperation and Development (2013) *Survey of Adult Skills*. OECD, Paris.
3. Prince's Trust (2012). *Down But Not Out: tackling youth unemployment through enterprise*. The Prince's Trust, London.
4. Piketty, T. (2014) *Capital in the 21st Century*. Harvard University Press, Cambridge MA.
5. The Economist (2104) Picking holes in Piketty. *The Economist*, 31st May, p.74.
6. Wilkinson, R. and Pickett, K. (2009) *The Spirit Level: why more equal societies almost always do better*. Equality Trust, London
7. Office for National Statistics (2014) *Measuring national well-being: economic well-being*. ONS, London
8. Organisation for Economic Cooperation and Development (2014) *Youth Unemployment*. OECD, Paris.
9. Ipsos Mori 2014. *People in western countries pessimistic about future for young people*. Ipsos Mori, London.
10. Ryan, A. and Tilbury, D. (2013) *Flexible Pedagogies: new pedagogical ideas*. Higher Education Academy, London.
11. Department of Energy and Climate Change (2014) *Implementing geological disposal: a framework for the long term management of higher activity radioactive waste*. DECC, London.
12. House of Lords Committee on Science and Technology (2000) *Science and Society:* Third Report. London
13. Royal Commission on Environmental Pollution, (1998. *Setting Environmental Standards*. Twenty-first Report. RCEP, London.
14. Wilsdon, J., and Willis, R. (2004) *See-through Science: Why public engagement needs to move upstream*. Demos, London
15. Macnaghten, P., Kearnes, M., and Wynne, B. (2005) Nanotechnology, governance and public deliberation: what role for the social sciences? *Science Communication, 27*, 268-291.
16. Burgess, J., Stirling, A., Clark, J., Davies, G., Eames, M., Staley, K., and Williamson, S. (2007). Deliberative mapping: a novel analytic-deliberative methodology to support contested science-policy decisions. *Public Understanding of Science, 16*, 299-322.
17. Chilvers, J. (2012) Reflexive Engagement? actors, learning, and reflexivity in public dialogue on science and technology. *Science Communication*. 35 (3), 283-310.
18. Royal Society Working Group on Nanotechnology and Nanoscience. (2004) *Nanoscience and Nanotechnologies: opportunities and uncertainties*. The Royal Society and the Royal Academy of Engineering, London.
19. Shepherd, JS (Chair) (2009) *Geoengineering the Climate: science, governance and uncertainty*. The Royal Society, London.
20. Council for Science and Technology, Science and Society Subgroup (2005) *Policy Through Dialogue: informing policies based on science and technology*. Council for Science and Technology, London.
21. Macnaghten, P. and Chilvers, J. (2012) Governing risky technologies. In (eds.) In S. Lane, F. Klauser, & M. Kearnes, *Critical Risk Research: practices, politics and ethics*. Wiley-Blackwell, London, 99-124.
22. Habermas, J. (1990) *Moral Consciousness and Communicative Action*. MIT Press, Cambridge, MA.
23. Johnson, J. (1991) Habermas on strategic and communicative action. *Political Theory*, 19 (2), 181-201
24. Horlick-Jones, T., Walls, J., Rowe, G., Pidgeon, N., Poortinga,, W. Murdock, G. and O'Riordan, T. (2007) *The GM Debate: risk, politics and public engagement*. Routledge, London.
25. Agriculture and Biotechnology Commission (2001) Crops on Trial. Department of Trade and Industry, London.
26. Lang, T. and Ingram, J. (2013) Food security twists and turns: why food systems need complex governance. In *Addressing Tipping Points for a Precarious Future* (eds. T. O'Riordan and T. Lenton), Oxford University Press, Oxford, 81-103.
27. Chilvers, J. (2009) Deliberative and participatory approaches in environmental geography. In *A Companion to Environmental Geography* (eds. N. Castree, D. Demeritt, D. Liverman and B. Rhoads), Wiley-Blackwell, Oxford, doi: 10.1002/9781444305722.chapter 24.
28. Bickerstaff, K. "Because we've got history here": nuclear waste, cooperative siting, and the relational geography of a complex issue. *Environment and Planning A*, 44, 2621-2628.

Chapter 6: The need for a common language

1. *UK threat level raised* (UK Security Service, 2010). Available from: https://www.mi5.gov.uk/home/news/news-by-category/threat-level-updates/uk-threat-level-raised.html
2. IPCC. IPCC Fifth Assessment WG1: The Physical Science Basis [Internet]. 2013. Available from: https://www.ipcc.ch/report/ar5/wg1/
3. Guyatt GH, Oxman AD, Vist GE, Kunz R, Falck-Ytter Y, Alonso-Coello P, et al. GRADE: an emerging consensus on rating quality of evidence and strength of recommendations. BMJ. 2008 Apr;336(7650):924–6.
4. Friedman JA, Zeckhauser R. Handling and Mishandling Estimative Probability: Likelihood, Confidence, and the Search for Bin Laden. Intell Natl Secur. 2014 Apr 30;0(0):1–23.
5. Pechey R, Spiegelhalter D, Marteau TM. Impact of plain packaging of tobacco products on smoking in adults and children: an elicitation of international experts' estimates. BMC Public Health. 2013 Jan 9;13(1):18.
6. Informed Choice about Cancer Screening. Publications [Internet]. ICCS. [cited 2014 Jul 7]. Available from: http://www.informedchoiceaboutcancerscreening.org/about-us/publications/
7. DEFRA. About the Climate change projections [Internet]. 2012 [cited 2014 Jul 7]. Available from: http://ukclimateprojections.metoffice.gov.uk/22537
8. Champkin J. Lord Krebs. Significance. 2013 Oct 1;10(5):23–9.

Chapter 6 Case Study: Adapting regulation to changing evidence on risks: delivering changes to pig inspection

1. Food Standards Agency *Review of official meat controls* (2014). Available from http://www.

food.gov.uk/enforcement/monitoring/meat/reviewofmeatcontrols/

Chapter 6 Case Study: Accurate Communication of Medical Risk

1. Tversky, A. and Kahneman, D. The framing of decisions and the psychology of choice. *Science* **211**, 453–458 (1981).
2. Sheridan, S. L. and Pignone, M. Numeracy and the medical student's ability to interpret data. *Effective Clinical Practice* **5**, 35–40 (2002).
3. Medicines and Healthcare Products Regulatory Agency *Side effects of medicines – FAQ* (2013). Available at http://www.mhra.gov.uk/Safetyinformation/Generalsafetyinformationandadvice/Adviceandinformationforconsumers/Sideeffectsofmedicines
4. Berry, D. C., Holden, W. and Bersellini, E. Interpretation of recommended risk terms: differences between doctors and lay people. *International Journal of Pharmacy Practice* **12**, 117–124 (2004).
5. Knapp, P., Raynor, D. K., Woolf, E., Gardner, P. H., Carrigan, N. and McMillan, B. Communicating the risk of side effects to patients. *Drug Safety* **32**, 837–849 (2009).
6. Cummins, C., Sauerland, U. and Solt, S. Granularity and scalar implicature in numerical expressions. *Linguistics & Philosophy* **35**, 135–169 (2012).

Section 2 High Level Case Study: Hydraulic Fracturing

1. Mair, R. *et al. Shale gas extraction in the UK: a review of hydraulic fracturing* (The Royal Society and The Royal Academy of Engineering, 2012). Available at https://royalsociety.org/~/media/policy/projects/shale-gas-extraction/2012-06-28-shale-gas.pdf

Chapter 7: How People Estimate Risks in Everyday Life

1. Tversky, A. and Kahneman, D. Availability: A Heuristic for Judging Frequency and Probability. *Cognitive Psychology* **5**, 207-232 (1973).
2. Kahneman, D. *Thinking, Fast and Slow* (Farrar, Straus and Giroux, New York, 2012).
3. Gigerenzer, G. *Risk Savvy: How to Make Good Decisions* (Allen Lane, London, 2014).
4. Kahneman, D. and Tversky, A. Prospect Theory: An Analysis of Decision Under Risk. *Econometrica* **47**, 263-291 (1979).
5. Loewenstein, G. F., Weber, E. U., Hsee, C. K. and Welch, N. Risks as Feeling. *Psych. Bull.* **127**, 267-286 (2001).
6. Thaler, R. H. and Sunstein, C. R. *Nudge: Improving Decisions about Health, Wealth and Happiness* (Yale University Press, New Haven, 2008)

Chapter 8: Perceptions of Risk

1. Kates, R.W. & Kasperson, X.J. Comparative risk analysis of technological hazards. *Proceedings of the National Academy of Sciences of the USA* 80, 7027-7038 (1983).
2. Rosa, E.A. & Clarke, L. Collective hunch? Risk as the real and the elusive. *Journal of Environmental Studies and Science* 2, 39-52 (2012).
3. Pidgeon, N.F., Hood, C., Jones, D., Turner, B. & Gibson, R. in *Risk – Analysis, Perception and Management: Report of a Royal Society Study Group* (eds F. Warner et al) 89-134 (The Royal Society, 1992).
4. Pidgeon, N.F. & Gregory, R. (2004) in *Blackwell Handbook of Judgment and Decision Making* (eds D. Koehler & N. Harvey) 604-623 (Blackwell).
5. Slovic P. *The Perception of Risk*. (Earthscan: London).
6. Loewenstein, G.F., Weber, E.U., Hsee, C.K. & Welch, N. Risk as feelings. *Psychological Bulletin* 127(2), 267-286 (2001).
7. Slovic, P., Finucane, M., Peters, E. & MacGregor, D.G. in *Heuristics and Biases: The Psychology of Intuitive Judgment* (eds T. Gilovich, D. Griffin & D. Kahnman) 397-420 (Cambridge University Press, 2002).
8. Pidgeon, N.F. & Fischhoff, B. The role of social and decision sciences in communicating uncertain climate risks. *Nature Climate Change* 1, 35-41 (2011).
9. Breakwell, G. *The Psychology of Risk* (Cambridge University Press, 2007).
10. Joffe, H. Risk: from perception to social representation. *British Journal of Social Psychology* 42, 55-73 (2003).
11. Douglas, M. & Wildavsky, A. *Risk and Culture: An Analysis of the Selection of Technological Dangers*. (University of California Press 1982).
12. Rayner, S. Cultural theory and risk analysis in *Social Theories of Risk* (S. Krimsky & D. Golding) 83-116 (Praeger, 1992).
13. Rippl, S. Cultural theory and risk perceptions: a proposal for better measurement. *Journal of Risk Research*, **5**(2), 147-166 (2002).
14. Kahan, D.M., Braman, D., Slovic, P., Gastil, J. & Cohen, G. (2009). Cultural cognition of the risks and benefits of nanotechnology. *Nature Nanotechnology* 4, 87-91
15. Corner, A., Venables, D., Spence, A., Poortinga, W., Demski, C. & Pidgeon, N.F. Nuclear power, climate change and energy security: exploring British public attitudes. *Energy Policy*, 39, 4823-4833 (2011).
16. Whitfield, S.C., Rosa, E.A., Dan, A. & Dietz, T. The future of nuclear power: Value orientations and risk perception. *Risk Analysis 29 (3)*,425-437 (2009).
17. Corner, A., Markowitz, E. & Pidgeon, N.F. Public engagement with climate change: the role of human values. *WIREs Climate Change*, doi: 10.1002/wcc.269 (2014).
18. Poortinga, W., Spence, A., Whitmarsh, L., Capstick, S. & Pidgeon, N. Uncertain climate: An investigation into public scepticism about anthropogenic climate change. *Global Environmental Change* 21, 1015-1024 (2011).
19. Feinberg, M. & Willer, R. The moral roots of environmental attitudes. *Psychological Science*, 24, 56-62 (2013).
20. Corner, A. A new conversation with the centre-right about climate change: Values, frames & narratives. (Climate Outreach & Information Network/BRASS Research Centre, Cardiff University 2013).
21. Davidson, D.J. & Freudenburg, W.R. Gender and environment risk concerns: a review and analysis of available research. *Environment and Behaviour* 28 (3), 302-329 (1996).
22. Henwood, K.L, Parkhill, K. & Pidgeon, N Science, technology and risk perception: From gender differences to effects made by gender. *Journal of Equal Opportunities International* 27(8), 662-676 (2008).
23. Beck, U. *Risk Society. Towards a New Modernity* (Sage, 1992).
24. Giddens, A. *The Consequences of Modernity* (Polity Press, 1990).
25. Tulloch, J. & Lupton, D. *Risk and Everyday Life* (Sage, 2003).
26. Henwood, K.L. & Pidgeon, N.F. *What is the Relationship between Identity and Technological, Economic, Demographic, Environmental and Political Change viewed through a Risk Lens? Foresight Future Identities Project* (Government Office of Science: London, 2013).
27. Packer, G. *The Unwinding: An Inner History of the New America* (Farrar, Straus and Giroux, 2013)
28. Pidgeon, N.F. Complexity, Uncertainty and Future Risks. *Journal of Risk Research* DOI 10.1080/13669877.2014.940599 (2014).
29. Henwood, K.L. & Pidgeon, N.F. in *The Ethics of Nuclear Energy: Risk, Justice and Democracy in the Post-Fukushima Era* (ed. B. Taebi & S. Roeser) (Cambridge University Press, 2015)
30. Irwin, A., Simmons, P. & Walker, G., Faulty environments and risk reasoning: the local understanding of industrial hazards. *Environment and Planning A* 31, 1311-26 (1999).
31. Bickerstaff, K. & Walker, G. Public understandings of air pollution: the 'localisation' of environmental risk. *Global Environmental Change* 11, 133-145 (2001).
32. Parkhill, K.A., Pidgeon, N.F., Henwood, K.L., Simmons, P. & Venables, D. From the familiar to the extraordinary: local residents' perceptions of risk when living with nuclear power in the UK. *Transactions of the Institute of British Geographers* NS 35, 39-58 (2010).
33. Bickerstaff, K., Simmons, P. & Pidgeon. N.F. Situating local experience of risk: peripherality, marginality and place identity in the UK foot and mouth disease crisis. *Geoforum* 37, 844-858 (2006).
34. Bruine de Bruin, W. & Bostrom, A. Assessing what to address in science communication. *Proceedings of the National Academy of Sciences of the USA* 110 (sup 3), 14062-14068 (2001).
35. Satterfield, T. In search of value literacy: Suggestions for the elicitation of environmental values. *Environmental Values,* 10, 331-359 (2001).
36. Henwood, K.L., Pidgeon, N.F., Sarre, S., Simmons, P. & Smith, N. Risk, framing and everyday life: methodological and ethical reflections from three sociocultural projects. *Health, Risk and Society* 10, 421-438 (2008).
37. Pidgeon, N.F. & Barnett, J. *Chalara and the Social Amplification of Risk* (Defra, 2013).
38. Kasperson, J.X. & Kasperson, R.K. in *Acceptable Evidence: Science and Values in Risk Management* (ed D. Mayo & R. Hollander) 9-28 (Oxford University Press, 1991).
39. House of Lords Select Committee on Science and Technology *Third Report: Science and Society (Session 1999-2000)*. (HMSO: London, 2000).
40. Wynne, B. in *Society, Technology and Risk*. (ed J. Conrad) 167-202 (Academic Press: New York 1980).
41. Slovic, P. Perceived risk, trust and democracy, *Risk Analysis*, 13(6), 675-682 (1993).
42. Flynn, J., Burns, W., Mertz, C.K. & Slovic, P. Trust as a determinant of opposition to a high-level radioactive waste repository: analysis of a

structural model. *Risk Analysis* 12(3), 417-429 (1992).
43. Poortinga, W. & Pidgeon, N.F. Exploring the dimensionality of trust in risk regulation. *Risk Analysis* 23, 961-972 (2003).
44. Cabinet Office *Risk: Improving Government's Capability to Handle Risk and Uncertainty*. (HMSO 2002).
45. Johnson, B. B. Exploring dimensionality in the origins of hazard related trust. *Journal of Risk Research*, 2(4), 325-354 (1999).
46. Siegrist, M., Earle, T.C. & Gutscher, H. *Trust in Cooperative Risk Management*. (Earthscan: London, 2007).
47. Walls, J., Pidgeon, N.F., Weyman, A. & Horlick-Jones, T. Critical trust: understanding lay perceptions of health and safety risk regulation. *Health, Risk and Society* 6(2), 133-150 (2004).
48. O'Neill, O. *A Question of Trust* (Cambridge University Press, 2002).
49. Fischhoff, B. Risk perception and communication unplugged: twenty years of process. *Risk Analysis* 15, 137-145 (1995).
50. Renn, O., Webler, T. & Wiedemann, P. *Fairness and Competence in Citizen Participation: Evaluating Models for Environmental Discourse* (Kluwer, 1995).
51. Stern, P.C., Fineberg, H.C. *Understanding Risk: Informing Decisions in a Democratic Society* (US National Research Council: Washington DC, 1996).
52. Pidgeon, N.F., Demski, C.C, Butler, C., Parkhill, K.A. & Spence, A. Creating a national citizen engagement process for energy policy. *Proceedings of the National Academy of Sciences of the USA*, DOI10.1073/pnas.1317512111 (2014).

Section 3 High Level Case Study: Flooding

1. Harries, T. The anticipated emotional consequences of adaptive behaviour – impacts on the take-up of household flood-protection protective measures. *Environment and Planning A* **44**, 649-668 (2012).
2. Johnson, C., Penning-Rowsell, E.C. and Parker, D.J. Natural and imposed injustices: the challenges in implementing 'fair' flood risk management policy in England. *Geographical Journal* **173**, 374-390 (2007).
3. Sayers, P.B., Galloway, G., Penning-Rowsell, E.C., Li, Y., Shen, F., Chen, Y., Wen, K., Le Quesne, T., Lei, W. and Yuhui, G. Strategic flood management: ten 'golden rules' to guide a sound approach. *International Journal of River Basin Management* (2014). DOI: 10.1080/15715124.2014.902378
4. Sayers, P., Galloway, G., & Hall, J. Robust decision making under uncertainty – Towards adaptive and resilient flood risk management infrastructure. In P. Sayers, *Flood Risk: Design, Management and Planning of Flood Defence Infrastructure* (Institution of Civil Engineers Publishing, London, 2012).
5. Hall, J. and Solomatine, D. A framework for uncertainty analysis in flood risk management decisions. *International Journal of River Basin Management* **6**, 85-98 (2008). DOI: 10.1080/15715124.2008.9635339
6. *UK climate change risk assessment: Government report* (Department for Environment, Food and Rural Affairs, London, 2012). Available at https://www.gov.uk/government/publications/uk-climate-change-risk-assessment-government-report
7. Penning-Rowsell, E.C., Haigh, N., Lavery, S., and McFadden L. A threatened world city: The benefits of protecting London from the sea. *Natural Hazards* **66**, 1383-1404 (2012). DOI: 10.1007/s11069-011-0075-3
8. *Flood defence partnership funding* (Department for Environment, Food and Rural Affairs, London, 2014). Available at https://www.gov.uk/government/publications/flood-defence-partnership-funding

Chapter 9: Context Matters to Human Perception and Response

1. Wynne, B. Redefining the issue of risk and public acceptance – the social viability of technology. *Futures* **15**, 13-32 (1983)
2. Renn, O. & Rohrmann, B. (eds) *Cross-cultural risk perception: A survey of empirical studies*. (Springer Verlag, Dordrecht, 2000)
3. Kates, R.W. The interaction of climate and society. In: *Climate Impact Assessment,* R.W. Kates , J.H. Ausubel & M.Berberian (eds), pp. 5-36. COPE 27 (John Wiley & Son, Chichester, UK, 1985)
4. Petts, J., Horlick-Jones, T. & Murdock, G. *Social amplification of risk: the media and the public*. Contract Research Report **329/2001**, (Health and Safety Executive, Sudbury . 2001). Horlick-Jones, T. (2008) Communities of risk research and risk practice: Divided by a common language. *Journal of Risk Research* **11(1-2)**, 169-174 (2008)
5. Tversky, A. & Kahneman, D. Availability: A Heuristic for Judging frequency and probability. *Cognitive Psychology* **4**, 207-232 (1973)
6. Whitmarsh, L.. Are flood victims more concerned about climate change than other people? The role of direct experience in risk perception and behavioural response. *Journal of Risk Research* **11(3)**, 351-374 (2008)
7. Green, D., Billy, J. & Tapim, A. Indigenous Australian's knowledge of weather and climate. *Climate Change* **100**, 337-354, (2010). Lefale, P. *Ua 'afa le Aso* Stormy weather today: traditional ecological knowledge of weather and climate. The Samoa Experience. *Climatic Change* **100**, 317-335 (2010). Gearheard, S., Pocernich, M., Stewart, J., Sanguya, J & Huntington, H.P. Linking Inuit knowledge and meteorological stations' observations to understand changing patterns of Clyde River, Nunavut. *Climatic Change* **100**, 267-294 (2010)
8. Wynne, B. Risk and social learning: reification to engagement. In: *Social Theories of Risk* (eds. S Krimsky & D. Golding, pp. 275-300. (Praeger, Westport, CT. 1992)
9. Kunreuther, H & Michel-Kerjan, E. *Encouraging Adaptation to Climate Change: Long-term Flood Insurance.* Issue Brief 09-13. (Resources for the Future, Washington DC, 2009).
10. Greenberg, M. Energy sources, public policy and public preferences; analysis of US national and site-specific data. *Energy Policy* **37(8)**, 3242-49 (2009)
11. Sadhra, S., Petts, J., McAlpine, S., Pattison, H. & McRae, S. Workers' understanding of chemical risks; electroplating case study. *Occupational and Environmental Medicine* **59(10)**, 689-695 (2002)
12. Fleming, S.M., Thomas, C.L. & Dolan, R.J. Overcoming status quo bias in the human brain. *Proceedings of the National Academy of Sciences* **107**, 6005-6009 (2010)
13. Harries, T. Feeling secure or being secure. Why it might seem better not to protect yourself against a natural hazard. *Health, Risk & Society* **10(5)**, 479-90 (2008)
14. Petts, J. The public-expert interface in local waste management decisions: expertise, credibility and process. *Public Understanding of Science* **6(4)**, 359-82 (1997)
15. Poumadère, M. & Mays, C. The dynamics of risk amplification and attenuation in context: a French case study. In: *The Social Amplification of Risk* , N, Pidgeon, R.E. Kasperson & P. Slovic (eds); pp. 209-242. (Cambridge University Press. 2003)
16. Kasperson, R.E. & Kasperson, J.X. Hidden Hazards. In: *Acceptable Evidence: Science and Value in Hazard Management*, D.C. Mayo & R. Hollander (eds)., pp.9-28. (Oxford University Press, 1991)
17. Macnaghten, P., Carro-Ripalda, S. & Burity, J. (eds) *A New Approach to Governing GM Crops: Global Lessons from the Rising Powers*. Durham University Working Paper,(Durham, UK , 2014)
18. Davis, C. & Fisk, J.M. Energy abundance of environmental worries? Analysing public support for fracking in the United States. *Review of Policy Research* **31(1)**, 1-16, (2014) Boudet, H. et al. 'Fracking' controversy and communication; using national survey data to understand public perceptions of hydraulic fracturing. *Energy Policy* **65**, 57-67 (2014)
19. Scafft, K.A., Borlu, Y. & Glenna, L. The relationship between Marcellus shale gas development in Pennsylvania and local perceptions of risk and opportunity. *Rural Sociology* **78(2),** 143-168 (2013)
20. Batel, S. & Devine-Wright, P. A critical and empirical analysis of the national-local gap in public responses to large-scale energy infrastructures. *Journal of Environmental Planning and Management,* DOI: 10.1080/09640568.2014.914020
21. Wynne, B & Dressel, K. Cultures of uncertainty – transboundary risks and BSE in Europe. In: *Transboundary Risk Management*, J. Linnerooth-Bayer, R.E. Lofstedt & G. Sjostedt, pp. 121-154, (Earthscan Publications Ltd, London. 2001)
22. Levidow, L. Genetically modified crops: what transboundary harmonisation in Europe?. In: *Transboundary Risk Management*, J. Linnerooth-Bayer, R.E. Lofstedt & G. Sjostedt, pp. 59-90, (Earthscan Publications Ltd, London, 2001)
23. Lofstedt, R. Risk versus hazard. How to regulate in the 21st Century. *European Journal of Risk Regulaiton* **2(2)**, 149-168, 2011
24. Scheer, D., Benighaus, C., Benighaus, L., Renn, O., Gold, S., Röder, B & Böl, G-F. The distinction between risk and hazard: understanding and use in stakeholder communications. *Risk Analysis* **34(7),** 1270-1285, 2014
25. Macnaghten, P & Jacobs, M. Public identification with sustainable development: investigating cultural barriers to participation. *Global Environmental Change*, **7(1)**, 5-24 (1997)
26. Harvatt, J., Petts, J. & Chilvers, J. Understanding householder responses to natural hazards: flooding and sea level rise comparisons. *Journal of Risk Research* **14(1-2)**, 63-82 (2011)

27. Bickerstaffe, K. & Walker, G. Public understanding of air pollution: the 'localisation' of environmental risk. *Global Environmental Change* **11(2)**, 133-145 (2001)
28. Niemeyer, S., Petts, J. & Hobson, K. Rapid climate change and society; assessing responses and thresholds. Risk Analysis **26(6)**, 1443-1456, 2005
29. Siegrist, M. & Gutscher, H. Flooding risks: a comparison of lay people's perceptions and experts' assessments in Switzerland. *Risk Analysis* **26(4)**, 971-79 (2006)
30. Petts, J. Health, responsibility, and choice: contrasting negotiations of air pollution and immunisation information. *Environment and Planning A*. **37**, 791-804 (2005)
31. Roco, M.C. Possibilities for global governace of converging technologies. *Journal of Nanoparticle Research* **10**, 11-29 (2008)
32. Owen, R., Stilgoe, J., Macnaghten, P., Gorman, M., Fischer, E & Guston, D.A Framework for Responsible Innovation. In: *Responsible Innovation: Managing the Responsible Emergence of Science and Innovation in Society*, R. Owen, J. Bessant & M. Heintz (eds), pp. 27-50 (John Wiley & Sons, Chichester, 2013)
33. Lee, R.G. & Petts, J. Adaptive Governance for Responsible Innovation. In: *Responsible Innovation: Managing the Responsible Emergence of Science and Innovation in Society*, R. Owen, J. Bessant & M. Heintz (eds), pp. 143-164 (John Wiley & Sons, Chichester, 2013)
34. Royal Commission on Environmental Pollution *Novel Materials in the Environment: The Case of Nanotechnology*. 27th Report. (The Stationary Office, London, 2008)
35. Guston, D. & Sarewitz, D. Real-time technology assessment. *Technology in Society* **24(1-2)**, 93-109, 2002.
36. Sykes, K & Macnaghten, P. Responsible Innovation – Opening up Dialog and Debate. In: *Responsible Innovation: Managing the Responsible Emergence of Science and Innovation in Society*, R. Owen, J. Bessant & M. Heintz (eds), pp. 85-107 (John Wiley & Sons, Chichester, 2013)
37. Bull, R; Petts, J. & Evans, J. The importance of context for effective public engagement: learning from the governance of waste. *Journal of Environmental Planning and Management* **53(8)**, 991-1010 (2010)
38. Murdock, G., Petts, J. & Horlick-Jones, T. After amplification: rethinking the role of the media in risk communication. In: *The Social Amplification of Risk* , N, Pidgeon, R.E. Kasperson & P. Slovic (eds); pp. 156-178. (Cambridge University Press, Cambridge, 2003)

Chapter 9 Case Study: MMR, Bowel Disease, Autism and Measles

1. Wakefield AJ, Pittilo RM, Sim R. Evidence of persistent measles virus infection in Crohn's disease. J Med Virol 39:345–353, 1993.
2. Farrington P, Miller E. Measles vaccination as a risk factor for inflammatory bowel disease. Lancet 345:1362, 1995.
3. Feeney M, Ciegg A, Winwood P, Snook J. A case control study of measles vaccination and inflammatory bowel disease. Lancet 350:764–766, 1997
4. Wakefield A, Murch SH, Anthony A, et al. Ileal-lymphoid-nodular hyperplasia, non-specific colitis, and pervasive developmental disorder in children. Lancet 351:637–641, 1998.
5. Chadwick N, Bruce IJ, Schepelmann S, et al. Measles virus RNA is not detected in inflammatory bowel disease using hybrid capture and reverse transcription followed by the polymerase chain reaction. J Med Virol 55:305–311, 1998.
6. Cedillo & Cedillo vs. Secretary of Health and Human Services, No. 98-916V, 57-58 (United States Court of Federal Claims, 2009): http://www.autism-watch.org/omnibus/cedillo.pdf
7. Taylor B, Miller E, Farrington CP, et al. Autism and measles, mumps and rubella: no epidemiological evidence for a causal association. Lancet 353:2026–2029, 1999.
8. Fombonne E, Chakrabarti S. No evidence for a new variant of measles-mumps-rubella-induced autism. Pediatrics 108(suppl 4):E58, 2001.
9. Medical Research Council. MRC Review of Autism Research: Epidemiology and Causes. London, Medical Research Council, 2001. Online. Available at: http://www.mrc.ac.uk/pdf-autism-report.pdf.
10. Dales L, Hammer SJ, Smith NJ. Time trends in autism and in MMR immunization coverage in California. JAMA 285:1183–1185, 2001.
11. Farrington CP, Miller E, Taylor B. MMR and autism: further evidence against a causal association. Vaccine 19:3632–3665, 2001.
12. Taylor B, Miller E, Lingam R, et al. Measles, mumps, and rubella vaccination and bowel problems or developmental regression in children with autism: population study. BMJ 324:393–396, 2002.
13. Madsen KM, Hviid A, Vestergaard M, et al. A population-based study of measles, mumps, and rubella vaccination and autism. N Engl J Med 347:1477–1482, 2002.
14. Smeeth L, Cook C, Fombonne E, et al. MMR vaccination and pervasive developmental disorders: a case-control study. Lancet 364 (9438):963–9, 2004.
15. Ramsay ME, Yarwood J, Lewis D, et al. Parental confidence in measles, mumps, and rubella vaccine: evidence from vaccine coverage and attitudinal surveys. Br J Gen Pract 52:912–916, 2002.
16. Effects of media reporting on MMR coverage. Commun Dis Rep CDR Wkly 12(35):30, 2002.
17. Tracking mothers attitudes to childhood immunisation 1991-2001. Yarwood J, Noakes K, Kennedy D, Campbell H, Salisbury D M. Vaccine 2005;23(48049):5670-87.
18. Drop in MMR jabs blamed on media scare (1998): http://news.bbc.co.uk/1/hi/health/120277.stm
19. Mason, BW and Donnelly PD Impact of a local newspaper campaign on the uptake of the measles mumps and rubella vaccine J Epidemiol Community Health 2000;54:473-474 doi:10.1136/jech.54.6.473
20. NHS Immunisation Statistics England 2012–13: https://catalogue.ic.nhs.uk/publications/public-health/immunisation/nhs-immu-stat-eng-2012-2013/nhs-immu-stat-eng-2012-13-rep.pdf
21. Ramsay ME *et al.* The Elimination of Indigenous Measles Transmission in England and Wales J. Infect. Dis. 2003; 187 (Supplement 1): S198-S207. doi: 10.1086/368024
22. MMR doctor struck from register (2010): http://news.bbc.co.uk/1/hi/health/8695267.stm

Chapter 10: Managing Existential Risk from Emerging Technologies

1. Beckstead, Nick et. al. (2014). "Unprecedented Technological Risks," Working paper. Oxford University, Future of Humanity Institute.
2. Office for National Statistics. (2012). "Mortality in England and Wales: Average lifespan, 2010." Available online at http://www.ons.gov.uk/ons/rel/mortality-ageing/mortality-in-england-and-wales/average-life-span/rpt-average-life-span.html
3. Matheny, Jason G. (2007) "Reducing the risk of human extinction." *Risk analysis* 27, 1335-1344, p. 1336.
4. For more detail, see Bostrom, Nick, and Milan M. Cirkovic, eds. (2008). *Global catastrophic risks*. Oxford University Press.
5. Jackson, Ronald J., et al. (2001). "Expression of mouse interleukin-4 by a recombinant ectromelia virus suppresses cytolytic lymphocyte responses and overcomes genetic resistance to mousepox." *Journal of Virology* 75: 1205-1210;
Nowak, R. "Disaster in the making." *New Scientist;* January 13, 2001.
Ramshaw, I. *XIII International Poxvirus and Iridovirus Symposium, Montpellier, France;* September 2000.
6. Buller, R.M.L. *Smallpox BioSecurity: Preventing the Unthinkable, Geneva, Switzerland*; October 21–22, 2003.
7. Imai, M. et al. "Experimental Adaptation of an Influenza H5 HA Confers Respiratory Droplet Transmission to a Reassortant H5 HA /H1N1 Virus in Ferrets," *Nature* 486, 420–428; June 21, 2012.
8. Fouchier, Ron et al. (2013). "Avian flu: Gain-of-function experiments on H7N9." *Nature* 500,150–151.
9. Lipsitch M, Galvani AP. (2014). "Ethical Alternatives to Experiments with Novel Potential Pandemic Pathogens." *PLoS Med* 11(5): e1001646.
10. Church, George. (2004). A synthetic biohazard non-proliferation proposal, Cambridge, MA: Havard University. URL: http://arep.med.harvard.edu/SBP/Church_Biohazard04c.htm.
11. Posner, Richard. (2004). *Catastrophe: Risk and Response*. p. 5. (Oxford University Press, Oxford).
12. Myhrvold, Nathan. (2013). "Strategic Terrorism: A Call to Action," in the *Lawfare* research paper series.
13. Rees, Martin. (2003). *Our Final Century*. (Heinemann, London).
14. Ibid. p. 48.
15. For example, variants of a framework called AIXI have learned how to play a variety of off the shelf computer games just from access to a video stream of the computer screen and trial and error. Bellemare, Marc et al. (2013). "The Arcade Learning Environment: an evaluation platform for general agents." *Journal of Artificial Intelligence Research* 47:253–79.
16. For the most detailed discussion of this set of issues, see Bostrom, Nick. (2014). *Superintelligence: Paths, Dangers, Strategies*. Oxford University Press. For related arguments, also see:

Chalmers, David John. (2010). "The Singularity: A Philosophical Analysis." *Journal of Consciousness Studies* 17 (9–10): 7–65.
Good, Irving John. (1965). "Speculations Concerning the First Ultraintelligent Machine." In *Advances in Computers,* edited by Franz L. Alt and Morris Rubinoff, 31–88. Vol. 6. New York: Academic Press.
Hawking, Stephen, Max Tegmark, Stuart Russell, and Frank Wilczek. (2014). "Transcending Complacency on Superintelligent Machines," *Huffington Post.*
Muehlhauser, Luke and Salamon, Anna. (2013). "Intelligence Explosion: Evidence and Import." In *Singularity Hypotheses* (Springer).
Yudkowsky, Eliezer. (2008). "Artificial Intelligence as a Positive and Negative Factor in Global Risk." In *Global Catastrophic Risks*, edited by Nick Bostrom and Milan Cirkovic (Oxford University Press, Oxford).

17. Allen, Paul, and Greaves, Mark. (2011). "The Singularity Isn't Near." *Technology Review. October, 12*, 2011.
Dennett, Daniel. (2012). The Mystery of David Chalmers. *Journal of Consciousness Studies*, 19(1), 86.
Horvitz, E., & Selman, B. (2009). Interim Report from the Panel Chairs. *AAAI Presidential Panel on Long Term AI Futures*.
Prinz, Jesse. (2012). Singularity and inevitable doom. *Journal of Consciousness Studies*, 19(7-8), 77-86.
Searle, John. (2014). "What Your Computer Can't Know." *New York Review of Books*.
18. Müller, Vincent C. and Bostrom, Nick. (forthcoming), 'Future Progress in Artificial Intelligence: A Poll Among Experts', *Journal of Experimental and Theoretical Artificial Intelligence*, Special Volume "Impacts and risks of artificial general intelligence" ed. V. Müller. Available at http://www.nickbostrom.com/papers/survey.pdf
19. Armstrong, S., Sotala, K., & Ó hÉigeartaigh, S. S. (2014). "The errors, insights and lessons of famous AI predictions–and what they mean for the future." *Journal of Experimental & Theoretical Artificial Intelligence*.
20. Horvitz, E., & Selman, B. (2009).
21. Hawking, et al. (2014).
22. Stilgoe, J., Owen, R., & Macnaghten, P. (2013). Developing a framework for responsible innovation. *Research Policy*, *42*(9):1568-1580.
23. Armstrong, S., Sotala, K., & Ó hÉigeartaigh, S. S. (2014). "The errors, insights and lessons of famous AI predictions–and what they mean for the future." *Journal of Experimental & Theoretical Artificial Intelligence*.
24. See Posner (2004, Chapter 3) and Matheny (2007).
25. Feldman, A. (1980) *Welfare economics and social choice theory*. Boston, MA: Martinus Nijhoff Publishing.
Kaul, Inge, Isabelle Grunberg and Marc A. Stern (eds.) (1999). *Global public goods: international cooperation in the 21st century*. NY: Oxford University Press.

Section 4 High Level Case Study: Natural Disasters and the Insurance Industry

1. *National Risk Register of Civil Emergencies* (Cabinet Office, London, 2013). Available at https://www.gov.uk/government/publications/national-risk-register-for-civil-emergencies-2013-edition
2. Lorenz, E. N. Deterministic Nonperiodic Flow. *J. Atmos. Sci.* **20**, 130–141 (1963).

Chapter 11: Bringing It All Together

1. Willetts, D. (2013) *Eight Great Technologies*, London: Policy Exchange http://www.policyexchange.org.uk/images/publications/eight%20great%20technologies.pdf
2. Tait, J. with Wield, D., Chataway, J. and Bruce. A. (2008) *Health Biotechnology to 2030.* Report to OECD International Futures Project, "The Bio-Economy to 2030: Designing a Policy Agenda", OECD, Paris, pp 51; http://www.oecd.org/dataoecd/12/10/40922867.pdf.
3. Tait, J. and Barker, G., (2011)Global food security and the governance of modern biotechnologies: opportunities and challenges for Europe. *EMBO Reports, 12,* pp763-768. (http://www.nature.com/embor/journal/v12/n8/pdf/embor2011135a.pdf)
4. Tait, J. and Lyall, C. (2005) A New Mode of Governance for Science, Technology, Risk and the Environment. In eds. C. Lyall and J. Tait, *New Modes of Governance*. Aldershot: Ashgate Publishing Ltd., pp 177-188.
5. Lyall, C. and Tait, J. (eds.) (2005) *New Modes of Governance: Developing an Integrated Policy Approach to Science, Technology, Risk and the Environment*. Aldershot, Hampshire: Ashgate Publishing Ltd.
6. Rhodes, R.A.W. (1994), The Hollowing out of the State: the Changing Nature of the Public Service in Britain, *Political Quarterly, 65*:138-151.
7. Osborne, D. and Gaebler, T. (1992), *Reinventing government : How the entrepreneurial spirit is transforming the public sector* (Reading, MA: Addison-Wesley).
8. Gillott, J (2014) *Bioscience, Governance and Politics*. Basingstoke, Hampshire, Palgrave Macmillan
9. Collins, H.M. and Evans, R. (2007) *Rethinking Expertise*. London: The University of Chicago Press.
10. Sunstein, C. (2005), *Laws Of Fear, Beyond The Precautionary Principle*, Cambridge University Press.
11. illis, R. and Wilsdon, J. (2004) *See-through science: why public engagement needs to move upstream.* London: Demos.
12. Adams, J. (2005) Hypermobility: a challenge for governance. In eds. Lyall, C. and Tait, J. *New Modes of Governance*. Aldershot: Ashgate Publishing Ltd.,
13. Sunstein C. R. (2009) Going to Extremes: How Like Minds Unite and Divide. Oxford, Oxford University Press
14. Tait, J. (2009) Upstream Engagement and the Governance of Science: the shadow of the GM crops experience in Europe. *EMBO Reports*. Vol 10, Special Issue, pp 18-22. (http://www.nature.com/embor/journal/v10/n1s/pdf/embor2009138.pdf)
15. Tait, J. (2001) More Faust than Frankenstein: the European Debate about Risk Regulation for Genetically Modified Crops. *Journal of Risk Research, 4(2),* 175-189.
16. Anon (2004) Editorial: going public. *Nature* **431:** 883
17. Willis, R. and Wilsdon, J. (2004) *See-through science: why public engagement needs to move upstream.* London: Demos.
18. Bhattachary, D., Calitz, J.P. and Hunter, A. (2010) *Synthetic Biology Dialogue*. Published by Biotechnology and Biological Sciences Research Council (BBSRC), Engineering and Physical Sciences Research Council (EPSRC) and ScienceWise, June 2010. (http://www.bbsrc.ac.uk/web/FILES/Reviews/1006-synthetic-biology-dialogue.pdf)
19. Stilgoe, J. and Kearnes, M. (2007) *Nanodialogues Report: engaging research councils*. London: Demos. (http://webarchive.nationalarchives.gov.uk/20091004173547/http://www.epsrc.ac.uk/CMSWeb/Downloads/Other/NanodialogueEngagingResearchCouncilsReport.pdf)
20. Jones, R. (2008) When it pays to ask the public. *Nature Nanotechnology*, 3, 578-579.
21. Mittra, J., Mastroeni, M. and Tait, J. (2014) *Engaging with Uncertainty and Risk in Agricultural Biotechnology Regulation: Delivering Safety and Innovation.* Report from ESRC Knowledge Exchange Project with Syngenta, Jan. 2014. (http://innogen.ac.uk/reports/883)
22. Seralini, GE, Clair, E, Mesnage, R, Gress, S, Defarge, N, Malatesta, R, Hennequin, D, DeVendomois, JS, (2012) Long term toxicity of a Roundup herbicide and a Roundup tolerant GM maize. *Food and Chemical Toxicology, 50(11),* 4221-31 (retracted)
23. Tait, J. (2001) More Faust than Frankenstein: the European Debate about Risk Regulation for Genetically Modified Crops. *Journal of Risk Research, 4(2),* 175-189.
24. Tait, J. (2007) Systemic Interactions in Life Science Innovation. *Technology Analysis and Strategic Management, 19(3),* 257-277, May 2007.
25. Mittra, J., Mastroeni, M. and Tait, J. (2014) *Engaging with Uncertainty and Risk in Agricultural Biotechnology Regulation: Delivering Safety and Innovation.* Report from ESRC Knowledge Exchange Project, Jan. 2014. http://innogen.ac.uk/reports/883

Chapter 11 Case Study: A Case History on GM Crops

1. Baulcombe, D. C., Dunwell, J., Jones, J., Pickett, J. and Puigdomenech, P. *GM Science Update A report to the Council for Science and Technology.* (2014). Available at https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/292174/cst-14-634a-gm-science-update.pdf
2. EuropaBio *Failures of the EU authorisation system for GMOs – Causes, Impacts and Solutions* (2013). Available at http://www.europabio.org/positions/failures-eu-authorisation-system-gmos-causes-impacts-and-solutions
3. Falck-Zepeda, J., Gruère, G. and Sithole-Niang, I. Genetically Modified Crops in Africa: Economic and Policy Lessons from Countries South of the Sahara. *Int. Food Policy Res. Inst. Rep. IFPRI Issue Brief 80* (2013). Available from: http://www.ifpri.org/sites/default/files/publications/ib80.pdf
4. Kalaitzandonakes, N., Alston, J. M. and Bradford, K. J. Compliance costs for regulatory approval of new biotech crops. *Nature Biotechnol.* **25**, 509–511 (2007).
5. Lai, J. *et al.* Genome-wide patterns of genetic variation among elite maize inbred lines. *Nature Genet.* **42**, 1027–1030 (2010).
6. Greaves, I. K., Groszmann, M., Wang, A.,

Peacock, W. J. and Dennis, E. S. Inheritance of Trans Chromosomal Methylation patterns from Arabidopsis F1 hybrids. *Proc. Natl Acad. Sci. USA.* **111**, 2017–2022 (2014).
7. Jones, J. D. G. *et al.* Elevating crop disease resistance with cloned genes. *Phil. Trans. R. Soc. Lond. B* **369**, 20130087 (2014).

Chapter 11 Case Study: Standards: Supporting emerging technologies as an accelerator of innovation

1. Taylor, J. M. *New Dimensions for Manufacturing: A UK Strategy for Nanotechnology* (Department of Trade and Industry, London, 2002). Available at http://webarchive.nationalarchives.gov.uk/20130221185318/http://www.innovateuk.org/_assets/pdf/taylor%20report.pdf
2. BSI is appointed by Her Majesty's Government as the UK National Standards Body (NSB), and represents the United Kingdom on the international and European standards organizations ISO, IEC, CEN, CENELEC and ETSI. BSI's scope covers all industry sectors, and its staff facilitates committees of experts that draft the standards they need on any business issue. BSI manages around 1,200 standards committees in total, including around 200 international and European committees. See http://www.bsigroup.co.uk/

Chapter 12: Ultimately a Decision Has To Be Made

1. Watson, J. D. and Crick, F. H. C. A structure for Deoxyribose Nucleic Acid. *Nature* **171**, 737-8 (1953).
2. I completed my two terms as Chair of the HFEA in January 2014. I write here in a personal capacity.
3. A previous successful consultation exercise on human-admixed embryos provided us with a good starting point.
4. Detailed information on these processes, plus all the material used in the consultation can be found at http://www.hfea.gov.uk/
5. HFEA *New techniques to prevent mitochondrial disease*. See http://mitochondria.hfea.gov.uk/mitochondria/what-is-mitochondrial-disease/new-techniques-to-prevent-mitochondrial-disease/
6. There were in fact 3 reports from the 'panel of experts' over the consultation period, in order to keep the scientific findings up to date. The first two were chaired by Prof. Neva Haites, the third by Dr. Andy Greenfield.
7. Mongomery, J. *et al. Novel techniques for the prevention of mitochondrial DNA disorders: an ethical view* (Nuffield Council on Bioethics, London, 2012). Available at http://nuffieldbioethics.org/wp-content/uploads/2014/06/Novel_techniques_for_the_prevention_of_mitochondrial_DNA_disorders_compressed.pdf
8. *Mitochondria replacement consultation: Advice to Government* (HFEA, London, 2013). Available at http://www.hfea.gov.uk/docs/Mitochondria_replacement_consultation_-_advice_for_Government.pdf
9. *Mitochondrial Donation: Government response to the consultation on draft regulations to permit the use of new treatment techniques to prevent the transmission of a serious mitochondrial disease from mother to child* (Department of Health, London, 2014). Available at https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/332881/Consultation_response.pdf
10. House of Commons Debate 1 September 2014, vol **585**, cols 93-122 (Hansard). Available at http://www.publications.parliament.uk/pa/cm201415/cmhansrd/cm140901/debtext/140901-0003.htm#14090125000001

Annex: How to Build Regulatory Frameworks for New Technologies

1. Dominique Auverlot, France Stratégie (dominique.auverlot@strategie.gouv.fr) ; Marie-Françoise Chevallier – Le Guyader, Institut des hautes études pour la science et la technologie ; Françoise Roure, CGE ; Jean-Luc Pujol, INRA; Aude Teillant, Research, Department of Ecology & Evolutionary Biology, Princeton University ; Clélia Godot, France Stratégie.
2. *Quelle France dans dix ans*, rapport de France Stratégie au président de la République, Éditions Fayard, 2014 ; or http://www.strategie.gouv.fr/publications/france-10-ans
3. Commission nationale pour le débat public.
4. written by the prefect Carrère
5. known as the Barnier laws (after France's Environment Minister)
6. Except for the airport of Notre-Dame-des-Landes. In this particular case, public debate failed to prevent the deployment of strong opposition that appeared at the start of the works and that has stopped its realization.
7. This paragraph has been written by Aude Teillant. See also Teillant A. (2011), *Toward a responsible development of nanotechnologies, Note d'analyse*, Centre d'analyse stratégique, novembre.
8. For a concise presentation of the context and proceedings of the debate, see Deslandes P. (2010), *Bilan du débat public sur le développement et la régulation des nanotechnologies,* CNDP.
9. *OGM et agriculture : options pour l'action publique,* septembre 2011, http://www.ladocumentationfrancaise.fr/rapports-publics/014000692/index.shtml
10. The Institute of Advanced Studies for Science and Technology organizes for professional leaders from every sector of society (research and higher education, business, media, government, elected people, associations, journalists, educators) a national training cycle where they can share their experiences of stakeholders in an international perspective.

© Crown copyright 2014

Printed on paper containing 75% recycled fibre content minimum.
First published November 2014
The Government Office for Science
URN: GS/14/1190B