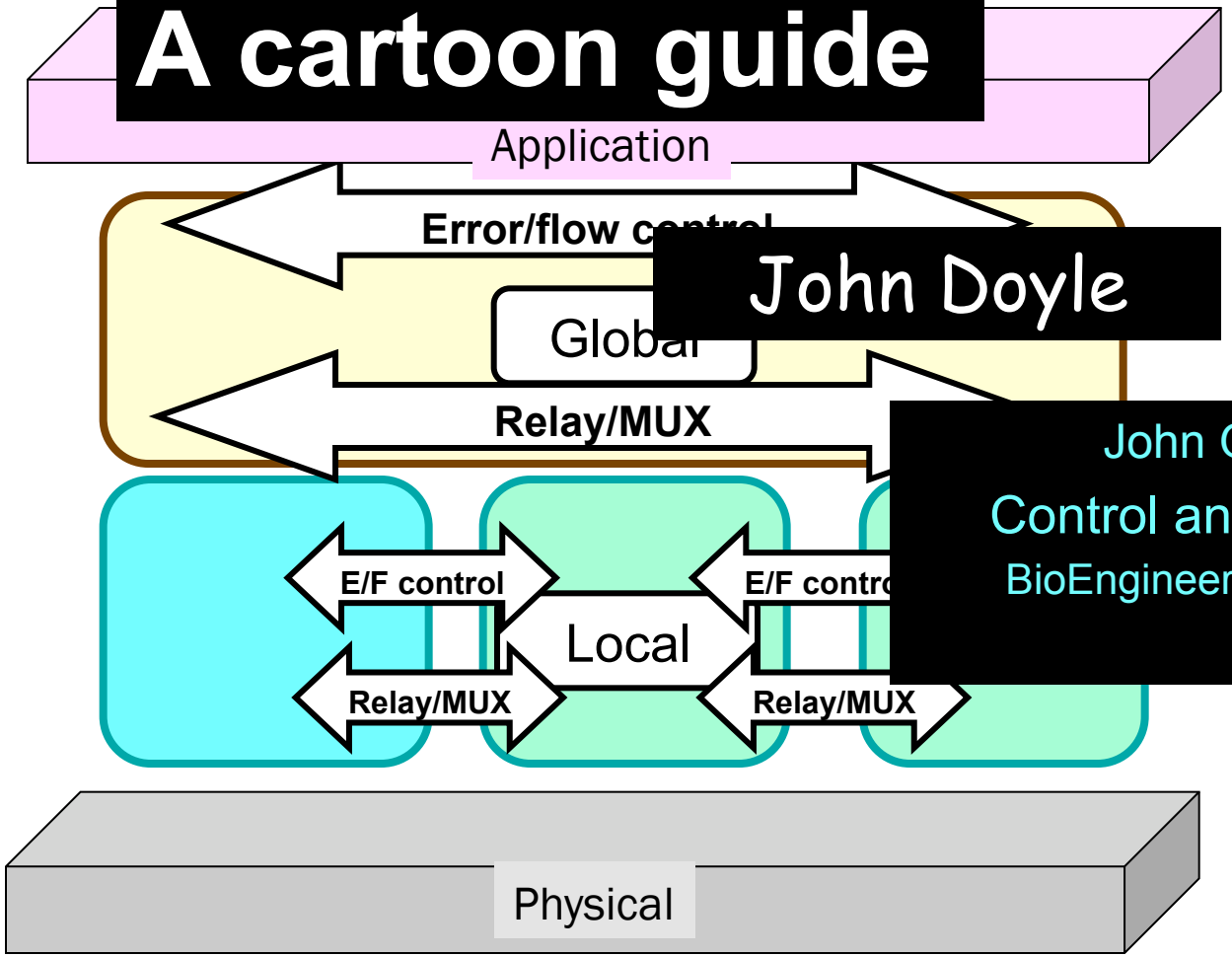
Complex Network Architecture: A cartoon guide



John Doyle

Reactions

Flow

Protein level

Reactions

Flow

RNA level

Flow

DNA level

John G Braun Professor
Control and Dynamical Systems
BioEngineering, Electrical Engineering
Caltech

Outline

- Not merely “complexity, networks, abstraction, recursion, modularity,…”
- But very specific forms of these that are needed for networks
- Emphasize fundamentals
- Illustrate with case studies and cartoons:

  Internet versus bacterial biosphere

  Operating systems

  Global brain architecture

  Smartgrid and cyberphysical

Next steps?

- New course this term? (CDS 213?)
- Flesh out details
- Integrated theory: control, comms, computing, thermo/statmech, optimization, games, etc
- Motivated by very generic network challenges

Network Math and Engineering (NetME) Challenges

- Predictive modeling, simulation, and analysis of complex systems in technology and nature
- Theoretical foundation for design of network architectures
- Balance rigor/relevance, integrative/coherent
- Model/simulate is critical but limited
  - Predicting rare but catastrophic events
  - Design, not merely analysis
  - Managing complexity and uncertainty

NetME as a discipline?

- Variety of existing networks to understand and challenges in designing new ones
- NetX = networking of domain X
  - NetOS = Internet
  - NetBio = systems biology
  - NetGrid = smartgrid
  - …
- Claim: There is a universal “net” subject that will enable NetX for many different X.
- Q: How much of each “X” do we need to know.

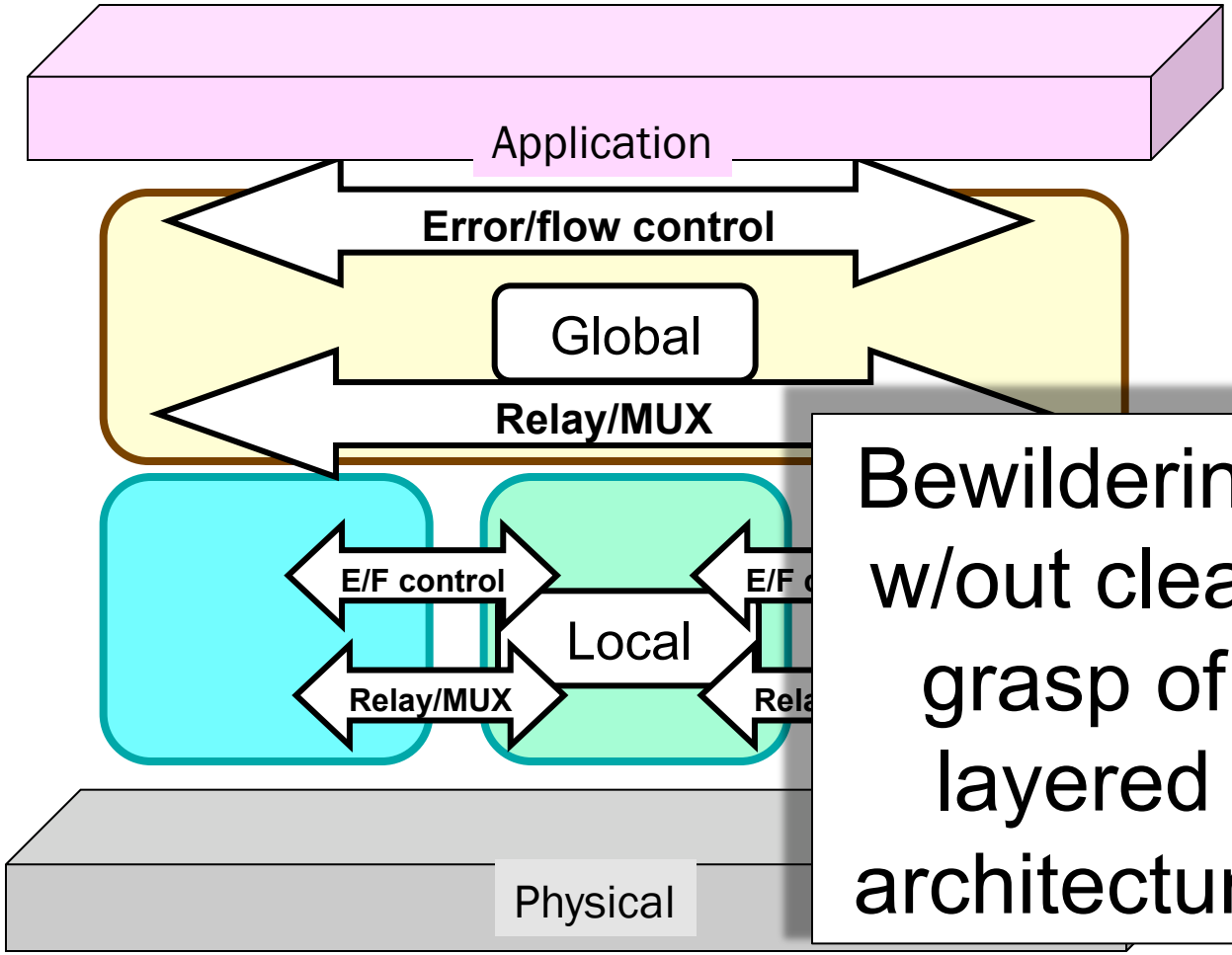
NetME now

- The foundations are fragmented into various “systems” subjects that need unification
- Available case studies are mixes of accident, history, and necessity, so extracting lessons learned is subtle
- Our strategy: Blend theory and “natural history”
  - Theory: math to unify/extend the fragments
  - Natural history: “enlightened” case studies
  - Teaching: better approaches to “Xes”
  - Need ∩ and extension, not just ∪
- Keep chasing “architecture”

213 logistics

- P/F only
- Units are flexible and individual
- No universal requirements
- Can focus on case studies or theory or whatever
- Hope to integrate with S. Low course and smartgrid
- No universal text but suggestions for those focusing on case studies

Huge range of dynamics
- Spatial
- Temporal



Bewildering w/out clear grasp of layered architecture

Reactions
Flow
Protein level

Reactions
Flow
RNA level

Reactions
Flow
DNA level

“Architecture”

- Most persistent, ubiquitous, and global features of organization
- Constrains what is possible for good or bad
- Platform that enables (or prevents) innovation, sustainability, etc,
- Internet, biology, energy, manufacturing, transportation, water, food, waste, law, etc
- Existing architectures are unsustainable
- Theoretical foundation is fragmented, incoherent, incomplete

Infrastructure networks?

- Power
- Transportation
- Water
- Waste
- Food
- Healthcare
- Finance

All examples of "bad" architectures:
- Unsustainable
- Hard to fix

Where do we look for "good" examples?

Informative case studies in architecture

- Internet and related technology (OS)
- Systems biology (particularly, bacterial biosphere)
- System medicine and physiology
- Ecosystems (e.g. So Cal wildfire ecology)
- Aerospace systems
- Electronic Design Autom. (Platform Based Design)

- Multiscale physics (turbulence, stat mech)
- Misc: buildings/cities, Lego, clothing/fashion, barter/ markets/money/finance, social/political

Important Influences We Hope to Include in This Course

- There increasingly many researchers/authors with increasingly coherent thinking about architecture
- Remarkably convergence across many fields
- Different language and domains so translation is difficult
- We'll have a few central case studies (primarily Internet and biology) but try to connect with some others

Primary focus for this course

- Biology/Medicine (Savageau, G&K, Mattick, Csete, Arkin, Alon, Caporale, de Duve, Exerc Physio, Acute Care, etc…)
- Internet (Kelly/Low, Willinger, Clark, Wroclawski, Day, Chang, Alderson, etc)

Other Influences We Hope to Include in This Course

- Architecture (Alexander, Salingeros,…)
- Aerospace (many, Maier is a good book)
- Philosophy/History (Fox Keller, Jablonka&Lamb)
- Physics/ecology (Carlson)
- Management (Baldwin,…)
- Resilience/Safety/Security Engineering/Economics (Wood, Anderson, Leveson, …)
- Platform Based Design: Alberto S-V, Lee, …

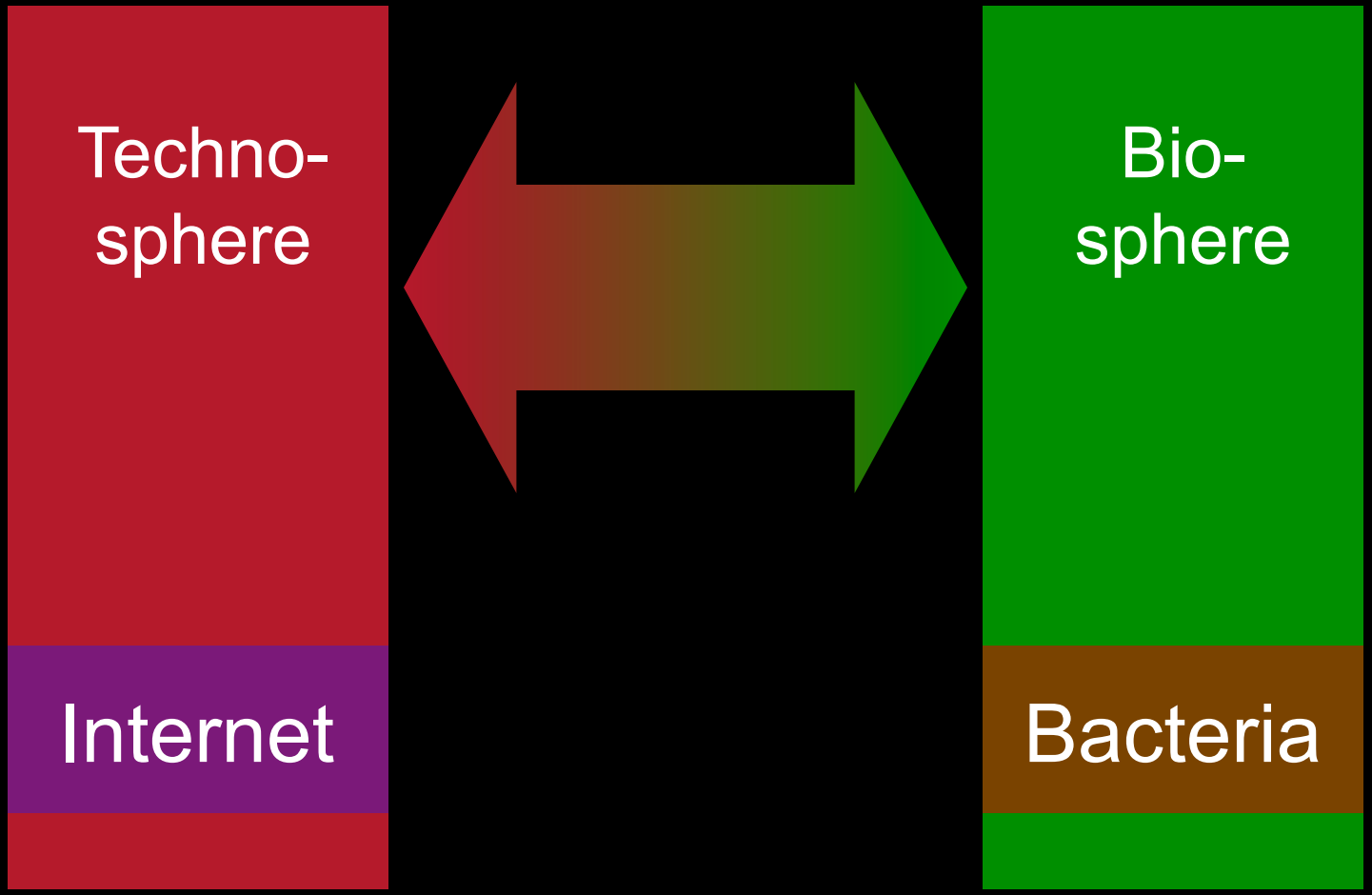
- Successful architectures
- Robust, evolvable
- Universal, foundational
- Accessible, familiar
- Unresolved challenges
- New theoretical frameworks
- Boringly retro?

Simplest case studies

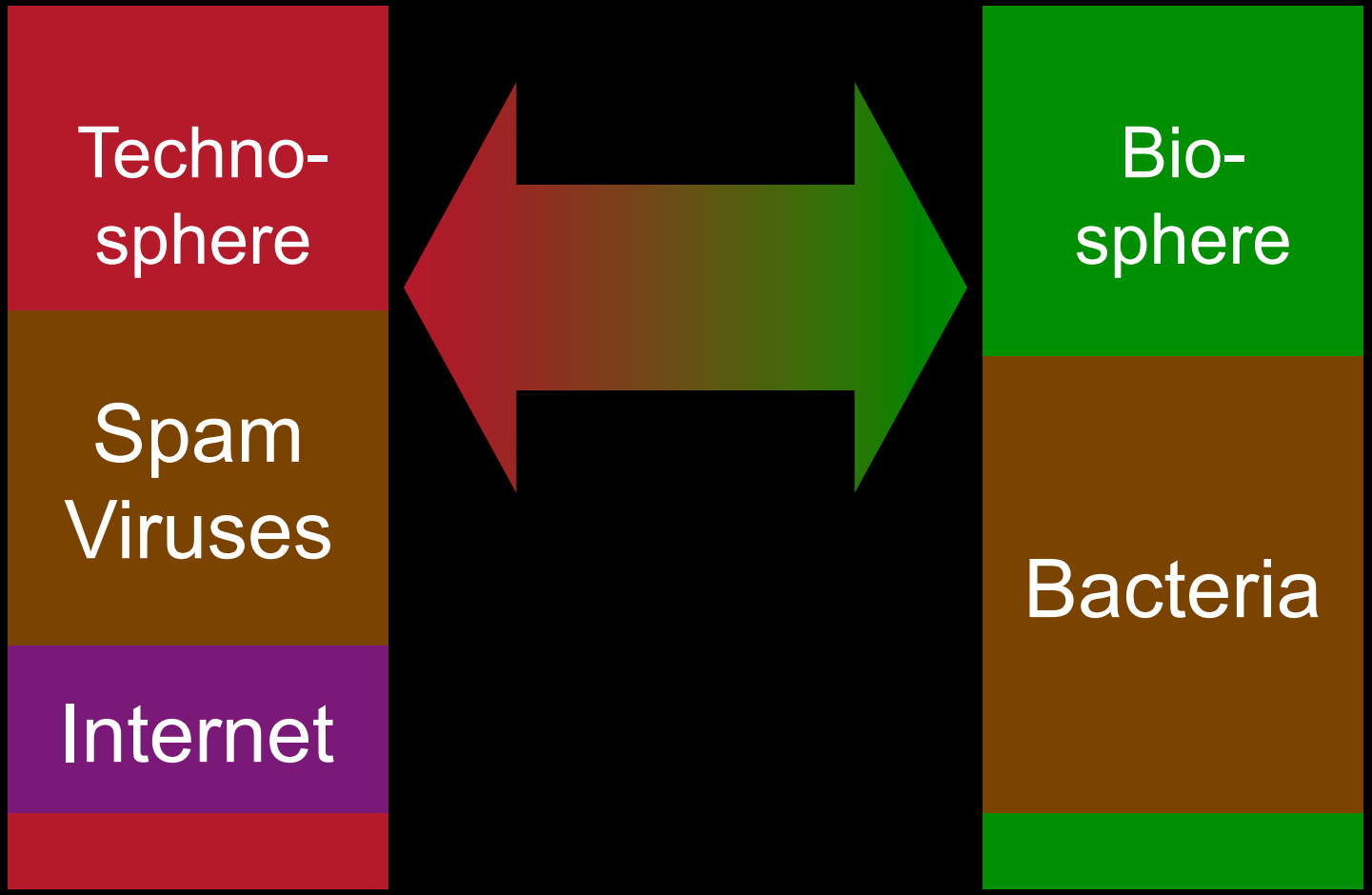
Internet

Bacteria

- Universal, foundational

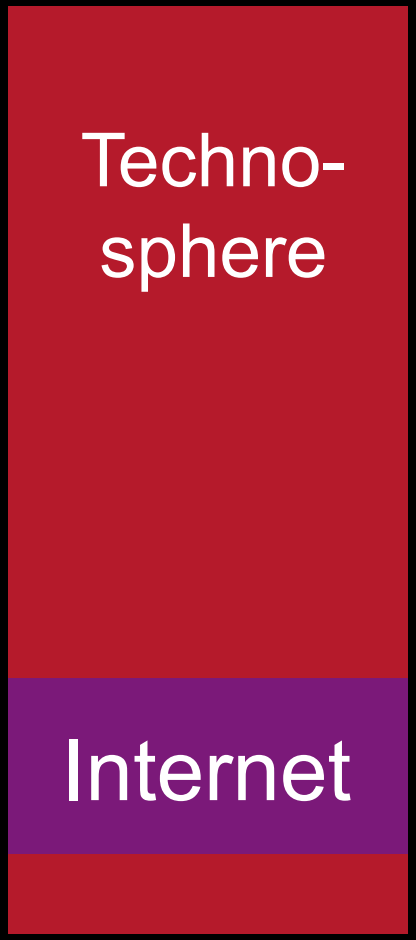


- Universal, foundational



Two lines of research:

1. Patch the existing Internet architecture so it handles its new roles



- Real time
- Control ***over*** (not just of) networks
- Action in the physical world
- Human collaborators and adversaries
- Net-centric ***everything***

Modern theory and the Internet

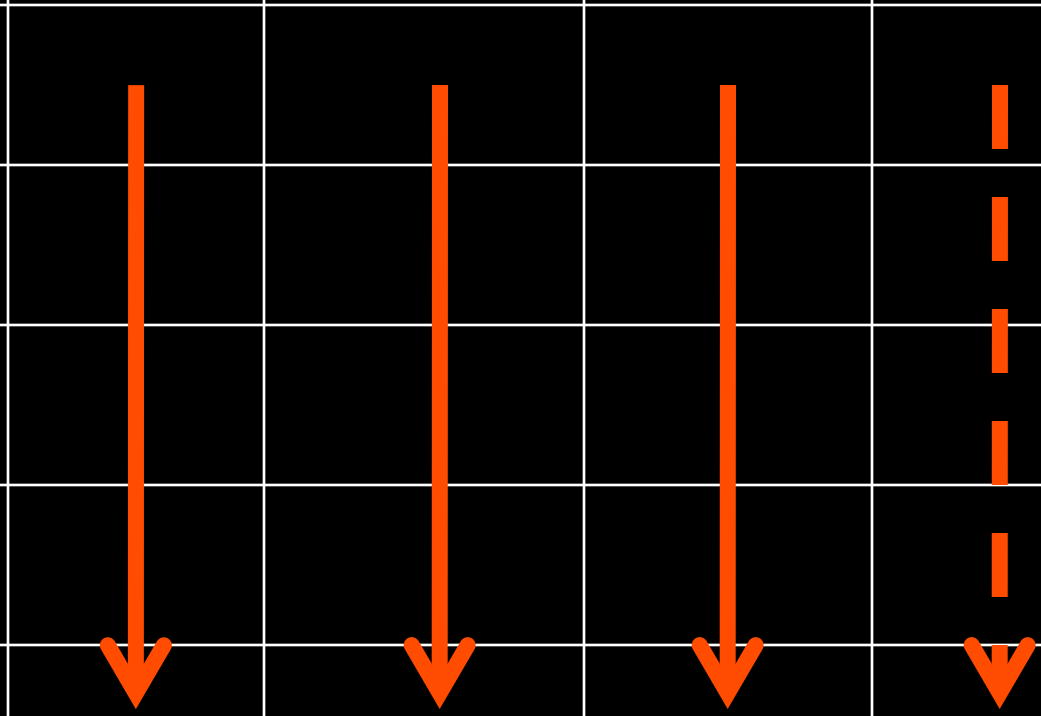
Levels of understanding

Verbal/cartoon
Data and statistics
Modeling and simulation
Analysis
Synthesis

Topics

Traffic
Topology
Control and dynamics
Layering
Architecture

Recent progress (1995-)

	Traffic	Topology	C&D	Layering	Architect.
Cartoon					?
Data/stat					
Mod/sim					
Analysis					
Synthesis					

Recent progress

	Traffic	Topology	C&D	Layering	Architect.
Cartoon					
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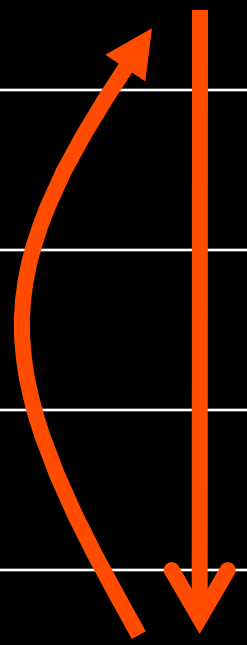
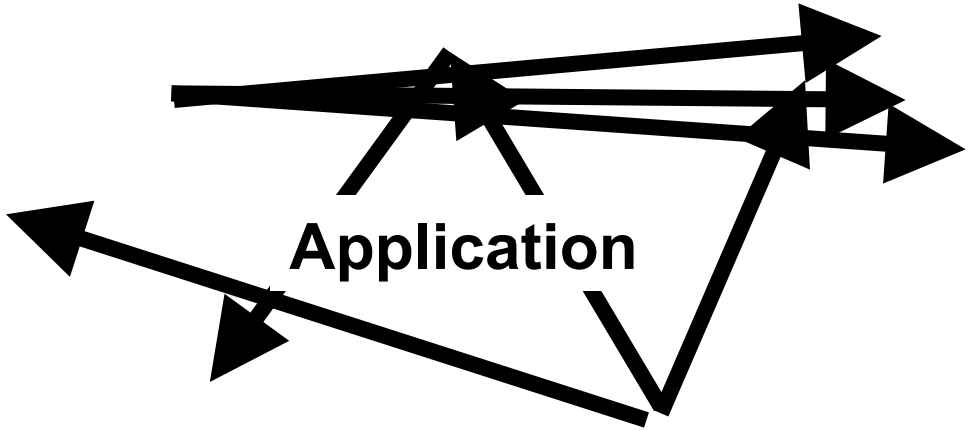
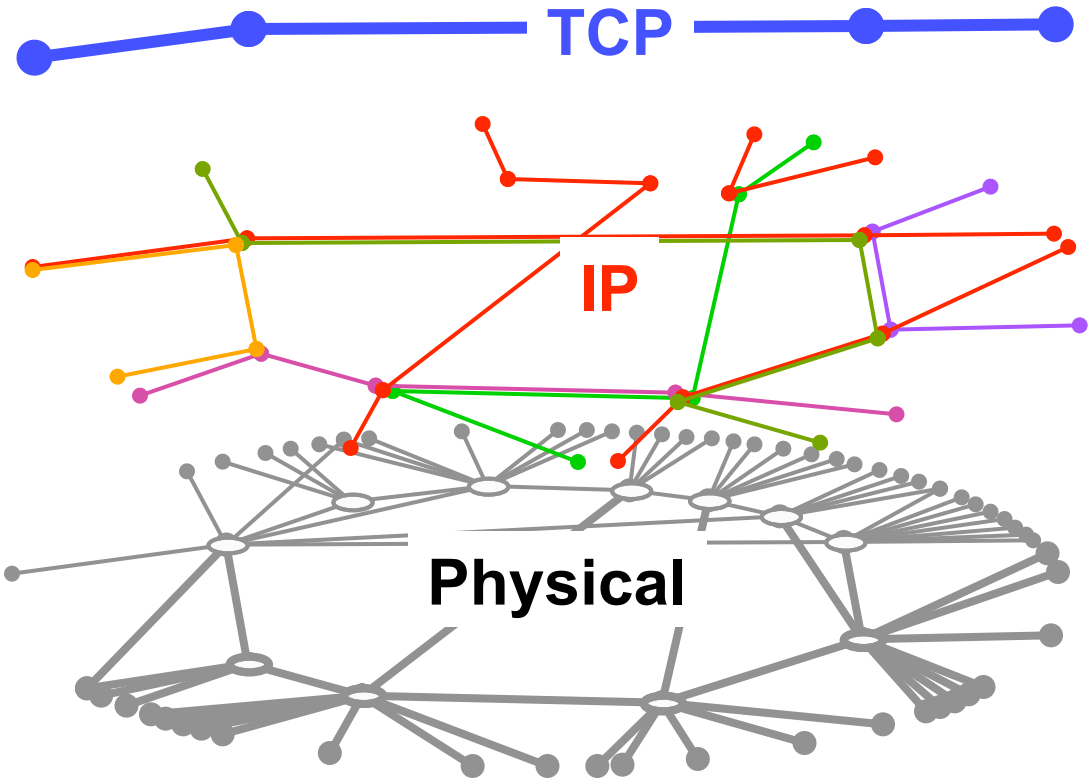
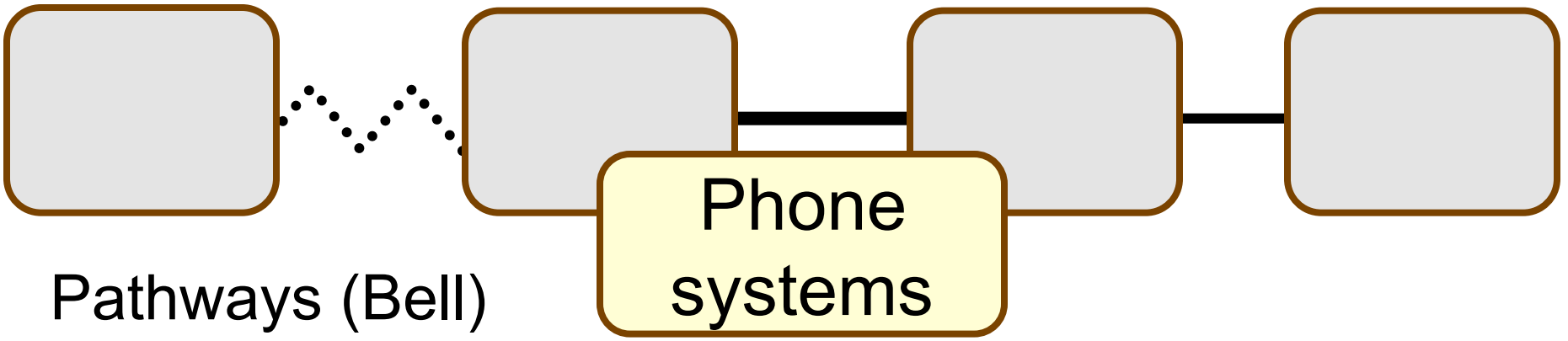


Architecture is ***not*** graph topology.



Architecture facilitates arbitrary graphs.

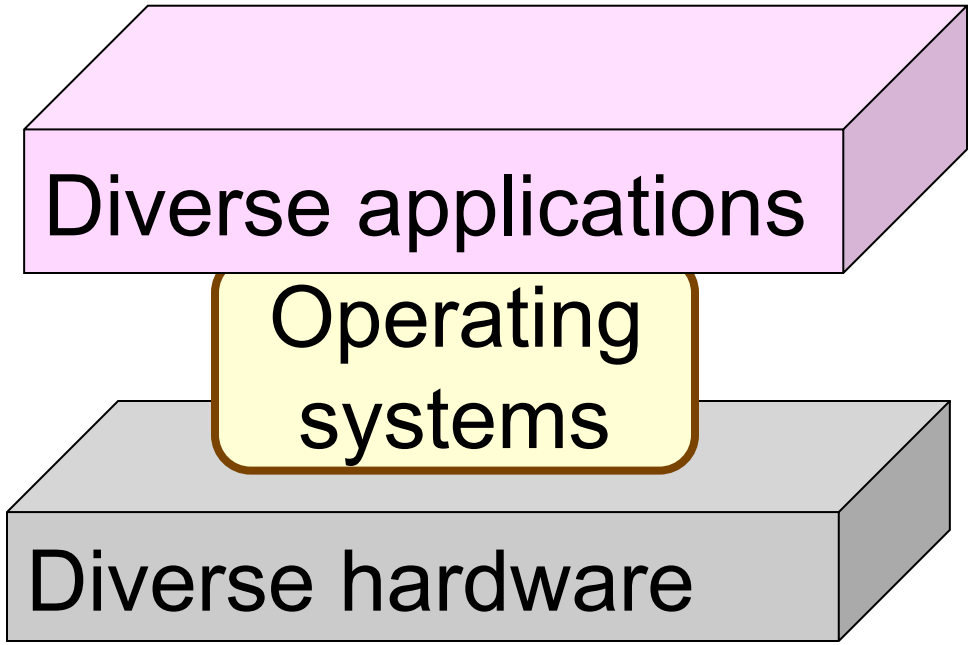




Pathways (Bell)
Communications

Layers (Net)
Computer

Ancient network architecture: “Bell-heads versus Net-heads”



Recent progress (1995-)

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Cartoon					
Data/stat					
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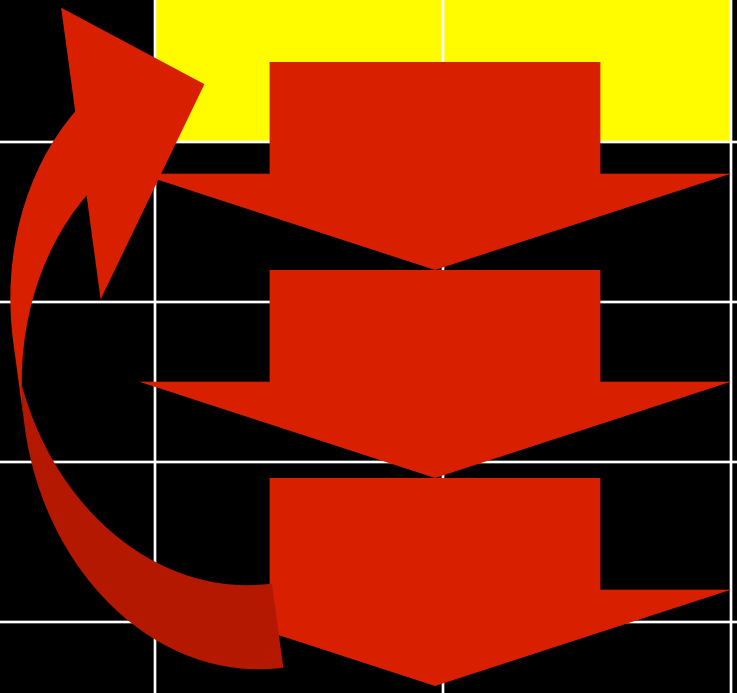
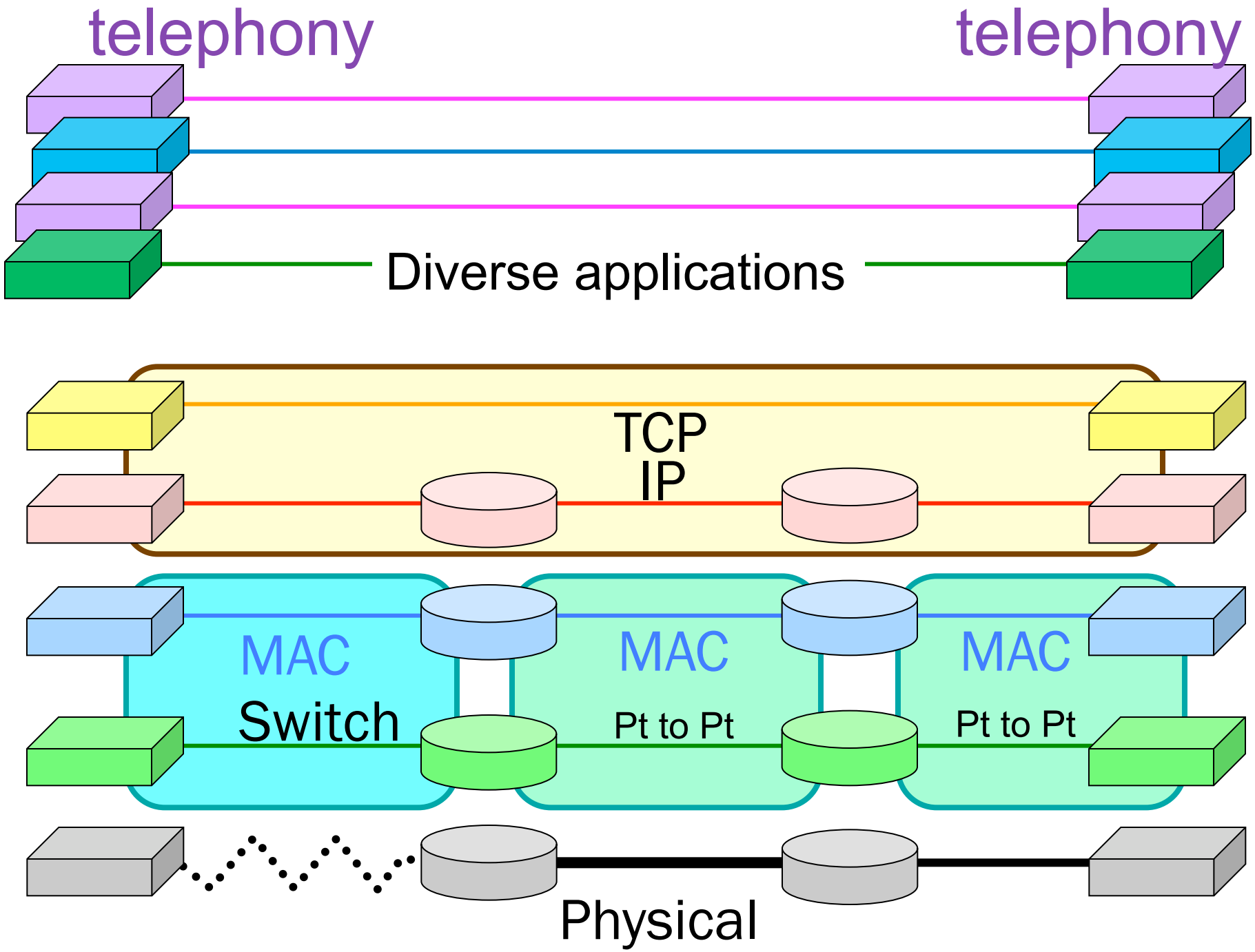
Analysis					
Synthesis					




telephony
telephony
Diverse applications
TCP
IP
MAC
Switch
MAC
Pt to Pt
MAC
Pt to Pt
Physical

Theoretical framework:
Constraints that deconstrain

Applications Deconstrained

$$\min_{\mathbf{x}} \left\{ \int \left(\left\| R\tilde{\mathbf{x}} - \mathbf{c} \right\|^2 + \left\| R\mathbf{x} - \mathbf{c} \right\|^2 \right) dt \right\}$$

$$\left| \begin{array}{l} \tilde{\mathbf{x}} = \arg\max_{\mathbf{v}} L(\mathbf{v}, \mathbf{p}), \quad \dot{\mathbf{p}} = R\mathbf{x} - \mathbf{c} \\ \Rightarrow x_s = \arg\max_{v} L_s(v, \mathbf{p}) \end{array} \right.$$

Resources Deconstrained

Enormous progress

- Layering as optimization decomposition
- Optimal control
- Robust control
- Game theory
- Network coding

Theoretical framework:
Constraints that deconstrain

Enormous progress
- Layering as optimization
- Optimal control
- Robust control
- Game theory
- Network coding

- Many robustness issues left unaddressed
- Secure, verifiable, manageable, maintainable, etc
- Architecture/policy, not part of control/dynamics
- How to expand the theory?

Cyber-Physical Theories?

- Thermodynamics
- Communications
- Control
- Computation

- Same robustness issues still unaddressed
- Architecture/policy, not part of any of these
- Each assumes an architecture a priori
- How to expand the theory?

Cyber

- Thermodynamics
- Communications
- Control
- Computation

Physical

- Thermodynamics
- Communications
- Control
- Computation

Internet

Bacteria

Case studies motivate integration

Cyber

- Thermodynamics
- Communications
- Control
- Computation

Physical

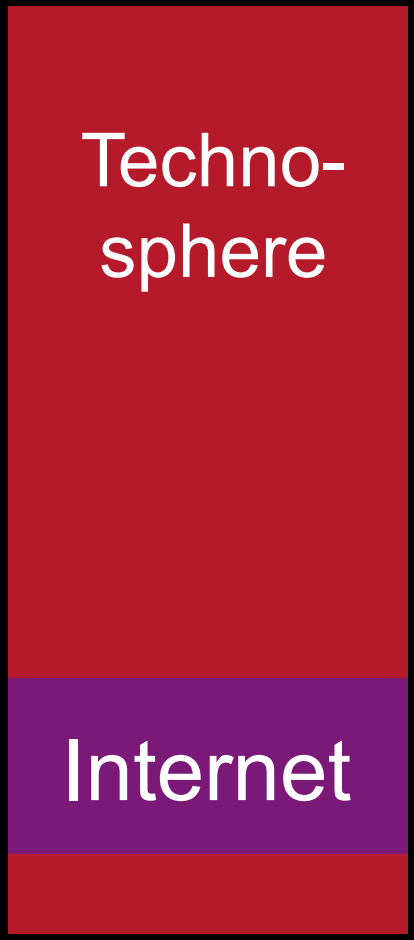
- Thermodynamics
- Communications
- Control
- Computation

Promising unifications

A start but more is needed

Two lines of research:

1. Patch the existing Internet architecture
2. Fundamentally rethink network architecture



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Architecture?

	Traffic	Topology	C&D	Layering	**Architect.**
Cartoon					?
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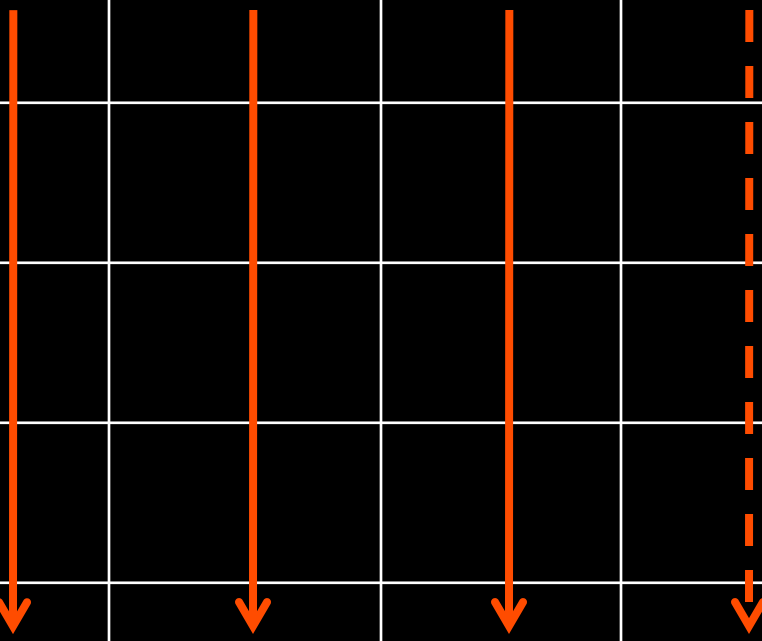

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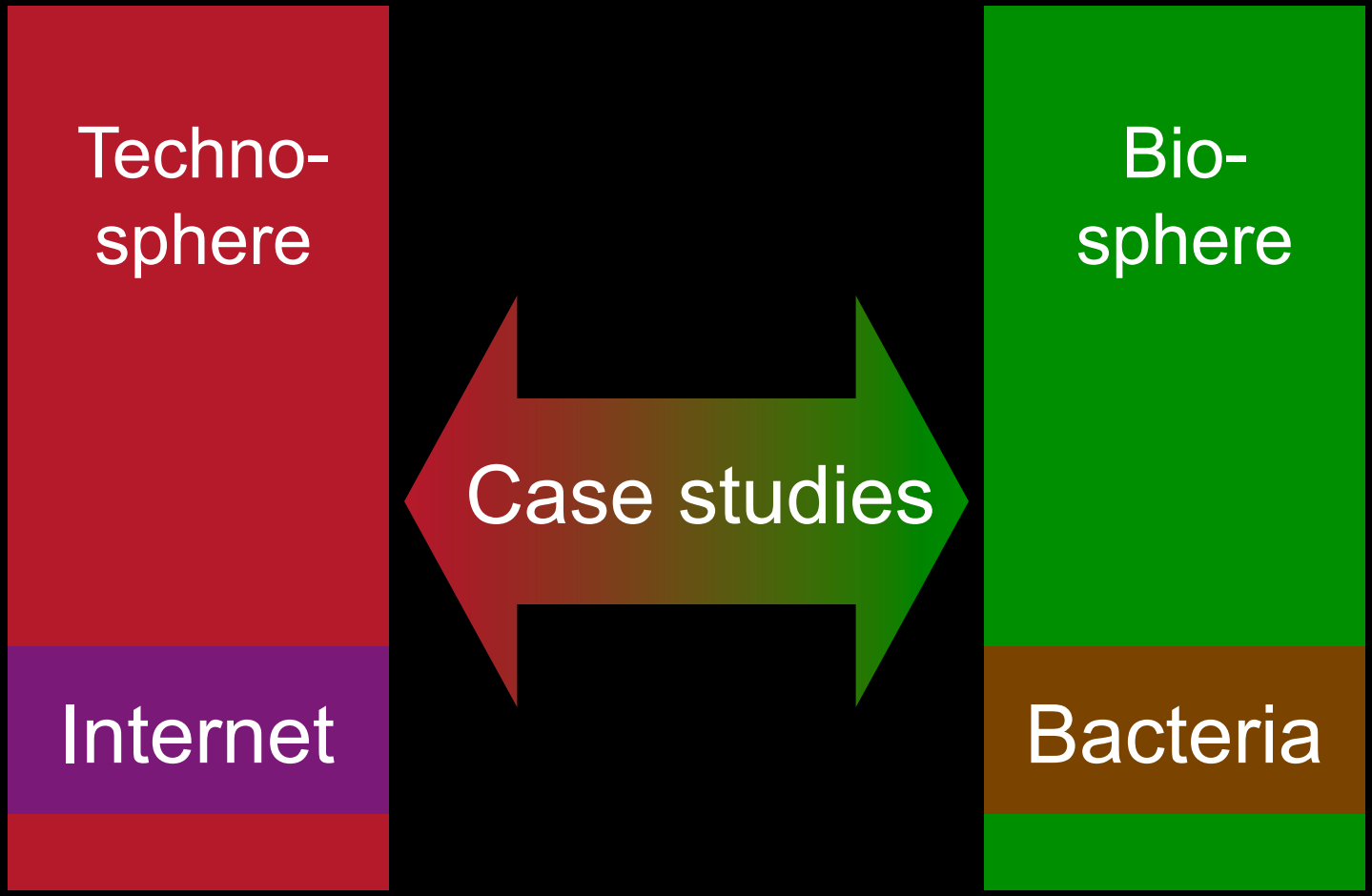
2. Fundamentally rethink network architecture



Biology versus the Internet

Similarities

- Evolvable architecture
- Robust yet fragile
- Constraints/deconstrain
- Layering, modularity
- Hourglass with bowties
- Feedback
- Dynamic, stochastic
- Distributed/decentralized
- ***Not*** scale-free, edge-of-chaos, self-organized criticality, etc

Differences

- Metabolism
- Materials and energy
- Autocatalytic feedback
- Feedback complexity
- Development and regeneration
- >4B years of evolution
- How the parts work?

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Differences

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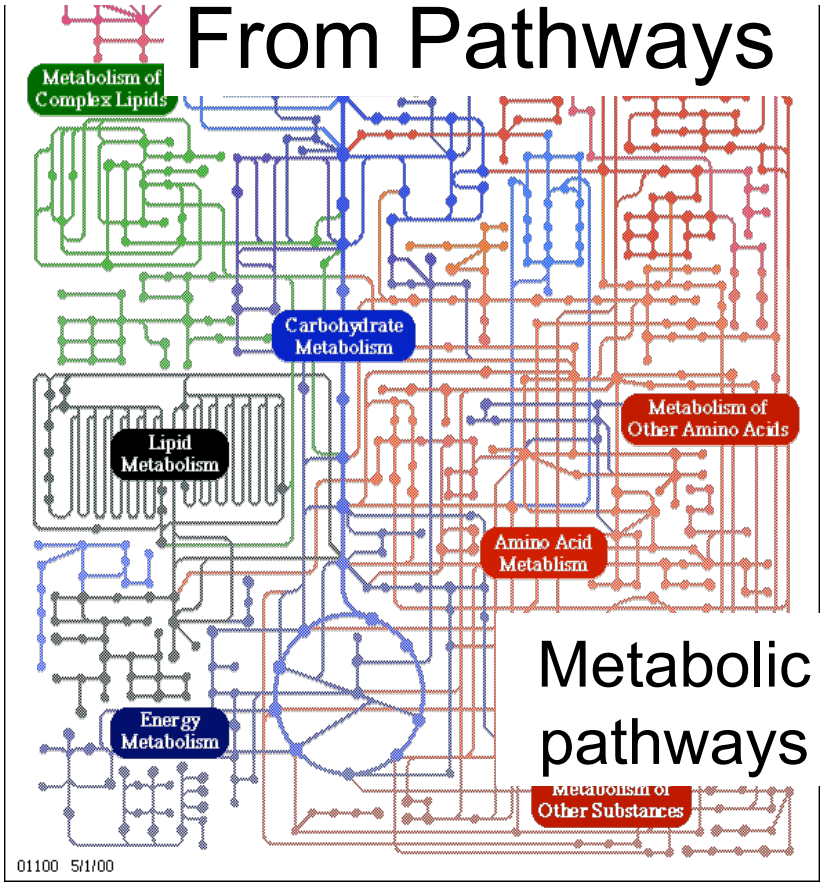
Focus on bacterial biosphere

"Central dogma"

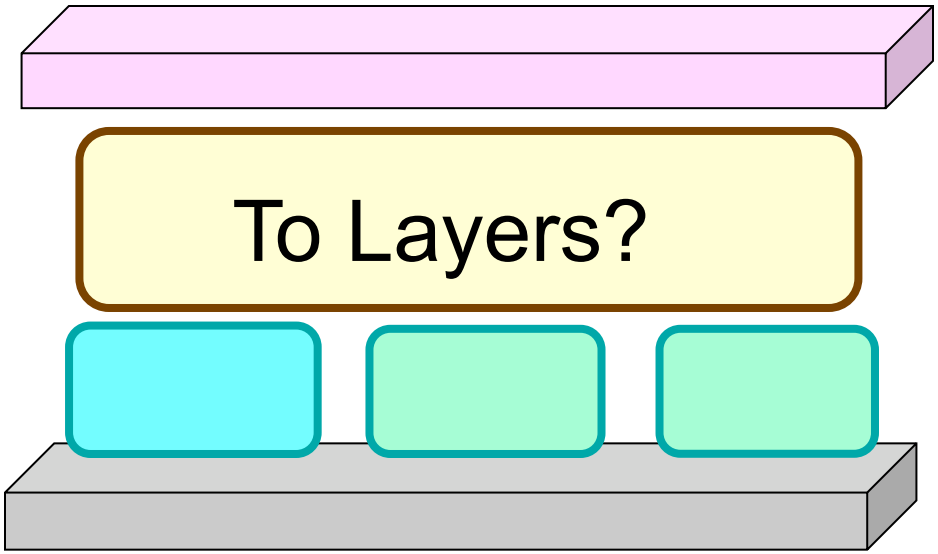
DNA → RNA → Protein

Network architecture?

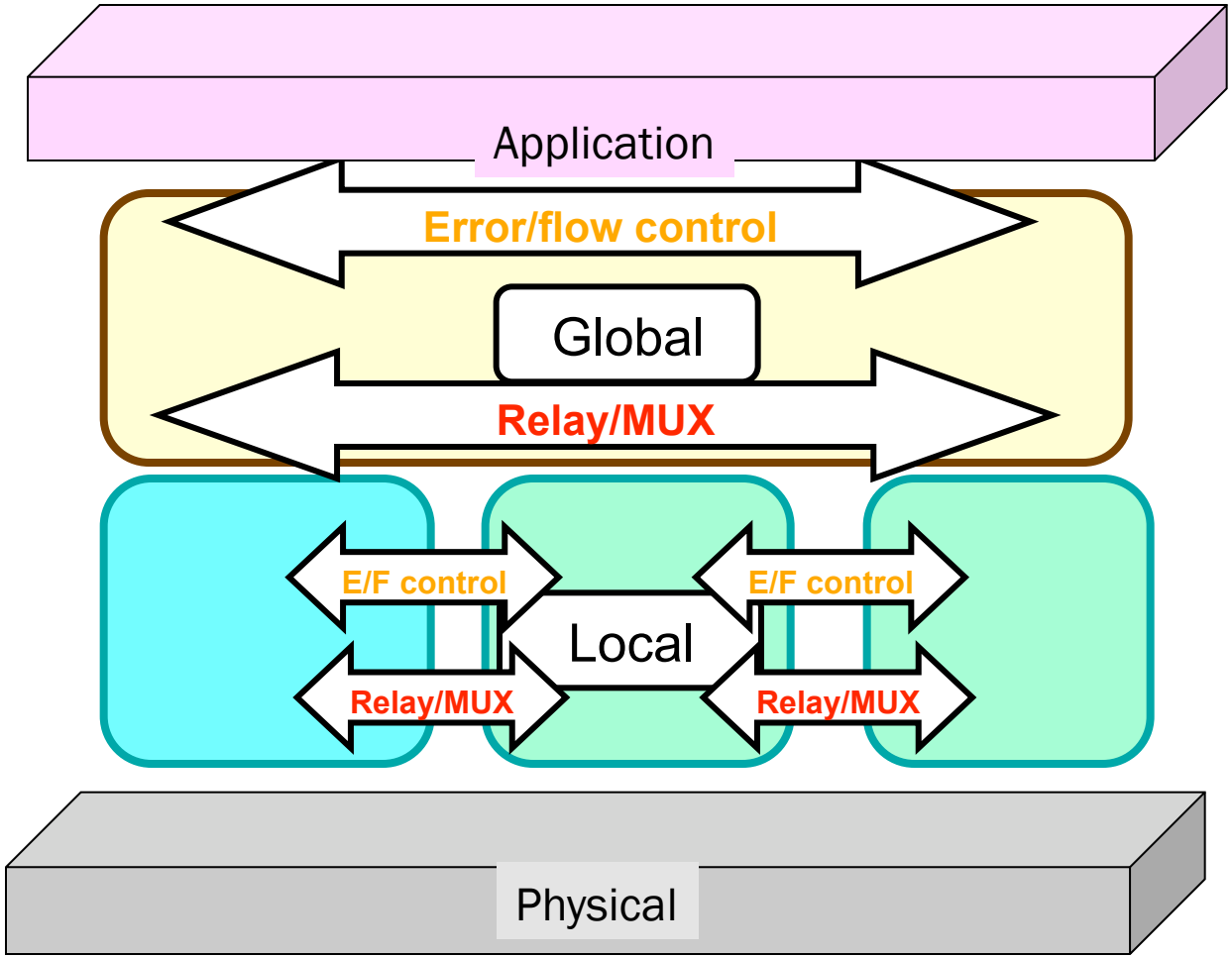
From Pathways



Metabolic pathways



Recursive control structure



Reactions
Flow
Protein level

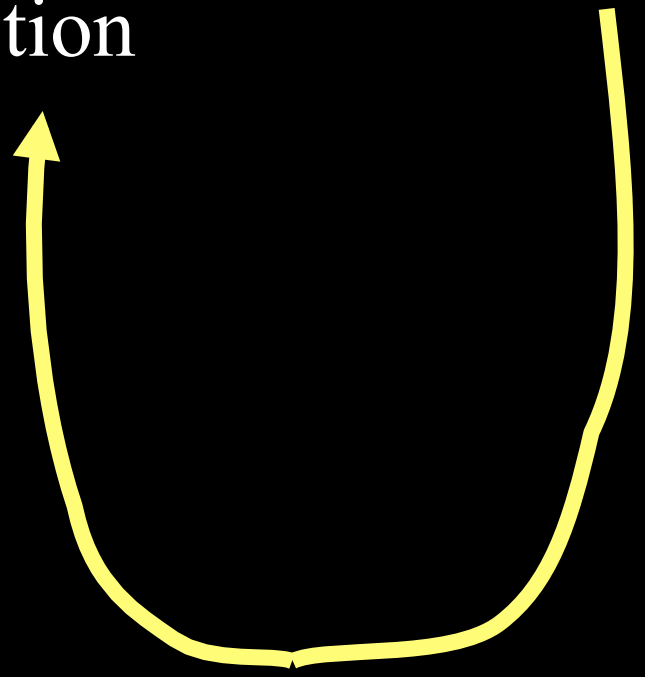
Reactions
Flow
RNA level

Reactions
Flow
DNA level

In the real (vs virtual) world

What matters:

- Action



What doesn't:

- Data
- Information
- Computation
- Learning
- Decision
- …

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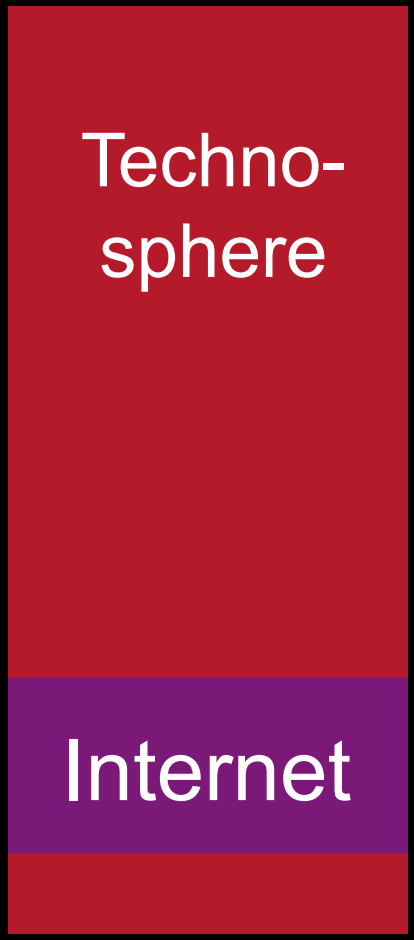

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