Constructing Scientific Understanding through Contextual Teaching

Peter Heering
Daniel Osewold (Hg.)

Frank & Timme

Verlag für wissenschaftliche Literatur

Peter Heering, Daniel Oswold (Hg.)
Constructing Scientific Understanding through Contextual Teaching

Peter Heering, Daniel Osewold (Hg.)

Constructing Scientific Understanding through Contextual Teaching

Frank & Timme
Verlag für wissenschaftliche Literatur

ISBN 978-3-86596-118-1

Herstellung durch das atelier eilenberger, Leipzig.
Printed in Germany.
Gedruckt auf säurefreiem, alterungsbeständigem Papier.

www.frank-timme.de

Contents

Preface

PETER HEERING, DANIEL OSEWOLD
Physics Education/History and Philosophy of Science, Carl-von-Ossietzky Universität, Oldenburg, Germany

Teaching is a question of context itself: as the Oldenburger Research Group Physics Education/History and Philosophy of Science accounts in their research for the historical context of science education, it appears to be consequential to focus on the role of the history of science in the teaching of science. Therefore, the goal of the *6th International Conference for the History of Science in Science Education* hosted in Oldenburg addressed the question of how historical context can promote the development of scientific understanding.

The richness of the 28 papers presented and the high quality of the discussions of the conference encouraged us to publish a volume, in which the majority of these stimulating papers is assembled. One reason why not all papers are to be found in this collection is due to the Editors tide timeline for the final paper submission. Some presenters had other obligations and could not submit their contributions in time. As editors, we considered it important to publish the obtained papers within a very short time as we feel that the topics presented and discussed are of major relevance to the future of our research field. This resulted in publication of nineteen conference papers in this volume.

We greatly appreciate the financial support of the German Science Foundation (Deutsche Forschungsgemeinschaft), the Ministry for Science and Culture of Lower Saxony, and the EWE Foundation (EWE-Stiftung), which made the realisation of this conference possible. We also thank the Carl-von-Ossietzky Universität Oldenburg for supporting the conference. Furthermore, our thanks go to the members of the Research Group Physics Education/ History and Philosophy of Science at the Carl von Ossietzky Universität that took the responsibility to make this conference a success. The publication of the conference proceedings was financially supported by the EWE foundation.

Peter Heering and Daniel Osewold
(The Editors)

Introduction

ROGER H. STUEWER
Program in the History of Science, Technology, and Medicine, University of Minnesota,
Minneapolis, MN 55455, USA

The papers that follow were presented at the Sixth International Conference for the History of Science in Science Education, which was held at the Carl-von-Ossietzky University of Oldenburg, Germany, July 10-15, 2006. They reflect the great diversity, vitality, and high quality of work on the many uses of the history of science in science teaching, to which the Oldenburg group has contributed so significantly for many years. Its leader, Falk Riess, is thus eminently qualified to sketch historically the use of historical experiments in physics teaching as presented below. The remaining papers then make clear that the use of history of science in science teaching has grown into a truly international endeavor: Science teachers from countries around the world are dedicating themselves to improving their courses at all levels of instruction by incorporating the history of science into them. The result is a remarkable diversity of means and approaches for improving the teaching of physics, astronomy, mathematics, and biology, as these papers demonstrate.

In physics, as part of an on-going research project aimed at replicating pioneering experiments to reveal their historical contexts and the difficulties in using them to produce reliable experimental data, Stephen Klassen shows how an understanding of the historical background and nature of Robert A. Millikan's oil-drop experiment can renew its pedagogical significance. Similarly, Arthur Stinner has connected the history of physics to classroom teaching through his large-concept approach as discussed in his new book. Other revealing endeavors are Shu-Chiu Liu's study of how grade-school students in Taiwan and Germany acquired their knowledge of models of the universe and of the nature of heat; Panagiotis Kokkotas and his colleagues' training program for primary-school teachers based upon the socioconstructivist and sociocultural approaches in studying the history of our understanding of freely falling bodies; and Barbara McMillan's fascinating teaching program for a Grade 4 curriculum on light that included historical stories and was aimed at addressing government-mandated learning outcomes in Manitoba.

In more specialized areas, Douglas Allchin challenges our understanding of the meaning of a physical law and the implications of that concept for science teaching. And Elizabeth Cavicchi presents a convincing case for the vital role that trust plays between teacher and undergraduate students, and among the students themselves, in carrying out historical experiments on light, mechanics, and electricity and in establishing a community of learners.

Then there is the crucial role of instruments. Gudrun Wolfschmidt shows how understanding the development and use of three instruments in magnetism – compasses, magnetometers, and radiotelescopes and satellites – provides an important context for teaching geophysics and astronomy. Pierre Lauginie emphasizes the pedagogical value of studying the attempts to determine the density of the Earth in the 18th century, the invention of the Cavendish torsion balance at the end of the 18th century, and its subsequent refinements, which yielded ever more precise values of the gravitational constant G. And Christian Sichau argues convincingly that the scientific instruments and apparatuses preserved in museums can be used as object stories to provide significant insights into the history and nature of science, and thus constitute the core strength of museums for science teaching.

Turning to astronomy, Jürgen Teichmann argues that three revolutions or evolutions in astronomy, in antiquity, in the 16th and 17th centuries, and in the 19th and 20th centuries, all of which were associated with much improved observational instruments, were closely connected to such fundamental philosophical questions as the uniqueness of life on Earth and man's place in the universe. And Don Metz presents a fascinating account of the enormous hardships that William Wales experienced in observing the transit of Venus of 1769 in northern Canada, which contributed to establishing the value of the astronomical unit.

In mathematics, Youjun Wang gives a captivating account of how ancient Chinese mathematicians solved mathematical problems involving the principle of congruency and the theory of limits by hands-on techniques. And Jeff Babb and James Currie sketch the history of the brachistochrone and its relationship to Snell's law, Fermat's principle of least time, and the calculus of variations, and show how this history motivated their students' understanding of the interplay between mathematics and physics.

In biology, David Rudge discusses a National Science Foundation program for middle school teachers that uses three episodes in the history of biology to promote their deeper understanding of the nature of science.

Finally, there are the generalists. Gábor Zemplén describes a provocative international baccalaureate theory-of-knowledge course based upon sociological and anthropological considerations that is aimed at showing students how scientists attempt to uncover sources of error and acquire reliable knowledge about the natural world. And Peter Heering argues that an examination of the great changes that occurred in the style of experimentation since the 18th-century Enlightenment can inform our science teaching today.

There is no Royal Road to effective science teaching, but the papers that follow provide a firm basis for confidence that the use of the history of science in science teaching, in one form or another, can contribute significantly to it on an international scale.

Teaching Science Lawlessly

DOUGLAS ALLCHIN
University of Minnesota, USA

Abstract. Boyle's law is the epitome of lawlike science in the classroom. Yet Boyle's law is not universal and invariant, as implied by the term 'law'. It does not hold at high pressures, low temperatures, or low volumes. It is based on constant temperature. It varies for different gases. Boyle's law—and other scientific "laws"—are not lawlike at all. An alternative is to teach a more complex view of nature, exhibiting only patches of regularity. In following scientists, teachers may focus on experiments as concrete models, such as Boyle's J-tube. Science education might well be ideally rooted in concrete apparatus and teaching experimental and analogical reasoning, not laws.

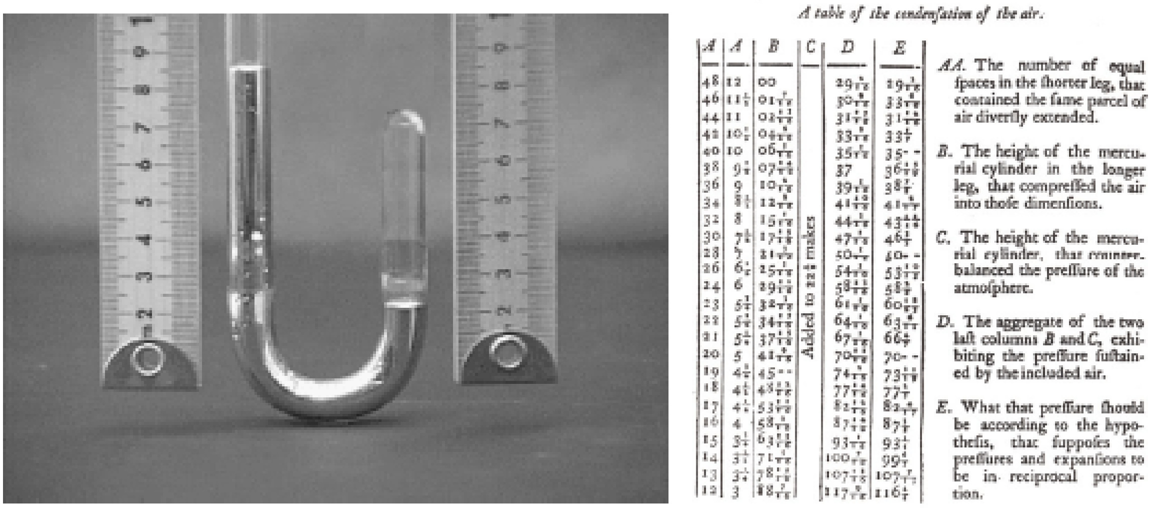
Introduction

Presented with a title like "Teaching Science Lawlessly," you may be envisioning science red in tooth and claw, chaotic nature careening out of control, or gangs of science teachers roaming through school hallways wielding huge Leyden jars ready to unleash electrical havoc on unruly students. That's not a bad image to start.

Let me couple that [Figure 1] with an appreciation: namely, for the opportunity to participate in this conference, where I might join in recognizing the achievements of the community here in Oldenburg under the Falk Riess' vision and leadership. I hope to elucidate how an image of lawlessness might serve this end: ultimately, as a tribute to the pioneering work here.

Towards that end, my central focus, and the occasion for analysis and commentary, is one of the most standard of benchmark concepts in introductory chemistry or physical science: Boyle's law. I focus on this law primarily because it is hard to find a science curriculum without it having a central place. It is central, I think, not because it informs students about how gases behave. Rather, it is a cultural icon that epitomizes the fundamental concept of a law. My aim is to profile an alternative that may better reflect science in real practice.

Most of you are no doubt familiar with the historical context of Boyle and his law. Boyle was interested in the "spring of air." Air exerts pressure when compressed. Borrowing from a device of Otto Guericke, Boyle enlisted Robert Hooke to build an "air pump". They did not generated a true vacuum, but the vessel did exhibit extremely low pressure. In 1660 Boyle published his findings on its many effects — on magnets, sound transmission, sealed bladders, burning candles, the life of small animals, and more. In response to criticism, Boyle further demonstrated the strength of the spring of air. He and Hooke compressed a small amount of air trapped in the end of a glass J-tube with increasing amounts of mercury. In a similar second set of experiments, they used the new air-pump to draw up the column of mercury to dilate the trapped air. In both cases, they recorded the volume of the trapped air and the corresponding height of the column of mercury (an indirect measure of its weight, or pressure). Students even today can graph his figures (Figures 2a and 2b) and see the inverse relationship of pressure and volume (Conant 1957).



A table of the condenſation of the air.

A A. The number of equal ſpaces in the ſhorter leg, that contained the ſame parcel of air diverſly extended.

B. The height of the mercurial cylinder in the longer leg, that compreſſed the air into thoſe dimenſions.

C. The height of the mercurial cylinder, that counterbalanced the preſſure of the atmoſphere.

D. The aggregate of the two laſt columns *B* and *C*, exhibiting the preſſure ſuſtained by the included air.

E. What that preſſure ſhould be according to the hypotheſis, that ſuppoſes the preſſures and expanſions to be in reciprocal proportion.

Figure 2a. Boyle's data on the condensation of air, showing that volume decreases as pressure from a column of mercury increases.

There are many ways to express Boyle's law. My analysis will be based on a narrow, but explicit version:

$$\Delta P \propto 1/\Delta V$$

The change in pressure is inversely proportional to the change in volume. (As the volume increases, the pressure decreases, and vice versa.)

What's Not in Boyle’s Law

The concept of scientific laws, such as Boyle's law, has a venerable tradition. Laws are empirically substantiated generalizations or regularities. For many, they are the basic units of scientific knowledge. Laws reflect a conception of nature as law-like or machine-like, as expressed in the mechanical philosophy, famously advocated by Boyle (Sargent 1995). Nature may thus be described by reducing phenomena to their parts and the laws that govern their interaction. Elucidating these laws is widely portrayed as the major goal of science. Familiar examples of laws might also include Snell's law of refraction, Galileo's law of the pendulum, Newton's laws of motion, Ohm's law of electrical resistance, and Mendel's law of independent assortment. As typically presented and interpreted, scientific laws are invariant and universal (Hempel 1966, 54, 58; Ziman 1978, 32; Kosso 1992, 52-60, 190; Woodward 2003, pp. 167, 236- 238, 265-266). Indeed, their very universality and invariance accounts for their value and authority as generalizations. Laws accordingly seem to earn central place in science education.

As Boyle's data show, Boyle's law certainly holds true in Boyle's J-tube. But is Boyle's law universal? Is it invariant? Is it truly lawlike? Does it hold in all cases? The answer is "no." It depends on context. *At high pressures*, the direct inverse relationship of pressure and volume breaks down (Figure 3). Henri Regnault (in 1852) and later Louis Cailletet noted this variation two centuries after Boyle's work. In modern terms, we might say that there is a limit to compression. Under very high pressures, a gas begins to behave more like a liquid than a gas. The scope of Boyle's law is limited. It only holds in the *restricted* domain of pressures up to approximately ten atmospheres. Never mind that these pressures are infrequently encountered in daily human life: the law is plainly not universal.

Perhaps the behavior of gases at high pressures is a rare, minor exception. Suppose one stipulates explicitly, then, that only certain pressures apply:

$$\forall P \not> \!\!\! \not> 0 \Rightarrow \Delta P \propto 1/\Delta V$$

For all pressures not substantially greater than zero, the change in pressure is inversely proportional to the change in volume.

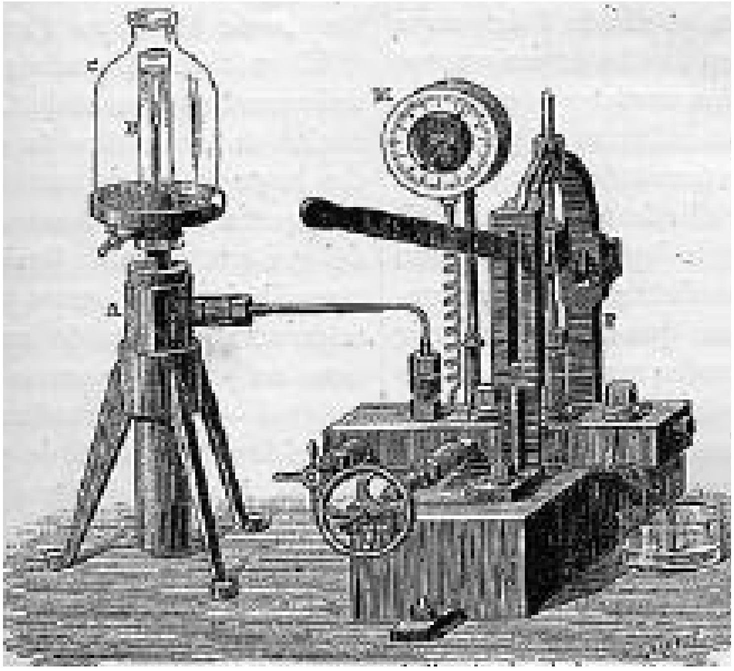


Figure 3. Cailletet's apparatus for examining gas under high pressure.

Is Boyle's law universal now? Well, no. At low temperatures, the inverse relationship breaks down, as well (Figure 4). Historically, this was noted by Thomas Andrews in the 1860s (Andrews 1869). Here, another context qualifies scope. But this case also introduces something unexpected: a new variable. The equation or formula does not even refer to temperature. An experimenter, for example, would need to be aware of temperature, if only to ensure that the temperature was not extremely low. The simple expression of Boyle's law hides this relevant variable entirely.

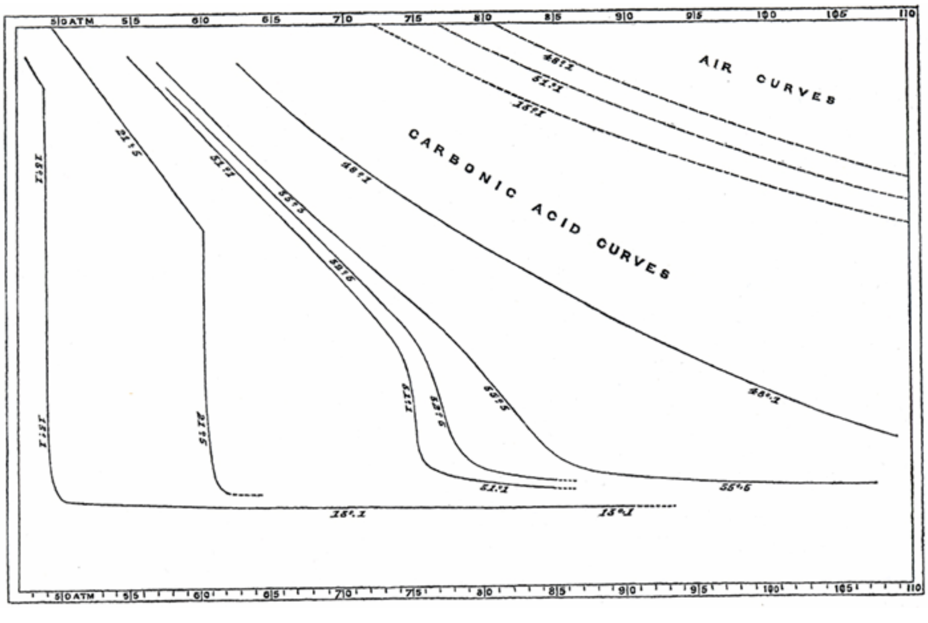


Figure 4. Effect of lower temperatures (successive curves to left)
on pressure-volume relationship of carbon dioxide (Andrews 1869).

Well, then, let us add both these conditions, or provisos:

$$\forall T >> 0 \mathbin{\&} \forall P \not>\not> 0 \Rightarrow \Delta P \propto 1/\Delta V$$

For all temperatures well above zero, and for all pressures not too high,
the change in pressure is inversely proportional to the change in volume.

Is Boyle's law "fixed" now? For example, with the provisos of scope, is the law now invariant? Well, no. Temperature is indeed important. — Not just the range of the temperature, but also its holding constant. As Boyle himself (and others of his era) noted, gas pressure is sensitive to changes in temperature, as exemplified in several apparatus for measuring temperature (Figure 5).

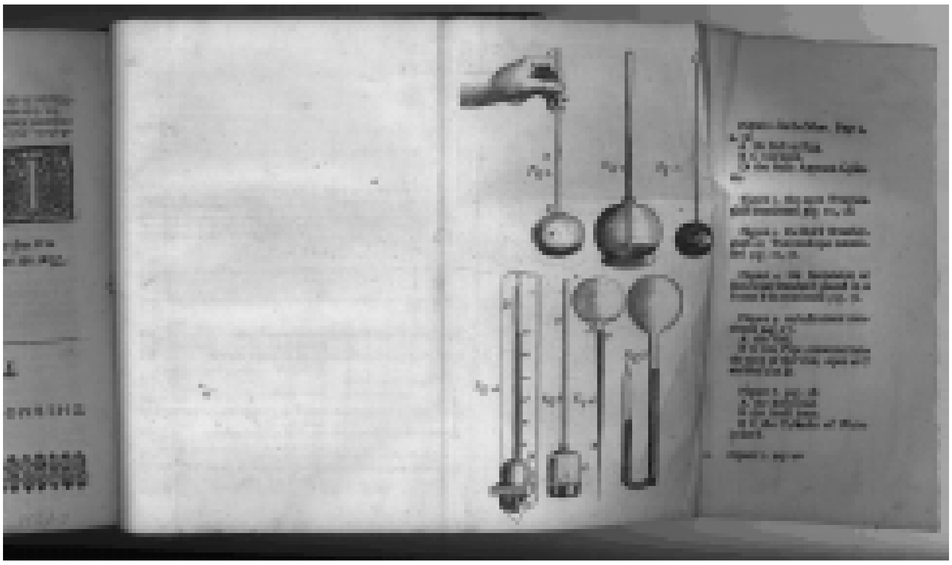


Figure 5. Instruments for indicating temperature change via changes in air volume.

A few decades later, of course, Jacques Charles (in 1787) and Joseph-Louis Gay Lussac (1802) formalized this in yet another law, which now bears (alternately) their names. Hence, while one may address the relationship of pressure and volume independently of temperature, temperature is nonetheless relevant. Constant temperature is a boundary condition. Sometimes it is expressed as a ceteris paribus clause: "all else being equal." But not all other things need to be equal. The amount of illumination, the relative motion of the system, or gravity exerted on it, have no effect on gas behaviour, so far as we know. No one need stipultate these as boundary conditions or imagine them in a *ceteris paribus* assumption. So specifying what must remain constant is important indeed if one expects the law to hold. The invariance of Boyle's law, ironically, depends on context.

Well, let us now add our additional boundary condition:

$$\forall T >> 0 \,\&\, \forall P \not\gg 0 \,\&\, \forall \Delta T = 0 \Rightarrow \Delta P \propto 1 / \Delta V$$

> For all temperatures well above zero, and for all pressures not too high, and at constant temperatures, the change in pressure is inversely proportional to the change in volume.

Is Boyle's law expressed fully now? No, still not yet(!). If the volume is very low (or the density very high), the volume of the gas molecules relative to the volume of the space between them becomes significant. Intermolecular interactions (London forces) become relevant. The behaviour of the gas changes noticeably. Moreover, because the size of the gas molecule matters, the variation is specific for each gas. Yet another factor qualifies Boyle's law. Even the qualifications are not regular. Moreover, any gas with strong polarities may also exhibit intermolecular forces, although of another sort. Such gases—carbon dioxide, for one—also vary from the simplified "ideal" (Figure 6). Ultimately, then, we must also take into account the nature or identity of the gas (or gases). Johannes van der Waals investigated these various dimensions of gas behavior in the 1870s and 80s, as well as the nature of some of the intermolecular forces, work that was recognized by a Nobel Prize in 1910. One can "correct" for the subtleties of molecular size and interactions, but the corrections (known as van der Waals constants) differ for each gas (Figure 7).

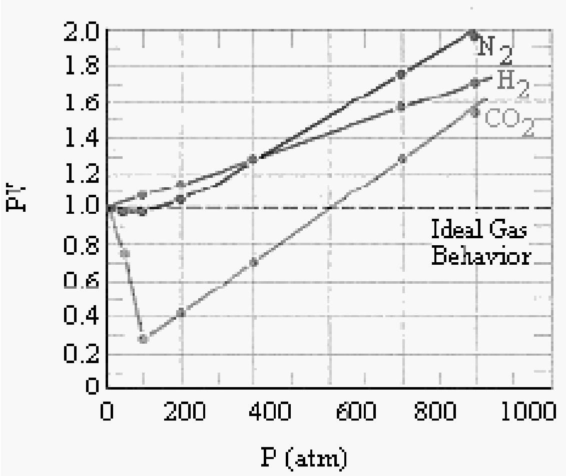
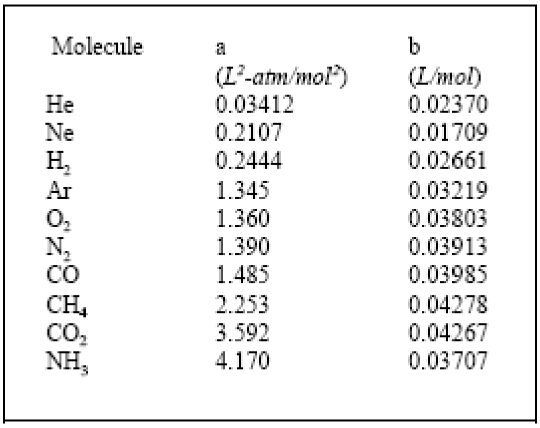


Figure 6. Different pressure-volume relationships for different gases.



Molecule	a (L^2-atm/mol^2)	b (L/mol)
He	0.03412	0.02370
Ne	0.2107	0.01709
H_2	0.2444	0.02661
Ar	1.345	0.03219
O_2	1.360	0.03803
N_2	1.390	0.03913
CO	1.485	0.03985
CH_4	2.253	0.04278
CO_2	3.592	0.04267
NH_3	4.170	0.03707

Figure 7. van der Waals contants for various Gases.

Thus, even his now well known generalized form of the gas law included variables specific for each gas:

$$\left(P + \frac{a}{V^2}\right)(V - b) = nRT$$

To be accurate, or realistic, Boyle's law must sacrifice universality. Boyle's law, like so many others, is only "lawlike" when qualified:

$\forall$ elastically compressible gases,

$\forall T >> 0 \,\&\, \forall P \not\gg 0 \,\&\, \forall V >> 0 \,\&\, \forall \Delta T = 0 \Rightarrow \Delta P \propto 1/\Delta V$

> For all elastically compressible gases, for all temperatures well above zero, and for all pressures not too high, and for all volumes well above zero, and at constant temperatures, the change in pressure is inversely proportional to the change in volume.

A critical analysis of Boyle's law exposes and highlights this double irony: universality comes at the cost of limited scope; invariance, only with conditions. The lawlike world of "for all..." is inseparably coupled with a set of contingent "if-and-only-if"s. This is the lesson typically missing when teaching Boyle's law: what's *not* in Boyle's law — a world full of context and contingency, not simple rules.

Another irony lurks in Boyle's law. That is, Boyle himself never stated it. He certainly produced data commensurate with the law, yet he did not write an equation for the relationship. He surely understood the mathematics of "what the pressure should be according to the hypothesis" (Boyle 1662; Figure 2), yet he was generally disinclined to characterize nature mathematically (Shapin 1996, pp. 333-338).

Figure 8: Boyle

Boyle also embraced the concept of laws in science: he advocated mechanical philosophy as well as the theological framework of construing nature in terms of inherently divine laws (Boyle 1661). Yet Boyle did not regard his findings about the condensation and rarefaction of air as a universal law in the sense now accepted. Rather, he referred to the spring of air more modestly, as a 'habit of nature' or 'custom of nature': local, perhaps contingent, in nature (Boyle 1661; Sargent 1995; Shapin 1996, pp. 328-330, 338-350). He was well aware, for example, that temperature and "atmospheric tides" affected the Torricelli tube, today's mercury barometer (Boyle 1660, pp. 65, 123, 133; 1682, p. 50). Boyle's law is not strictly Boyle's. Teachers might thus profitably reflect on Boyle's own modest posture.

Rampant Lawlessness

One may well be tempted to imagine that there is no need for such caution, that Boyle's law is an exception and that most scientific laws are universal and invariant as promised. Not so. Consider Galileo's "law" of the period of the pendulum:

$$t = 2\pi\sqrt{\frac{l}{g}}$$

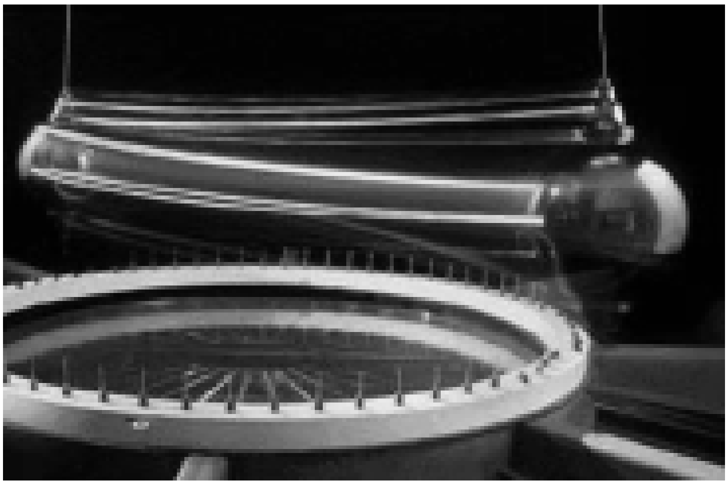


Figure 9: Pendulum

(where *t*= the time of the period, *g*=9.8 m/sec2; *l* is the length). This formula only works (and with limited precision, at that) for pendulums with small angles of swing (generally reported as less than 10°). The familiar equation is an approximation based on the broader characterization:

$$\frac{d^2x}{dt^2} + \frac{g}{l}\sin(x) = 0$$

(where *x* is the angle of swing). This may be universal, but it is rarely used. It cannot be solved analytically and requires iterative substitution even to approximate solutions. But even this expression assumes that the mass is concentrated on a single point and that no friction affects either the fulcrum or the interaction of the pendulum and its medium. These are not just boundary conditions, but unrealizable idealizations, as all the physicists here well know.

Ohm's Law of electrical resistance, too, has numerous exceptions: for example, at high current densities. Many common materials "violate" Ohm's Law: temperature-sensitive resistors (such as filaments in incandescent light bulbs, or sensors in digital thermostats); air (whose threshold resistance results in bolts of lightning); diodes (common electronics components), light-sensitive resistors, piezoelectrics (used in touch-sensitive switches), weak electrolyte solutions, varistors and high-vacuum electron tubes, as well as other more technical variants.

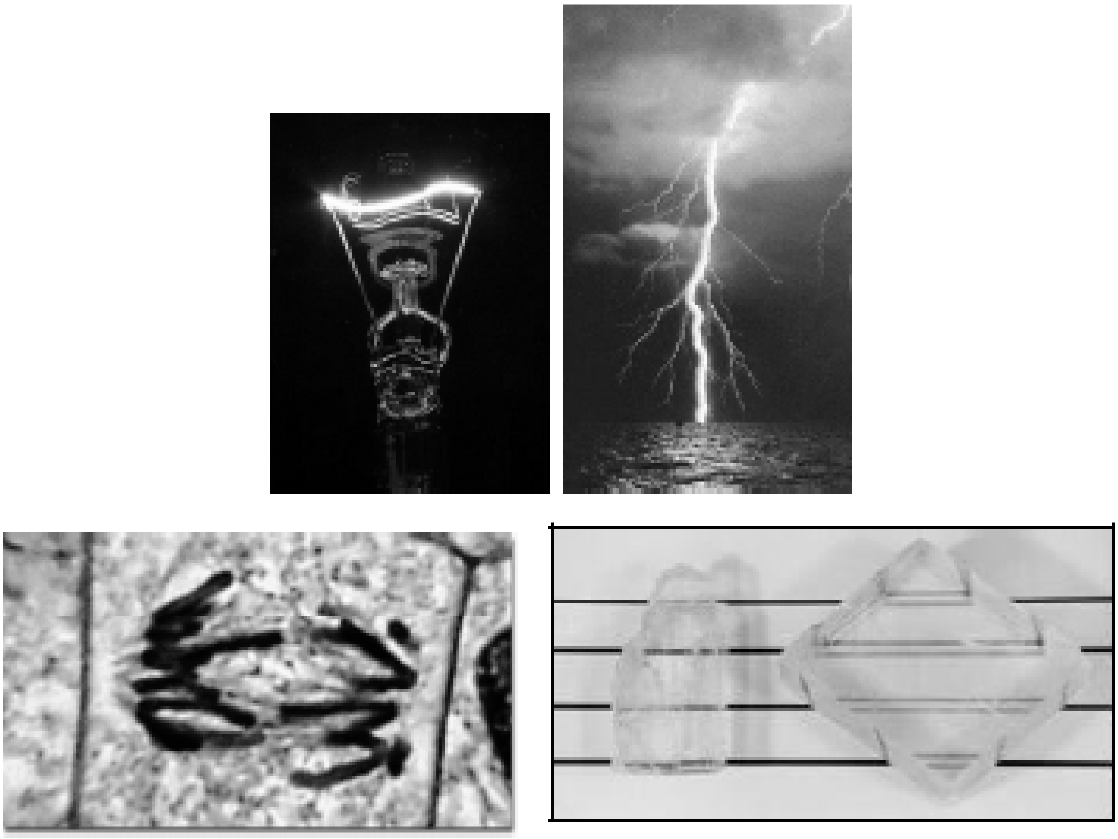


Figure 10: Light bulb, Lightning, chromosome and calcite

Newton's Laws of Motion do not apply at relativistic velocities (approaching the speed of light), and (like the pendulum law) exclude friction. Mendel's Law of Independent Assortment breaks down, as most students learn, for genes linked on the same chromosome. Snell's Law of Refraction does not apply for 'Icelandic spar', or calcite. In all these cases, laws seem very unlawlike. Scope circumscribes universality. Boundary conditions and exceptions limit invariance. That is, context matters.

One need not contend that these or other scientific laws are completely invalid. Nor need one discount their informativeness. The emphasis, instead, is on context. Few professional scientists or philosophy of science—nor likely anyone here—deny that laws are ultimately contextual. For example, Toulmin (1960, pp. 31, 63, 78-79, 87) underscores that laws have particular scope of application, or *domains*. He, along with Kuhn (1970), suggest that articulating this scope is a major function of scientific research. Still, Toulmin and others contend, the provisos are not part of the law. Of course, that is a philosophical sleight of hand. Only by erasing these conditions does a law acquire the illusion of universality. Laws, if not *false*, are illusory. They attain law-like status only by arbitrary specification of background conditions—a control which may be locally informative, but not universally valid.

Context depends on perspective. Interpretations of foreground and background rely on convention (Figure 11). So one may ask: why are laws central, and the exceptions "exceptions"? Why regard "laws" as primary? I am inviting a gestalt switch whereby cases now framed as "outside the scope" or "not within the boundary conditions" are framed instead as inside the system.

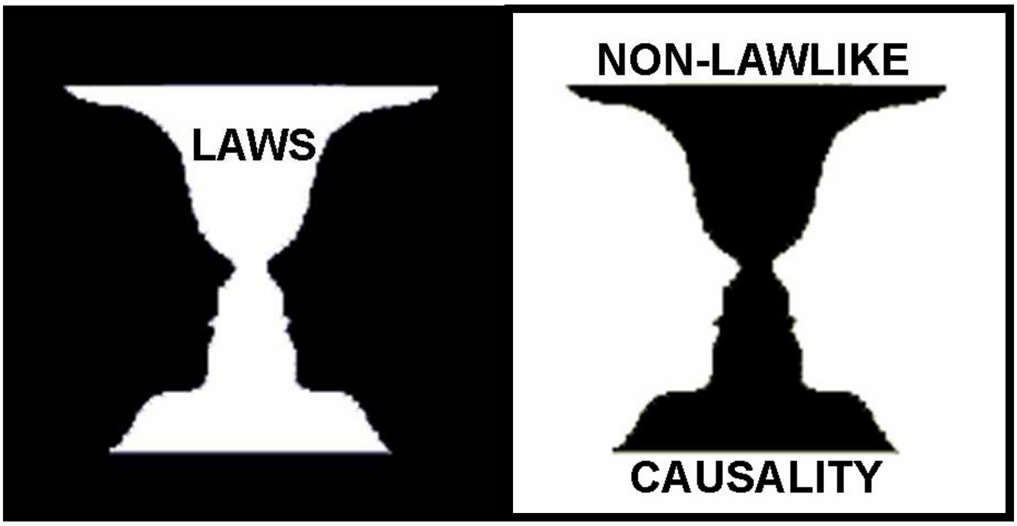


Figure 11. Gestalt

One denies laws privilege. Accordingly, the unlawlike earns parity. Boyle's law becomes a special case: no less true, but narrowly so, *contingent* on a particular context. It demarcates a patch of local regularity. The alternative perspective embraces the whole, of which Boyle's law is only a part. An unrepentantly staunch realist does not present an *idealized* gas law as even a simplification of all *real* cases. Laws are the *exception*, not the rule. They require special explanation, just as they need special experimental conditions to be observed in a lab. Laws are local, not universal. Generalities are contingent, not invariant.

Accordingly, one may be impressed by an apparatus where Boyle's law is observable, such as Boyle's J-tube. A change in volume is observed only when the system is closed. In an open system, such as the atmosphere, a gas under pressure does not change volume. It moves: hence, wind (Figure 12)! Indeed, the cases where Boyle's law holds are few: pistons (say, in internal combustion engines), industrial boilers, some ventilation systems.

Figure 12. Pressure in an open system creates wind, not a change in volume.

Boyle's law is not "basic" at all. It is an esoteric scientific fact. Few students will ever need to know or apply Boyle's law in either their personal or professional lives. Yet it is *de rigeur* for science education. The ultimate lesson of Boyle's law is not about how gases behave: it is about laws and characterizing nature as essentially lawlike — and that lesson is grossly misleading. We live in a world where weather happens. We need to teach equally about non-lawlike, or lawless, nature.

Lawless Causality

To accommodate lawless science, one needs to readjust the basic framework of causal thinking. But how can one think causally *without* a law? (Is it even possible?!) The mere image of lawless science, of course, bristles with potentially disruptive images of anarchy. It reeks of chaos and disorder. But the effect is purely linguistic. Consider the contradiction, for example, in claiming that a natural phenomenon violates or deviates from a law of nature. The *language* links law and order in the civil realm. We need to ensure that our thinking about science is not biased by meanings in cultural contexts. A lawless nature may seem to imply indeterminism. However, science without laws need not be any less deterministic.

Lawless science fits with an alternative conception of causality. Conventionally, laws reduce the world into component parts and causes. Laws are the basic units. Laws are like billiard balls (Figure 13). Each moving billiard ball expresses a mechanical vector: a cause. One ball hits another with an observable effect. The second ball may, in turn, hit another, and then perhaps another, leading to a causal cascade. Laws lead to thinking in terms of causal chains. Even where a cue ball hits a whole rack of fifteen balls, with scattering effects, all calculable (in principle) from the cue ball's original vector.

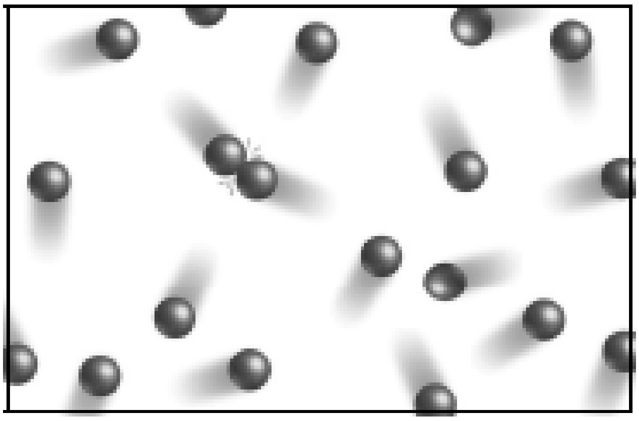


Figure 13. The kinetic theory of gases: molecules as metaphorical billiard balls.

The complex event is explained by *compounding* individual causal events, layering one cause upon another. This reductionistic view is nicely exemplified, of course, by the kinetic theory of gases, the modern explanation for Boyle's law. Gas molecules act like billiard balls colliding in three-dimensional space. The pressure is a collective effect of all the movements of the individual gas molecules, each with their own discrete contributing cause.

The alternative conception of causality is more holistic. It underscores multiple simultaneous causal factors. It resonates with a *state system* view of causality. That is, effects are not attributed to individual causes, or even to a composite of overlapping causes. Rather, effects are due to the state of the entire system. One identifies the whole as "the" cause, differentiating—but not privileging—individual elements. Pressure does not increase *merely* due to a decrease in volume, as suggested by Boyle's law. Rather, pressure increases due to the change in volume *and* extant pressure *and* temperature *and* overall volume *and* type of gas — *even when* the temperature does not change. The behavior of gases is always, not just sometimes, multivariate. Just so for pendulums, electrical resistance, inheritance, etc.

For further perspective on framing causality, consider the playful devices of Rube Goldberg (Figure 14). He delighted viewers by imagining how a modest action, such as emptying an ice cube tray or cooling hot soup, resulted from an elaborate and improbable series of events.

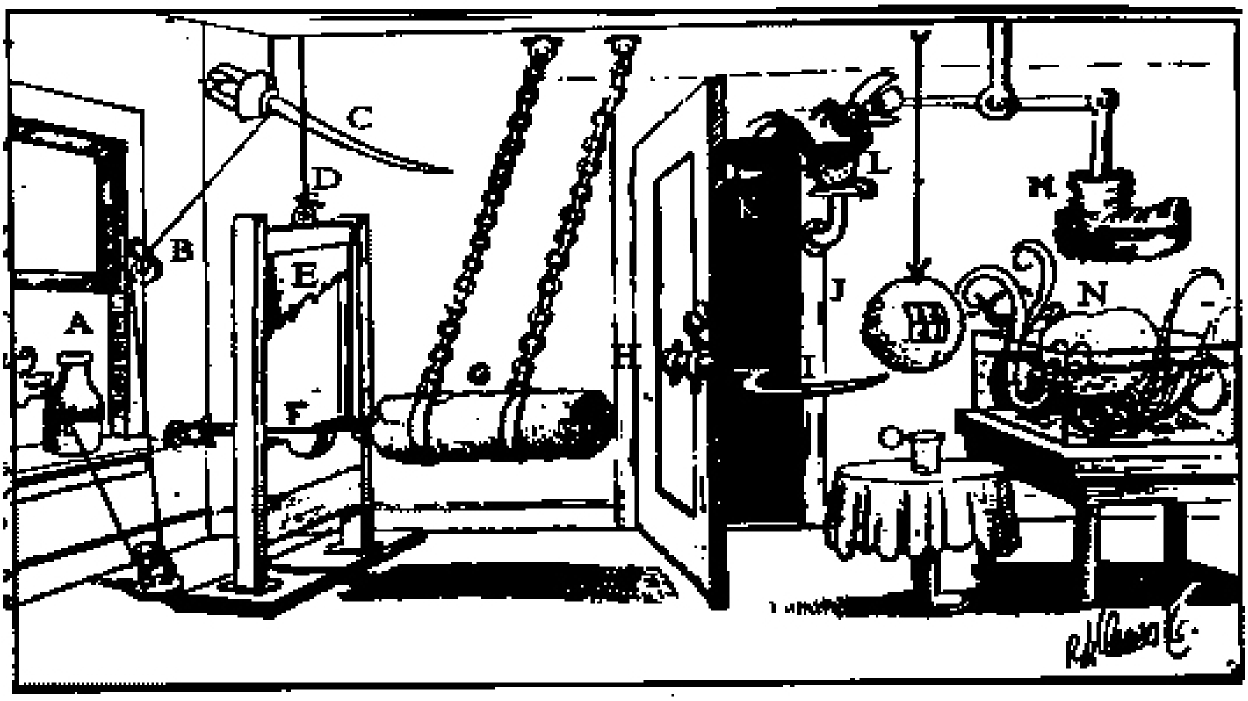


Figure 14. A Rube Goldberg device for making fresh orange juice. (Wolfe 1998)
Rube Goldberg is the ® and © of Rube Goldberg, Inc., www.RubeGoldberg.com

The humor arises chiefly from the convoluted causal pathway, underscoring the (otherwise humorless) association of simple causes with simple effects. Goldberg's elaborate mechanisms also highlight causal lineages, often labeled in an alphabetical sequence. At the same time, his devices are funny precisely by being incredibly contingent. If a rolling ball is not preset, a falling hammer not lifted, a spring not prewound, the causal cascade is interrupted. The design elicits a fun anticipation of several successive "only-if"s. The causal scenario is exceptionally fragile. Action depends on the whole structure at once. The arrangement and setup— the context—is critical. The causal lineage is merely an artifact of the causal structure—primed throughout, but not triggered. Goldberg's baroque and apparently silly devices, then, offer sophisticated commentary on reductionistic causal perspectives. Their whimsy helps celebrate a contingent view of causality.

Consider again the reductionist's billiard balls. Here, the status of the whole billiard table is important (Figure 15a). One cannot assume that balls are intially at rest: the system may already be complex and active, not passive in response. Nor can one assume the balls to be of the same material (like different gases perhaps?). They need not react in uniform ways: identical vectors underdetermine a collision outcome.

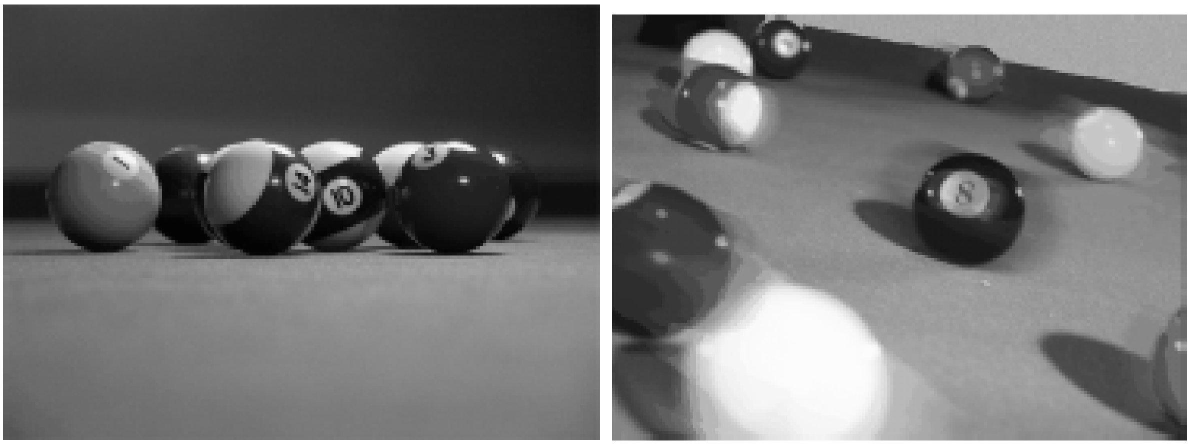


Figure 15. Billiard-ball causality, *not* assuming the table is flat or uniform.

The billiard table environment also matters: it may not be level, or remain level (anymore than the temperature of a gas). A tilted table affects all the components at once, even when the balls are not colliding (Figure 12b). Some causal factors may undulate the surface, generating different local conditions across the table, leading again to different responses for apparently similar collisions. Some balls may contain iron, so changes in the magnetic field (context) may matter more than the interactions of individual balls (parts). With uniform balls on a level billiard table—which stays level—simple interactions may indeed be discernible. But that is a special case. The state system view looks well beyond the billiard balls—or individual gas molecules—as component causes. It emphasizes the whole and the contexts of the parts.

Let me note, at this juncture, that this presentation is derived and adapted from a larger project of mine, still in progress, on "The Gender of Boyle's Law." One could probe the history of laws in science and show that the approach is based on theology and a world view that values technology, control and mechanical philosophy (Steinle 2002). Or one could delve into the growing literature on models and mechanisms (Glennan 1996; Machamer, Darden and Craver 2000; Bechtel 2006), or on lawless nature (Cartwright 1999). Today, however, I want to profile further the concrete alternatives of lawless causality.

From Laws to Material Models

So: strip the lawlike status from Boyle's law and it may seem as if nothing remains. What remains, of course, is Boyle's J-tube (Figure 16) as an exemplar and concrete model, Kuhn's (1970) core sense of paradigm (see also Giere 1995, 1999).

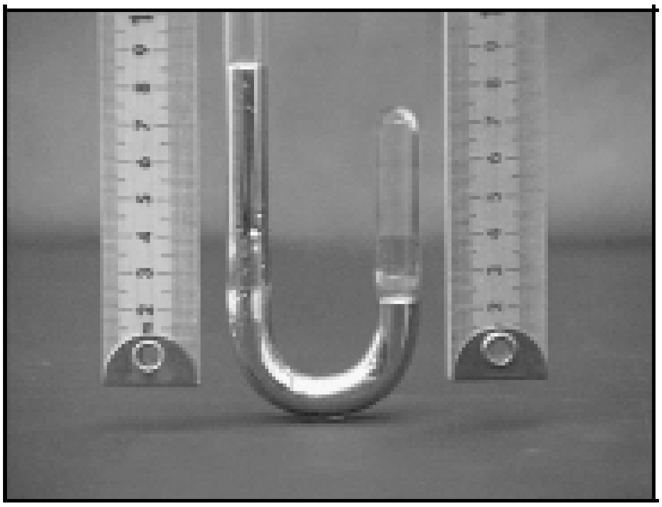


Figure 16. Boyle's J-tube (recreated).

A focus on models and particularity underscores the importance of material culture and experimental systems in investigation, as profiled recently by Hans-Jörg Rheinberger (1996). Here, one does not appeal to general laws. Rather, one compares other cases to Boyle's original. To the extent that the conditions are the same — including pressure, temperature, etc. — one expects to find similar behavior. The reasoning is primarily analogical, not deductive. It is also direct, not indirect. One does not detour through a general law, first by abstracting Boyle's J-tube, then by deciding whether a new case is an authentic example of the general law. Reasoning from case to case does require, however, clear attention to the variables and details of context. One quickly learns the basis and limits of similarity, an integral part of the exemplar, or paradigm. The lawless alternative to Boyle's law is Boyle's J-tube. It is eminently teachable.

Although lawless science challenges lawlike thinking, the legal system (on a cultural level) provides an instructive metaphor. In practicing law, especially in juridicial contexts, one distinguishes between statute (or code) law and common law. Statute law is based on rules, or codes: like the laws of nature. One assesses actions in reference to the law's general and explicit statements. One reasons deductively. Common law, by contrast, is case-based. One assesses actions based on precedent, or similar cases encountered in the past. Interpretation emphasizes the basis for similarity. One reasons chiefly analogically. Of course, numerous variables, or bases for similarity, are usually possible. The effectiveness of an analogy may be highly contingent. Context plays a major role. Yet the multitude of benchmarks can be beneficial, especially in interpreting complex cases. Under statute law, statutes may overlap and indicate conflicting interpretations. Case-based reasoning can often resolve this. Both frameworks provide viable systems of law and interpreting justice. Imagine lawlike science resonating with statute law, "lawless" science with common law.

Accordingly, Boyle's J-tube is significant primarily as a precedent. To apply Boyle's law, for example, one depends on being able to match the particular conditions of Boyle's J-tube. It is no surprise, perhaps, that scientists who subsequently revised Boyle's law typically followed Boyle's model by using mercury in J-tubes. For example, with the construction of the Eiffel Tower (Figure 17), Louis-Paul Cailletet was able to build and support a column of mercury of unprecedented height. With it, he could examine the same system, but now with pressures up to a hundred atmospheres.

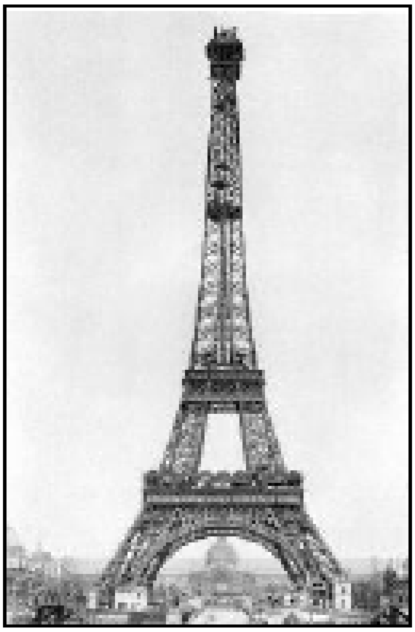


Figure 17. Eiffel Tower in 1889, where Louis Cailletet built a tall, high-pressure manometer.

He studied the limits to Boyle's law by probing variations in the original set-up. Indeed, scientists often focus primarily on *experimental systems,* rather than on specific concepts (Rheinberger 1996). The lineage of investigation is often shaped by the materials and opportunities at hand, not by a theoretical master-plan. While Boyle's J-tube may be local and contextual, it is no less valuable on that account. Indeed, its particularity functions to guide reasoning through analogy—and to help keep it in check. Historically, Boyle's J-tube —not the law— may be the more fundamental benchmark, and that may serve as the critical clue for what one teaches about the nature of science.

How, indeed, does one adapt teaching to accommodate the wider view of causality, to open student awareness of the context of laws and of lawless nature? The ultimate import of my comments, here and at this time (under these *particular* circumstances), may finally be clear. If one were to assemble a science education curriculum founded on the importance of material systems and experimental exemplars, one could hardly do better than follow the model set by this institution. Here is a paradigmatic environment for teaching science without laws. In teaching with historical perspectives and replicas of original apparatus (Figure 15), the role of precedent in science is made clear.

Students equally learn the role of concrete experimental models. While there are other aims at work here, the instructional framework supports appreciation of scientific reasoning and practice beyond laws.

Let me highlight (perhaps celebrate) just two examples of what one may learn from this approach. Each underscores the importance of understanding the materiality, not just the concepts of experimental practice. Recreating the work of Joule on the mechanical equivalent of heat (Figure 18) would seem simple enough: after all, it's been done before.

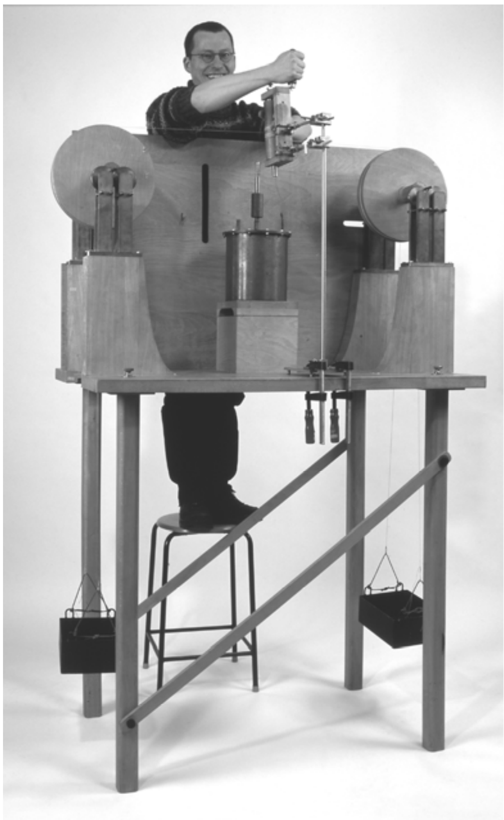


Figure 18. Recreation of Joule's apparatus for investigating the mechanical equivalent of heat.

However, efforts here led to important discoveries. One factor they traced was particular dimensions of the paddle that rotated through the water chamber of the