Reexamining several episodes reveals the complexity and human richness of science in the making

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pontaneous generation, the question of whether life can originate from nonliving materials, was an important issue during the early development of microbiology. Recently, historians have added new details about several key episodes in the spontaneous generation debate. By attempting to understand these episodes in their appropriate historical contexts, we can better appreciate how this branch of science developed.

Moreover, this reexamination illustrates how the making of scientific knowledge can be fraught with misunderstandings because of differing assumptions or when the use of incommensurate apparatus led those working in the same field to talk past one another.

History of science, when done well, reveals a realistic, complex, rich picture with which to educate new practitioners, one that does not create heros to whom we can never measure up and villains who never existed. Furthermore, showing how science is integrated into its larger cultural context avoids the stultifying compartmentalization of knowledge that so often occurs and gives a much fuller appreciation of how science developed from philosophy and has come to have a unique character.

Just as "natural philosophy" was not synonymous with "science" until fairly recently, neither did "experiment" always mean what it does now

1668—the Tuscan Court and the Meaning of "Experiments"

Francesco Redi, natural philosopher to the same Tuscan court that had been the patron of Galileo, is an important figure in the early spontaneous generation debates. From experiments in 1668, Redi showed that maggots come from fly eggs, not from rotting meat. The appearance of maggots in rotting meat had previously been widely attributed to spontaneous generation.

In his experiments, Redi placed samples of many different types of meat and fish in glass jars, with one set of jars open to the air and the other set covered with fine muslin cloth. While maggots never appeared in the meat of the covered jars, flies crawled about on the cloth and sometimes laid eggs there. Those eggs hatched into maggots, disproving spontaneous generation as their origin.

Louis Pasteur, T. H. Huxley, Darwin's famous apologist, and other historians touted Redi's "controlled" experimental approach. The reputations of Pasteur and Huxley and the way in which the simplicity of Redi's experiment lends itself to inclusion in textbooks have contributed to our sense of the history of spontaneous generation debates. The overall narrative came to be dominated by stories of "dueling experiments." The spontaneous generation debate, like other issues within natural philosophy, increasingly featured experiments as important elements from the late 17th century onward.

Just as "natural philosophy" was not synonymous with "science" until fairly recently, neither did "experiment" always mean what it does now. Many natural philosophers in the 17th century were interested not only in the in-

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FIGURE 1

Plate from Buffon's *Histoire naturelle* depicting an 18th-century scientist using the compound Cuff microscope. Perhaps because of the illustration, many assumed that Buffon and Needham had used this instrument to make their observations, when in fact they had used the much superior Wilson screw-barrel design (Figure 2). Compound microscopes of that era suffered from severe chromatic and spherical aberration, and the Cuff microscope had a maximum magnification of only about 100x.

Figure courtesy of the Yale University Library

trinsic power of the experimental method, but also in the power of publicly conducted "experiments" as a way to convince audiences, including prospective patrons, that this enterprise was qualitatively different from book-dominated natural philosophy and subjective and often traumatic religious disputes. Instances in Redi's career, especially his relationship to the Medici Grand Dukes, exemplify this other use of experimentation, according to I? Findlen of the University of California, Davis. She describes Redi as "a courtier who deployed the natural and human resources that his environment offered to shape experimental narratives that met the expectations of a patrician and largely court-based audience." In this setting, Findlen contends, "Redi's primary concern was to establish an unshakeable foundation for his particular point of view; his success at court was predicated on such certainty. His technique grounded scientific inquiry firmly in repeated observation and demonstration, 'testing and retesting."' But he also said that he did experiments "in order to make myself more certain of that which I am already most certain." For Redi in his primary role as courtier, "experiment" meant something quite different from what it means today, particularly with regard to the role of "preconceived expectations." The purpose of experiments and the standards of proof in that environment were also quite different, Findlen points out. Often experiments resulted from suggestions made by the Grand Duke, who was the ultimate authority in debates that ensued. Moreover, the Grand Duke authenticated experiments and any narratives that emerged from them. Thus, Findlen notes, "Redi counted upon the weight of princely authority to confirm the results of his experiments. In an absolutist court, the testimony of the Grand Duke was unimpeachable."

With this richer sense of what experiment meant when Redi lived and worked, the validity of an ahistorical narrative that compares his work with experiments performed by Pasteur, Tyndall, and their antagonists two centuries later comes into doubt.

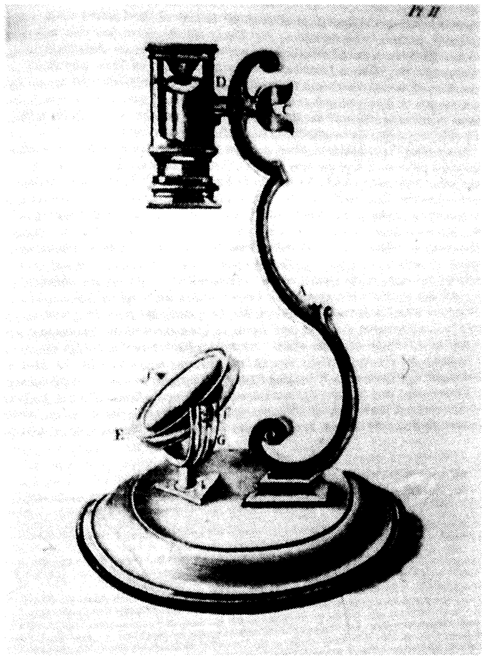
Historians Reexamine Links between Theory, Experiment

Historians of science are reexamining how theory and experiment interact. According to a popular notion, "proper science" can only occur when the scientist approaches an experiment with no "preconceived ideas" about the outcome, "letting the chips fall where they may." In histories of the spontaneous generation debates, the "losers" often are described as biased by their belief in a "vital force," whereas the "winners," such as Redi, Spallanzani, Pasteur, and Tyndall, are portrayed as open-minded investigators. In *Three Centuries of Microbiology,* for instance, the 1 9th-century British proponent of spontaneous generation, H. C. Bastian, is said to have "held to his faith in spite of the fact that his arguments were destroyed with monotonous regularity by Pasteur and his collaborators."

Meanwhile, Spallanzani, Pasteur, and others are described as able to defeat their foes by virtue of possessing better instruments, especially superior microscopes. Thus, T. H. Huxley portrayed Spallanzani's 1 &h-century contemporaries, the Comte de Buffon and his collaborator John Needham, as "armchair philosophers" who cooked up a doctrine of "organic molecules," a vital "plastic force," and spontaneous generation in part because their inferior microscopes provided fuzzy images to support fuzzy ideas they wanted the data to confirm.

T. H. Huxley's 19th-century version of that earlier debate became an object lesson for generations of young scientists. "The scholarly tradition has concluded that either the observations (of Buffon and Needham) were faulty, the

FIGURE 2



Single-lens Wilson screw-barrel microscope used by Buffon to make his observations in support of his interpretation of the theory of spontaneous generation. In this theory, small bacterium-size particles, which Buffon called "organic molecules," clumped together to form living "animalcules."

instruments deficient, or the interpretations demonstrative of excessive a priori theorizing," notes P. Sloan of the University of Notre Dame, South Bend, Ind. "But these received analyses leave several nagging difficulties when examined closely. . . . Buffon was a critical and self-reflective scientific methodologist . . ."

Contemporary critics of Buffon and Needham, including Spallanzani in the 1770s, claimed bias at least partly because they assumed the pair to have worked with a British Cuff compound microscope (Fig. 1), which had a maximum magnification of only about 100× and produced severe chromatic and spherical aberration. However, according to Sloan, Needham used a high-quality single-lens microscope of the Wilson screw-barrel design (Fig. 2), capable of at least 400× magnification "with outstanding resolution."

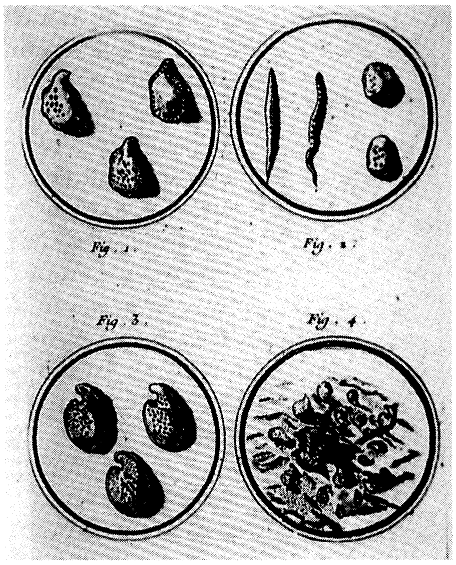
"This microscope was from all indications superior to the simple microscope employed in the famous experiments by Spallanzani," Sloan points out. "Spallanzani, not Buffon and Needham, was the technically handicapped party in this debate."

In Retrospect, Alleged "Nonscientific" Biases Shifted

Even while Needham and Spallanzani debated, the notion of ovist preformation, the idea that each egg contains all future generations, was also under debate. Needham and Buffon argued in favor of epigenesis, saying that spontaneous generation invalidated preformation theories and threatened to undermine the Cartesian mechanical Deist world view. Their opponents had as much preconceived reason for disbelieving spontaneous generation as Buffon and Needham had for believing it. Spallanzani eventually came down on the side of preformation and rejected Needham's theory. In this instance, Spallanzani's microscope surely revealed no homunculi inside eggs or sperm cells (Fig. 3), meaning he, too, was "philosophizing."

Many, including Voltaire, feared that Needham's claims supported atheism and materialism. They also thought that this theory implied that life could originate by a random combination of substances, making it contrary to religious beliefs and a natural philosophy still in the service of demonstrating a beneficent Creator. Because this chance combination of chemicals is a widely embraced modern hypothesis

FIGURE 3



Spallanzani's drawings of infusory animals. Spallanzani attacked Buffon and Needham on technical grounds, claiming that their observations were flawed by the use of inferior equipment. Spallanzani's own observations were made with "an instrument incapable of the short-focal-length, high-resolution work permitted by the Wilson screw-barrel design," according to P. Sloan. Spallanzani's contention that Buffon was imagining smaller particles was a key component of his argument against spontaneous generation, but as Sloan points out, "Spallanzani, not Buffon and Needham, was the technically handicapped party in this debate."

Figure courtesy of the Regenstein Library, University of Chicago about the origin of life, it is curious that Buffon and Needham are not celebrated as thinkers far ahead of the religious biases of their time.

In their own era, fellow clerics Needham and Spallanzani moved from mutual respect in the 1750s to ceasing all communication in 1780.

The experiments of Needham and Buffon, and the organic molecule theory, became a classic example of a priori science and faulty hypothesis-making. However, their experiments were too advanced for their historical era, raising observational difficulties which others could not, for technical reasons, resolve.

Pasteur and Pouchet Revive the Debate a Century Later

Louis Pasteur's experiments in the 1860s on spontaneous generation, particularly his "swan-necked flasks," are part of the Pasteur-Pouchet debate of the 1860s. Subsequently, because the historical introduction to Pasteur's memoir served as the model for describing this controversy, it is important to note that it fits what I call the model of "dueling experiments," meaning the debates are stripped of their crucial philosophical context. It is remarkable how asymmetrically historians have treated Pasteur on the importance to his work of the use of preconceived ideas. The same traits that for Buffon and Pouchet are seen as failings in truly scientific approach are for Pasteur the mark of a genius not allowing himself to be too-rigidly bound. For example, Pasteur chose to omit an entire chapter of the story, i.e., his argument that parasitic worms arise by spontaneous generation. So dominant has Pasteur's master narrative been that it was only in the early 1970s, through historical detective work by J. Farley of Dalhousie University, Halifax, Nova Scotia, Canada, that this omission was restored.

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Pasteur claimed that germs must be the source of growth in previously boiled infusions. His opponents pointed out that his results proved only that dust is another necessary ingredient for spontaneous generation in his yeast-sugar-water infusions. Historians point out, as did Pouchet and others at the time, that Pasteur never replicated some of Pouchet's most convincing experiments: those involving boiled hay infusions, which contain heat-resistant endospores of *Bacillus subtilis*. If Pasteur had tested such infusions in his swan-necked flask, Farley and Geison pointed out 20 years ago, "the debate might have ended quite differently."

Why did the French Academy of Sciences award the victory to Pasteur and declare the spontaneous generation controversy settled once and for all? Spontaneous generation was at the time just as politically and religiously charged a subject as it had been 100 years earlier for Buffon and Needham. Although spontaneous generation had been associated with the doctrine of transmutation of species, Darwin's On *the Origin of Species* subjected that doctrine to renewed debate. The first French translation of Darwin's work, by Clémence Royer, appeared in 1862 and was prefaced by her long diatribe against the Catholic Church, which was, however, on cozier terms than ever with the conservative government. In France, Darwin's theories were considered "a politico-theological doctrine allied with forces which threatened the Church and State," according to G. L. Geison of Princeton University, Princeton, N. J. Because of this association, spontaneous generation was "perceived as a threat to the belief in a providential Creator." Hence, the outcome of the Pasteur-Pouchet debate "carried implications of enormous importance to the political fabric of the Second Empire."

While Pasteur was truly an experimental genius compared to Pouchet, his no-preconceptions portrayal of himself is not true. For example, he viewed life as dependent upon a cosmic asymmetric force, a belief that arose in part from his study of crystals. He was convinced that Pouchet was wrong, not so much because spontaneous generation was impossible, but because Pouchet was not aware of the importance of asymmetric forces to the problem of life and was not approaching the experiments by that route. Pasteur, who was well aware that his important scientific patrons were fully entrenched in the conservative regime, kept silent about his own attempts to produce spontaneous life in the laboratory while, in public, he vocally refuted the work of Pouchet.

The British Spontaneous Generation Debate in the 19th Century

Mv own research has been on the British scientific and medical community of the 1860s and 1870s, which contained many entrenched advocates of spontaneous generation and those most resistant to the germ theory of disease. British doctors then favored a theory, first promulgated by Justus Liebig in the early 1840s, that contagious disease is analogous to fermentation, which could be spread by chemical toxins locally. When the cause of cholera was incorrectly attributed to a fungus in 1849 but then refuted, many British physicians who leaned toward the germ theory felt that it had been discredited. Thus, when Pasteur's claims reached Britain, doctors there were skeptical about living microbes being the source of contagion. Instead, they favored chemical poisons as that source, viewing microbes as a by-product of the disease process. Thus, when physicist John Tyndall gave a lecture, "Dust and Disease," in January 1870, endorsing the germ theory of Pasteur, many British doctors took offence. They accused Tyndall of being an interloper in biology and medicine and claimed there were important technical reasons for their skepticism about the germ theory. In particular, Tyndall's version of the germ theory denied any role to the patient's "constitution." Thus, according to Tyndall, if germ-laden dust particles fell into an individual, he or she would always get sick, but not if the particles, or "germ clouds," landed elsewhere.

Chief among medical professionals who opposed Tyndall was Henry Charlton Bastian, professor of pathological anatomy at London's University College Medical School. Bastian, an avowed proponent of evolution, did many experiments trying to show that microorganisms arise by spontaneous generation, or "biogenesis." Bastian and many others interested in natural selection thought that Darwin's theory required spontaneous generation to explain the original common ancestor of all species. Bastian also thought that bacteria in diseased patients resulted from spontaneous generation, as by-products of the disease process. By 1875 he had published the results of hundreds of experiments in which he showed that bacteria could be found in tubes of numerous infusions that had been boiled for various periods. Tyndall devised an ingenious dust-free cabinet in which to carry out similar experiments, attempting to refute Bastian's claims. Meanwhile, Tyndall's close friend T. H. Huxley concluded that Bastian "had gotten out of his tubes exactly what he put into them." Huxley and Tyndall agreed that living things somehow survive boiling. Moreover, organisms as complex as protozoa must come from "seeds" or "germs" of similar organisms. They also lobbied to convince their scientific colleagues that Bastian was either a poor experimenter or a fraud and cheat.

When Huxley addressed the British Association in Liverpool in September 1870, he moved to gain the rhetorical upper hand by redefining the terms, asserting that "biogenesis" meant life from other life. He stated that although "abiogenesis" was possible, it could only have occurred in the conditions of the primitive earth. This dualistic terminology was rapidly picked up and propagated in textbooks. Thus, it is more than a little ironic that Huxley had hijacked the term "biogenesis" from Bastian, who was using it to mean exactly the opposite, i.e., spontaneous generation! For Huxley, redefining the terms of the debate was the single most effective stroke that guaranteed him victory.

By 1876, Tyndall had increasing difficulty with experiments carried out in his dust-free cabinet. Infusions that previously were sterilized after only 5 minutes of boiling could not be sterilized even after hours of boiling. That same year the German botanist Cohn identified certain species of *Bacillus*, especially common in hay and cheese, that showed growth after extended boiling because they produced heat-resistant endospores. Once informed of Cohn's work, Tyndall immediately understood the source of his own recent difficulties. Of course, Cohn's insights also showed that Tyndall and Huxley were wrong about Bastian being a sloppy, incompetent experimenter. However, precisely that version of Bastian appeared in textbooks until quite recently. Pasteur's student Emile Duclaux was the only contemporary writer who credited Bastian for sticking to his experimental results. Indeed, without Bastian to goad them, Pasteur, Cohn, and Tyndall might never have discovered that they were wrong about bacteria surviving in boiled hay infusions because of heat-resistant spores. Pasteur never accepted that chance events enabled "abiogenic" materials to coalesce into the first organisms—a belief now widely held among biologists.

The British debate of the 1870s reminds us of how recent is the alliance we take so much for granted between medicine and laboratory science. Many of the best minds among the doctors of that time, including a number sympathetic to Darwin, coolly evaluated the available evidence, including Pasteur's swan-necked flasks, and concluded that a germ theory of disease was still too fanciful. We should not ridicule them as blind, unscientific, or less intelligent than modern doctors, nor should we consider their alternative theories of disease primitive or simplistic. Restoring real, intelligent human beings to the so-called "losing" roles in historical scientific debates surely gives us a more realistic account of both old and modern scientific triumphs.

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