SACRED BOVINES

A COMEDY OF SCIENTIFIC ERRORS

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William Shakespeare may well have foreshadowed the modern television sitcom. His comic misadventures were expertly crafted. In *A Comedy of Errors*, for example, twins (with twin servants), each separated at birth, converge unbeknownst to each other in the same town. Mistaken identity leads to miscommunication. More mistaken identity follows, with more misdelivered messages and yet more misinterpretations. Hilarious consequences ensue. It is a stock comedic formula in modern entertainment. A character first makes an unintentional error. Then ironically, in trying to correct it, things only get laughably worse.

Science, we imagine, is safeguarded against such embarrassing episodes. In the lore of scientists, echoed among teachers, science is "self-correcting." Replication, in particular, ensures that errors are exposed for what they are. Research promptly returns to its fruitful trajectory. Serious stuff, science.

But just such a case of compounded error occurred in science in the late 18th century. Joseph Priestley discovered that plants can restore the "goodness" of air that had been fouled by animals or combustion. But others could not replicate his results. Even Priestley himself. After further work, Priestley attributed the observed effect to a different cause – only to find later that the new conclusion itself was mistaken! For us now, the story seems amusing, but it is also nonetheless instructive. The case invites us to reconsider the sacred bovine that science is "self-correcting," especially due to failures of replication. Indeed, this reassessment leads us deeper into reflecting on our romantic idealizations of science, an enduring legacy of Priestley's Enlightenment period, centuries ago.

The story begins in the early 1770s, in Leeds, England. Joseph Priestley – minister, avid experimentalist, and self-taught chemist – had been investigating various kinds of air. At this time, he was examining various ways of making air noxious: by the putrefaction of dead mice or cabbage, by the fumes of burning charcoal, by mice breathing the air, or by candles burning out in it (all processes that exhaust the oxygen, in today's terms). Such "air" would not support animal respiration. What was the nature of this "air" and how might it be remedied? Priestley, who liked to "tinker" with variations of his experiments, investigated the possible airs emitted by plants, as well. He later recalled:

> On the 17th of August 1771, I put a sprig of mint into a quantity of air, in which a wax candle had burned out, and found that, on the 27th of the same month, another candle burned perfectly well in it. This experiment I repeated, with the least variation in the event, not less than eight or ten times in the remainder of the summer. (Priestley, 1781, pp. 52–53)

Then he tested just oil of mint, to see if the effect was caused merely by the plant's aromatic "effluvia." It was not. Subsequently, he tried the experiment with balm, groundsel, and spinach. All modified the air to support sustained burning. Animals, too, could breathe longer in the treated air. Plants, Priestley had found, could restore the "goodness" of the air depleted by respiration or combustion. American correspondent Benjamin Franklin immediately perceived the global implications: plants help restore the atmosphere that humans and other animals foul. The system ensures our survival. That view fit neatly with Priestley's religious belief in an intentionally designed (and rational) natural world. It was a remarkable discovery. For this and other work on airs, the Royal Society in 1772 awarded Priestley the Copley Medal, then the most prestigious honor in science.

Others were eager to build on Priestley's discovery about plants and the restoration of air. But they could not always get the same results. Today, we might say that they frequently failed to replicate his experiment. That led to some confusion. Priestley returned to his experiments himself, but only a half-decade later. By then he had moved to a new city – and a new experimental workspace. Like others, he could not consistently obtain his earlier results. Indeed, in some cases, the plants now seemed to *worsen* the quality of the air! His original claims seemed awkwardly in question. Should he "retract" them? Priestley had already received the Copley Medal and his findings had been praised by the President of the Royal Society. And the original conclusions fit comfortably with his worldview. He thus discounted the significance of the negative results: "one clear instance of the melioration of air in these circumstances should weigh against a hundred cases in which the air is made worse by it" (quoted in Nash, 1957, p. 360). Once the "discovery" had been made, Priestley seemed reluctant to acknowledge that it might be an error.

Priestley persisted. Following his habits, he explored more minor experimental variations, without any major theory or hypothesis to guide him. Eventually he noticed an apparent role for sunlight. In his first set of studies, he had apparently missed the significance of a nearby window, absent in his new workspace. Priestley now had a new relevant variable: light. At this point in the story, the informed modern observer may anticipate next the triumphant "discovery" of the role of light in photosynthesis. With the error virtually solved, one is poised for a "happily ever after" denouement. But here the comedy of error unfolds differently. Perhaps, Priestley wondered, light alone – *not* plant life – was key? Accordingly, he tried simple samples of well water exposed to sunlight, without plants in them. They, too, yielded the "purer," more respirable air. Priestley now felt confident that he had identified the source of error in his original work. The process of restoring the air, he concluded, was related to light, not plants! Error resolved. Or so it seemed, ironically, to Priestley.

Of course (from a modern perspective), it was the newly revised conclusion that was in error. Here, the scene shifts to others working on the problem. Jan Ingenhousz, among others, noticed that the well water left in sunlight also generates a green scum. They connected the green scum to green plants. With further microscopic analysis they concluded

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that the scum was living algae. They also restored the air. So, plants or microscopic algae – both green living matter – could transform the air. But only in light, they now realized. Ingenhousz demonstrated the connection more fully through an extensive series of controlled tests. Both green plants and light together were needed to restore the air, not one or the other. Ingenhousz, and then others, also perceived that the plants producing good air in light was opposite to plants burning, which used up good air and released light. The plants were absorbing the light somehow to make fuel. That coincided with restoring the air. It was the reverse of combustion. Here, emerging in part from Priestley's successive errors, was the discovery of what we now call photosynthesis.

Priestley had noticed the green scum, too. But he had considered it an incidental byproduct of the enriched atmosphere. No light, no bubbles, no scum. In retrospect, Priestley's experimental results were ripe for mistaken identity. Correlation could resemble causation, in two ways. First, the light seemed directly responsible for the restored air. Priestley saw, but discounted the significance of, the correlated green matter. Second, the enriched air seemed to cause the green scum, not the other way around. If we laugh, it is because we can see how easily we, too, could have been mistaken. To his credit, Priestley acknowledged his error, once the new explanation had been clearly demonstrated. Error remedied, lessons learned, plot resolved. Scene fades wistfully, as comedic humility lingers.

Priestley's successive errors offer an opportunity to reflect on error in science. According to standard accounts, replication is the chief mechanism for identifying experimental error. Failure to replicate means that one should jettison the results as wrong. In this case, that would have been ill advised. Priestley's original findings were correct. Rather, the "failed" replications were problematic. Ultimately, Priestley did not know at first – and was thus unable to specify to others – the exact conditions in which his plants had restored the air. When the role of light became clear, replications then "succeeded." But even then, repetition alone did not thereby confirm that Priestley's new conclusion about the exclusive role of light was correct.

Priestley's errors did not merely announce themselves. Contrary to popular expressions, the data do not speak for themselves. Observations need to be interpreted. Errors, too. Here, finding and characterizing the error required further scientific work. Priestley and others had to identify both light and green plants as key factors. Ingenhousz's controlled studies were needed to isolate the relevant variables and to demonstrate their joint significance. In a sense, he had to successfully replicate Priestley's *errors*, while *also* showing what caused the errors. Fixing errors in science is not just about discrediting or discarding "negative" results. Paradoxically, perhaps, it involves understanding them. At the same time, this yields new knowledge.

One may reflect further on just how Priestley's error was discovered and remedied. First, it required motivation and resources. Priestley had wealthy subscribers and the patience to persist at endless variations of his experiments. Ingenhousz, too, had both the interest and leisure time to devote to research. Science proceeds concretely and materially, not through imagination or ideas alone. Second, identifying the green "scum" as plant life required a microscope. That was a technological contribution. One also needed the disposition and skills to use the microscope, which Priestley largely lacked, but others supplied. Finally, interpreting the correlation of light and green scum depended on a repertoire of alternative theoretical perspectives, here shared across the scientific community. The case of Priestley's errors and their resolution ultimately helps convey the nature of science, or how science works (Allchin, 2012).

According to standard accounts, science is "self-correcting." Here, Priestley's errors were ultimately corrected, but perhaps not due to any systematic or automatic "self-correcting" method. The process took several years of focused effort. Error correction cannot be taken for granted.

The image of science as "self-correcting" reflects a kind of rosy intellectual optimism that flourished among the elite in Priestley's era and has largely persisted since. Benjamin Franklin (1837) expressed the view well: "Truth is uniform and narrow; it constantly exists, and does not seem to require so much an active energy, as a passive aptitude of soul in order to encounter it." For Franklin (and many others), one need not explain the emergence of knowledge. Insight is supposed to unfold naturally. And effortlessly. Priestley's case shows how this Enlightenment view, which still haunts some science education (Matthews, 2009a, b), is ill informed. Sources of error and occasions for "mistaken identity" permeate science. It requires work to articulate what's right, and to sort out what is the case from what merely appears to be so. That is how we generate knowledge. Resolving Priestley's errors was thus largely also the story of discovering photosynthesis.

Priestley's mishaps might amuse us today, but the reflective practitioner laughs with him, not at him. His mistakes remind us of the very human dimension of science – and of our own potential for error.

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