must be in order for it to be noticed.

Among early economists, however, Daniel Bernoulli's theory was largely ignored until the twentieth century, when mathematician John von Neumann and economist Oskar Morgenstern — in their endeavour to lift economics from "plausibility considerations" to a mathematical science — provided an axiomatic framework for utility theory and decision-making in 1944. A few years later, economist Milton Friedman and statistician Leonard Savage, puzzled by the fact that many gamblers also take out household insurance, argued that utility functions have bulges and dents. Economist Harry Markowitz adapted utility functions in 1952 such that individuals consider their current wealth as a baseline, and are either risk-averse or risk-taking depending on whether potential losses or gains are relatively small, medium or large.

At about the same time, economist Maurice Allais pointed out that utility theory does not always account for people's behaviour. Faced with lopsided choices — for example, the certainty of $1 million versus a chance of obtaining either hundreds of millions or nothing at all — people do not necessarily choose the 'rational' outcomes. Paradoxes such as these led sociologist and economist Herbert Simon to propose in the mid-1950s that humans are unable to gather all relevant information and to process it. As a result, they do not try to maximize their expected utility but, instead, set themselves more modest goals that will satisfy them.

In 1979, psychologists Daniel Kahneman and Amos Tversky developed prospect theory, which follows Daniel Bernoulli's lead but with some differences: losses hurt more than gains feel good; decisions depend on how the questions are framed; and probabilities are perceived to be smaller than they actually are, except for very small probabilities, which are perceived to be larger.

Three centuries on, Nikolaus Bernoulli's letter remains topical. Although he was not the one who provided the answer to the intriguing puzzle and, indeed, he resisted Cramer's and his cousin Daniel's explanations, it was his prompting of his friend to look deeply into the mathematics that set in motion a completely new way of thinking about risk, uncertainty and what money and wealth mean to people. ■

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ILLUSTRATION BY HARRY CAMPBELL

Mind the metaphor

Imagery can help to bridge conceptual boundaries, but it can also cause trouble — as shown by the proliferation of engineering talk in biology, argues **Eleonore Pauwels**.

DNA barcodes, gene-shuffling, BioBrick parts and cells as hardware: synthetic biology is saturated with metaphors. And it is not an isolated case. In 1976, evolutionary biologist Richard Dawkins coined the term 'selfish gene' to explain a DNA-centred view of evolution. Ecologists built a whole metaphorical language around the idea of the 'household of nature', including terms such as competition and colonies. Beyond the natural sciences, the father of psychoanalysis, Sigmund Freud, described the restoration of an ego damaged by neurosis as the "reclamation of flooded lands".

As a public-policy scholar, I have spent the past five years listening to synthetic biologists talk about their hopes, successes and failures. At first, I was intrigued by the pervasiveness of computing and engineering metaphors, both in conversations between scientists at the bench, and in policy discussions and public communications. Increasingly, I wanted to know what might be 'lost in translation' between these metaphors and reality. In collaboration with my colleague Andrea Loettgers, a philosopher of science at the California Institute of Technology in Pasadena, I reviewed the use of metaphors in the laboratory and in the public sphere.

We looked at several sources, including more than 1,000 synthetic-biology articles, interviews with synthetic biologists and four years of US press coverage on the subject, as well as policy reports, US congressional hearings and bioethics-commission meetings. We found that although metaphors are essential in enabling science and in communicating research to the rest of the world, their use can also mislead the public, and even scientists themselves.

With the emergence of molecular biology in the 1940s, the idea of DNA as the 'software of life' became popular in the scientific community[1,2]. Then, in the late 1990s, computer scientists, physicists and engineers were fuelled by the idea that they might ▶

be able to direct cells in the same way that people program computers. In the laboratory, researchers started to use computing and engineering metaphors — switches, oscillators and logic gates, for instance — both to guide the design of synthetic constructs and to understand how natural systems function.

Almost immediately, scientists were confronted with the uncertainties and constraints of engineering in the cellular context. Engineering concepts and metaphors could serve only as inspiration; they were and are subject to much tinkering, owing to the complexity of biology. For instance, describing genetic systems as though they are electrical ones (whereby genes are switched on and off) works to a degree. But unlike switching on a light, which depends only on the flow of electricity, the activation of a particular gene depends on numerous parameters, and the precise effects of all of these different influences are often hard to pin down.

Despite the necessary fluidity surrounding their use, engineering metaphors have proved so robust as to create an identity among merging research communities. Indeed, the power of metaphors resides in their ability to serve as translational devices between different articulations of science — an essential function when cross-field collaboration results in the building of a new discipline, as has been the case for synthetic biology.

Scientists using metaphors among themselves are often aware of, and even careful to point out, the subtleties that could be misconstrued. Problems tend to arise when metaphors are used outside the laboratory.

Along with numerous journalists crowding the room at a May 2010 press conference in Washington DC, I listened transfixed as biologist Craig Venter announced that his team had become the first to build a self-replicating bacterial cell in the laboratory[3] (see go.nature.com/xnq5h4). His words transformed a complex biological procedure into a science-fiction storyline: "This is the first self-replicating species we've had on the planet whose parent is a computer."

Later that year, in a hearing convened by the US Committee on Energy and Commerce, Jay Keasling, a pioneer of synthetic biology based at the University of California, Berkeley, similarly described how synthetic biologists assemble "standardized well-characterized components from existing well-studied organisms, much like how one might assemble a computer from standard components such as a hard drive, sound card, motherboard and power supply".

Faced with explaining the messy complexity and uncertainty of science to the public, it is understandable that scientists reach for metaphors. But discourse such as Venter's and Keasling's sends a message to policy-makers and laypeople that scientists can already make biological systems that are reliable and controllable. It widens rather than closes the gap between scientific realities and the expectations of policy-makers and the public.

CONVEYING BELIEF

Psychologists at Stanford University in California showed in 2011 (ref. 4) that people's views on how to manage crime varied drastically, depending on whether they were told that criminal activity is a 'virus' or a 'wild beast'. It is because metaphors are so crucial to the perception of an idea that scientists need to use them with such care.

When new technologies emerge, optimism and enthusiasm often trump humility. In their excitement at making a discovery, many scientists, engineers and entrepreneurs suddenly believe that they can predict and control outcomes in complex physical and biological systems — and they frequently use metaphors to convey that belief.

One way to safeguard against runaway metaphors is to involve experts from diverse disciplines in the assessment of emerging technologies. Often, the sharing of expertise and outlooks helps to temper rhetoric and unpack what could get lost in translation. For instance, molecular biologist Bonnie Bassler of Princeton University in New Jersey argued in front of the 2010 US Presidential Commission for the Study of Bioethical Issues that the title of Venter and colleagues' 2010 *Science* paper[3] ('Creation of a bacterial cell controlled by a chemically synthesized genome') "does not represent the scientific findings" in it, and that "the authors did not create. They cloned."

Organizers of the Science and Technology Innovation Program at the Woodrow Wilson International Center for Scholars in Washington DC have developed a strategy that could provide a model for practitioners across many disciplines. At the Wilson Center, experts and non-experts from different disciplines and sectors come together to discuss the science and implications of specific technological applications that are soon to be commercialized. Some of the latest examples include an arsenic biosensor and an algal biofuel.

Such collaborations between scientists, social scientists and policy-makers can drastically improve awareness of how powerful language can cut both ways. ■

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