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Transformational thinking

The mathematics of Joseph Fourier, born 250 years ago this week, shows the value of intellectual boldness — influencing everything from data processing to machine-learning algorithms.

When you listen to digital music, the harmonies and chords that you hear have probably been reconstructed from a file that stored them as components of different frequencies, broken down by a process known as Fourier analysis. As you listen, the cochlea in your ears repeat the process — separating the sounds into those same sinusoidal components before sending electrical signals to the brain, which puts the components together again.

Fourier analysis allows complex waveforms to be understood and analysed by breaking them down into simpler signals. And it's a shining example of the power and value of intellectual boldness.

The roots of the idea go back to the mid-1700s, when the Italian mathematical physicist Joseph-Louis Lagrange and others studied the vibration of strings and the propagation of sound. But it was one of Lagrange's pupils, Joseph Fourier, who in 1822 truly founded the field that carries his name.

Fourier was born 250 years ago this week, on 21 March 1768. Today, there is virtually no branch of science, technology and engineering that is left untouched by his ideas. Modern versions and analogues of his theory help researchers to analyse their data in almost every discipline, powering everything from YouTube's videos to machine-learning techniques.

Among the scientists who benefited is Ingrid Daubechies, an applied mathematician, who in the 1980s helped to develop the theory of wavelets, which generalized Fourier analysis and opened up previously inaccessible problems. Wavelets were one of the main data-analysis tools used to detect gravitational waves for the first time in 2015, to worldwide acclaim. "He's one of my heroes," Daubechies says.

Before he inspired a revolution in science, Fourier helped to trigger one in his native France. He came of age in the ferment of the 1790s and signed up as a committed *révolutionnaire français* — a decision that almost led to him losing his head to the guillotine during the Reign of Terror that followed the establishment of the First Republic. He joined the army of Napoleon Bonaparte on his invasion of North Africa, alongside dozens of other experts in science, medicine and engineering. With colonial zeal, Napoleon claimed that these intellectuals would help to spread the civilizing values of the Enlightenment.

Fourier worked in Egypt as an administrator, where his efficiency and smart ideas prompted Napoleon to earmark him for a similar position home in France. Back in gloomy northern Europe, Fourier became obsessed with heat and started to apply his mathematical skills to understanding how heat was transferred. He is widely credited as the first scientist to discuss how the greenhouse effect could warm the planet.

He also wanted to understand how heat propagates in a solid object. He discovered the equation that governs this, and showed how to solve it — predicting how the temperature distribution will evolve, starting from the known distribution at an initial time. To do so, he broke the temperature profile down into trigonometric functions, as if it were a sound wave. Crucially, his analysis included functions for which temperature was allowed to have 'discontinuities', or abrupt jumps. This possibility horrified mathematicians at the time, who were much more comfortable with smooth curves that promised aesthetic simplicity. Fourier stuck to his guns and, as he developed his ideas, started to win his critics over.

Beyond breaking down a function into frequencies, Fourier created a 'dual' profile that encodes all those frequencies, and that became known as the Fourier transform. In the twentieth century, the Fourier transform became central to quantum mechanics, showing how physical quantities such as position and momentum are 'dual', or complementary, to each other. This means that they cannot be known simultaneously with arbitrary precision: this 'Heisenberg uncertainty' is now seen as one of the fundamental principles of nature. And crystallographers now understand that the X-ray diffraction patterns of a crystal are the Fourier transform of the crystal's structure.

> ***"Today, there is virtually no branch of science that is left untouched by his ideas."***

Modern incarnations of Fourier analysis include the 'fast Fourier transform' and 'discrete Fourier transform', which allow faster and more-efficient processing of large amounts of information, including data produced by astronomers.

Fourier would surely be delighted that his ideas have endured. Writing to a friend 229 years ago, he lamented his lack of achievement up to that point: "Yesterday was my 21st birthday; at that age Newton and Pascal had already acquired many claims to immortality."

He succeeded in his fifties. Patience is a virtue, but so is a willingness to pursue intuition to conclusions that conventional wisdom deems illogical. Fourier did that and so stands as a scientific giant who should be remembered and appreciated by researchers everywhere. ■

Getting engaged

Dialogue with the public requires a willingness to accept uncomfortable truths.

Earlier this month, the United Kingdom's Royal Society released the results of a survey of public attitudes to genome-editing technologies. It reported a curious finding: whereas bioethicists like to make the distinction between changes that will and won't be inherited by future generations, the survey respondents didn't. They seemed just as comfortable with genome editing to correct a genetic disorder in embryos as in adult cells. Previous exercises showed the same sentiment.

Public engagement, just like science, can be messy and head in unexpected directions. That cannot, and must not, be a reason not to do it: science has a duty to respond to the views of the public it seeks to serve and represent. And done properly, public engagement can give research more impact and relevance. In general, however, engagement exercises have been viewed by scientists as a one-way transmission of information from experts to the public. This leaves researchers open to the charge that they merely seek public endorsement. Too often, previous attempts to incentivize engagement have burdened individual scientists, who may lack the training, time or funding, resulting in poor-quality engagement and a 'tick-box' mentality.

There are encouraging signs that the scientific community is ready to up its game. Funders such as the US National Institutes of Health and the Wellcome Trust aim to learn more from social-science research on how to improve engagement with stakeholders. The US Food and Drug Administration has established a working group that intends to improve the agency's engagement with patients. The fact that the Royal Society commissioned an analysis of its own efforts, and made the results of that evaluation public, is also good news. However, its failure to seek early input from people who could be first affected by the technology, such as those living with disease or disability, is a missed opportunity.

Change is in the air. In this issue of *Nature*, two Comment pieces suggest ambitious models to improve public engagement (pages 435 and 438), also in the field of genome editing. One calls for a global forum whose members push the discussion beyond the technical abilities of genome editing, and collect a wide diversity of views about its potential applications.

The other article advocates a large consortium that would break down the idea of one, homogeneous 'public' by investigating the distinctions that exist between different communities, such as farmers' unions and parent-and-toddler groups. Smaller engagement processes can also be made more democratic. Researchers could visit participants in their own communities, to encourage open discussion. And when it comes to issues such as genome editing, it is important to include input from a range of stakeholders, such as activists, patient advocates, and church representatives, in the research-planning stages.

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A World View column this week (page 415) describes an example of how policymakers listened to the public in South Korea, regarding controversial plans to build more nuclear reactors. Faced with growing public concern and even violent protests, the government put together a deliberative poll in which diverse groups of voters were given educational materials and brought together for three days of discussions with experts on both sides of the debate. The resulting poll revealed a surprisingly nuanced stance among the public: ongoing construction of nuclear reactors should continue, the majority said, but the government should pull back from plans to build more. The government followed these suggestions; the violent protests stopped.

As these and other efforts spread and become more sophisticated, engagement can become more about consultation and democracy, and less about the marketing of science. That will benefit researchers and the broader public alike. ■

Asymmetry rules

Singular symposium explores the pervasive presence of symmetry violations.

Those who believe that art and science share common ground (and not everyone does) often point to the concept of symmetry. Science, from fundamental physics to developmental biology, prizes symmetry, and Plato equated it with beauty and harmony. Still, art built on geometric symmetry is rare: even the blockish abstract paintings of Piet Mondrian and the psychedelic art of Bridget Riley have scant use for planes of reflection.

There's a much stronger case to be made for asymmetry as a point of intersection. It's a case bolstered by an intriguing conference held in France last week. The First European Asymmetry Symposium in Nice has a vigorously transdisciplinary programme, which aims to focus and encourage research on asymmetry in systems as diverse as the mouse zygote and market economies, chemical structure, Japanese art and neuroscience.

For all their celebration of symmetry in the laws of nature, physicists conjure more from its breaking. The four fundamental forces are presumed to stem from successive symmetry breakings in the very early Universe, and all the riches of condensed matter and crystallography spill forth from reductions of symmetry. The same is true in biology, in which a progressive elaboration of form is a feature of both evolution and development.

It was the symmetry breaking of a presumed-spherical egg that motivated Alan Turing to develop one of the most fertile models for the emergence of form from uniformity, in 1952. He might not have been right about that aspect of morphogenesis, but his model does explain other types of biological patterning, from animal markings to the ridges of the canine palate. The same ideas reach across disciplines to account for patterning in chemical mixtures and windblown sand.

More surprisingly, perhaps, asymmetry could be fundamental to aesthetics, too — perhaps reflecting what the art historian Martin Kemp calls a 'structural intuition' that lets us discern vitality in organic form; by contrast, geometric perfection creates a sense of sterility.

"There is no excellent beauty that hath not some strangeness in the proportion," said Francis Bacon (the seventeenth-century philosopher, not the twentieth-century artist, although the latter might well have agreed). Symmetry, once grasped, loses any capacity to surprise us.

The value of asymmetry in molecular science is well established. Louis Pasteur postulated the idea of molecular chirality (to describe molecules whose mirror-image forms cannot be superimposed on each other), and chemistry has pursued the idea almost obsessively since. For synthetic chemists, this particular asymmetry is a maddening challenge: natural molecules are full of chirality, but it's very difficult to produce one form selectively.

As Pasteur concluded, chirality has a central role in life's mysterious origin: the puzzle of why, for example, all chiral amino acids in proteins are of the left-handed variety remains unresolved. (Ditto the right-handedness of nucleotides and DNA's right-handed helix.) Why was symmetry broken, and was it by chance or necessity? Did the fundamental asymmetry of physics — the left–right 'parity' violation by the weak force — play a part in biasing the outcome?

Such questions are always worth revisiting. Whether they will mean much to the economists and linguists at the Nice meeting, say — to whom asymmetry typically means non-reciprocity of inter-agent relations and has nothing to do with spatial structure — remains to be seen.

Arguably, there is more common ground here with physicists studying topology, whether in the connectivity of complex networks or in the handedness of electron band structures of 'topological matter'.

Still, in that multiplicity of meaning lies much of the attraction of asymmetry. When symmetry is broken, choices are made: which forking path to take? Why enter this valley and not that one? Why these laws and not those? Why (it seems) more matter than antimatter? Why is quantum spin 'up' and not 'down'?

Making such choices between alternatives, when neither is obviously preferable, is often a dilemma for artists, too. Perhaps what is truly unifying for artists and scientists is the realization that, of all the many possible worlds, asymmetry makes the actual one unique. ■