A thing of beauty

Even when the evidence was going against them, Nobel prize-winners Murray Gell-Mann and Richard Feynman clung on to cherished theories just because they thought they were "beautiful". **Arthur I. Miller** wonders what drove them

ARE beauty and science compatible? Do scientists have the right to use the word beauty? Could art and science even be forging a common visual language that brings them historically closer than ever?

For physicists and mathematicians, at least, the answer is an emphatic "yes". In 2002, Steven Weinberg wrote: "The great equations of modern physics are a permanent part of scientific knowledge, which may outlast even the beautiful cathedrals of earlier ages." And back in the 1960s, Paul Dirac famously asserted that: "It is more important to have beauty in one's equations than to have them fit experiment." Richard Feynman, too, insisted on believing in one of his theories even when it seemed to contradict experimental data. "There was a moment when I knew how nature worked," he wrote in 1957. "[The theory] had elegance and beauty. The goddamn thing was gleaming."

So what makes an equation or a theory beautiful? For most art theorists and artists, beauty is subjective, but not for scientists. To scientists symmetry is beauty and therefore objective: scientists seek out mathematical equations that retain their form no matter how they are transformed. The mathematical equation for a sphere, for example, does not change when its coordinates are inverted. A sphere is still a sphere when viewed from any perspective, even in a mirror. This is the mathematical reason why the sphere is often considered the most perfect of forms.

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In *Les Trois Musiciens*, Picasso plays with "good form", the laws that enable us to make sense out of chaos

And if experiments on the decay process of elementary particles produce the same results when viewed in a mirror, they exhibit "mirror symmetry", associated with the law of the conservation of parity. Call it what you will, there is a basic element in most scientific theories that scientists believe they can quantify objectively as "aesthetics" or "beauty".

Why is symmetry so important? Why is it the term that scientists use synonymously with beauty? For many, it goes back to that fraction of a second after the big bang, some 13.7 billion years ago, when there was only one force – an instant of purest symmetry. When this symmetry was broken, the four forces of the physical world emerged: the gravitational, electromagnetic, nuclear and weak forces. The universe is now seen as being made up of broken symmetries. What scientists are trying to do is to find this primordial symmetry by hypothesising other symmetries that unify these four forces. When scientists look for explanations for what "breaks" these symmetries, they discover particles. Theories which exhibit the maximum symmetry – such as those unifying fundamental forces, like the electroweak theory – are considered "beautiful theories", and they usually turn out to be correct, which seems to justify the hunt for symmetry.

Symmetry need not be tied to visual imagery – the need could reflect an intuition about how nature ought to be. This was Einstein's starting point in 1905 when he introduced aesthetics into 20th-century physics. In his first paper that year, he argued that the "profound formal distinction" scientists made that particles of electrons emit waves of light was unwarranted. Why not just hypothesise particles of electrons emitting particles of light? Thus, his discovery that light could also be a particle emerged from his minimalist aesthetic.

His formulation of the theory of relativity also sprang from this aesthetic. The electromagnetic theory of the day offered two radically different explanations of how a current is generated in a wire moving relative to a magnet, depending on whether the current was observed by someone riding on the wire or on the magnet. To Einstein the two explanations were redundant: worse, they were asymmetrical. Surely the only real difference was viewpoint? Having unmasked this asymmetry, he could extend the principle of relativity to electricity, magnetism and light.

Two years later, Einstein applied the aesthetic of minimalism yet again. Day-dreaming in his job at the Patent Office in Bern, Switzerland, he considered the case of a falling stone, drawn towards the ground by gravity. The physicists of the day distinguished between the "inertial mass" of the stone, as it appeared in Newton's law, which related the force acting on an object to its mass times its acceleration, and the stone's "gravitational mass", which is its mass as described in Newton's law of gravity. Precision measurements indicated they were probably the same. Why have two masses when one sufficed? It was another asymmetry.

Ignoring experimental accuracy, Einstein took them to be exactly equal, a breathtaking leap which led him to realise that acceleration and gravity were relative to each other. This was to be the basis for his general theory of relativity – a theory scientists often describe as the most beautiful theory ever proposed.

For me its beauty goes beyond the minimalist, or conceptual, beauty of Einstein's earlier discoveries. It lies in its mathematical representation – and I use the term "representation" because mathematics is the means by which scientists represent nature, in the same way artists use paint and canvas.

Jackson Pollock's drip paintings unintentionally captured fractal patterns, the deep signature of nature

Einstein was struggling to find a mathematical version of Newton's gravitational theory which would keep its form when moved from one point to another in four-dimensional space-time. If the equations Einstein sought could satisfy this, then the laws of nature for every observer would be the same. This is the principle of relativity. Each observer (the different observers on a magnet and a wire, or the different observers viewing a Cubist painting) sees a different aspect of the same phenomenon. Einstein had achieved this symmetry with his special relativity theory; his aim was then to find a generalisation of it to include gravity.

He accomplished this by expressing his new theory in terms of tensors – complex mathematics that described a flexible geometry of space-time whose shape was determined by the bodies in it. Gravity turned out to be a deformation of space caused by these bodies. As an incidental benefit, this mathematics revealed some surprising features of nature, such as that starlight could be bent by massive objects – verified in 1919. It also predicted that a dying star might begin an eternal collapse and fall into a well in space from which nothing could escape, not even light – what we now know as a black hole.

Here, however, Einstein's aesthetic sense failed him: he dismissed black holes as an ugly solution to a beautiful theory. After all, how could something as big as a star possibly collapse to a point of infinite density? Most other physicists agreed. Tellingly, when black holes finally entered the scientific mainstream in the 1960s, the mathematical theory behind them was re-worked in new ways to reveal their essential beauty. They have since actually been observed.

Dirac's statement at the start of this essay on the importance of "beauty in one's equations" was intended for Erwin Schrödinger. In Schrödinger's first attempt to concoct his famous wave equation, he looked for one that agreed with relativity theory. The equation he came up with, however, was not supported by experiment. Eventually he produced the Schrödinger equation, which was not beautiful, but did at least fit the data. Dirac thought that Schrödinger should have ignored the data and persevered in his pursuit of a beautiful equation.

Dirac did just that. He discovered an ▶

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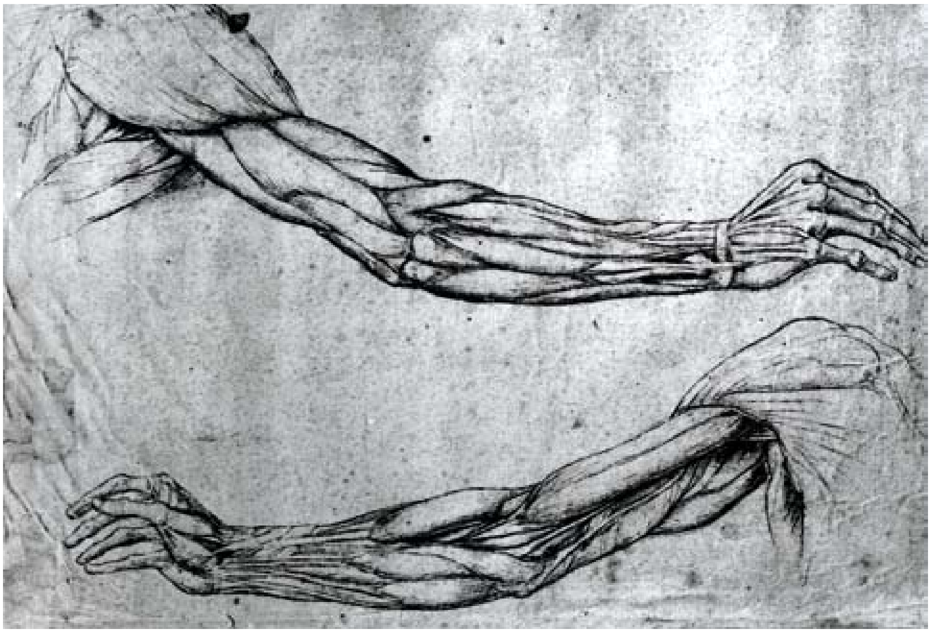

equation that was consistent with relativity theory but represented in a mathematics unfamiliar to most physicists – spinors, intermediate between vectors and tensors. The problem was that it predicted particles with negative energy, which everyone thought an impossibility. Werner Heisenberg condemned it as the "saddest chapter in theoretical physics". Shortly afterwards, Dirac realised that these particles were actually antiparticles with positive energy. They were later discovered in the laboratory. Once again insisting on beauty in a mathematical theory revealed unexpected features of nature.

Dirac's equation dates back to 1928. By then the "battle between the waves and the particles", as Heisenberg called it, was over. It had been fought purely over aesthetics: the aesthetics of waves versus the aesthetics of particles, and the choice of mathematical formalism to describe it. What was at stake was the representation of physical reality. Schrödinger wrote that he was "repelled" by Heisenberg's quantum mechanics because it was formulated in an ugly mathematics. Schrödinger preferred his own wave mechanics with its classical imagery of electrons as waves.

Heisenberg replied that Schrödinger's "pictures" were "crap". Niels Bohr came to the rescue with his insistence on an aesthetic that included both waves and particles, thus satisfying most of the physicists involved. But the problem of finding the right, beautiful, visual imagery persisted when it came to the world of the atom. It was solved by Feynman in 1948. The Feynman diagrams, generated by the mathematics of quantum mechanics, provide a glimpse into the atomic world.

Could science and art ever move as close as they were in the late medieval world of Leonardo da Vinci?

Now, the advent of quantum mechanics led physics full circle back to Plato who, some 3000 years earlier, had regarded mathematics as the only way to glimpse the reality beyond appearances. The beauty of the mathematics of quantum theory turns out to be fine-tuned, linking each symmetry in nature to a law of conservation, such as the conservation of energy and of momentum. These laws help us fashion the mathematics of a theory correctly. Whenever physicists have proposed theories that violated them, they have failed.

Sometimes, however, a law of conservation is violated. The law of the conservation of parity, for example, states that a theory's mathematical structure should show a symmetry between left and right – the symmetry of the sphere. As the ancient Greeks knew, beauty can be enhanced by a small degree of asymmetry. Nature agrees. When an elementary particle decays because of the "weak interaction", it produces an electron and a neutrino, and it violates parity. Asymmetry is what the data shows so it has to enter the equation. But how to do it without creating ugliness?

In 1957, experimental evidence weighed heavily against Murray Gell-Mann and Richard Feynman's theory of weak interactions. As we saw, Feynman had declared that the theory "had elegance and beauty. The goddamn thing was gleaming". In other words, it had an inner perfection that suggested it could be generalised further, it hinted at how to unify the weak and electromagnetic interactions, and its mathematical representation was the simplest that could be constructed.

Despite the high reputation of the physicists responsible for the actual experiments, Feynman and Gell-Mann's response was that there was something wrong with the experiments. They were right. Thus although experiments are essential for scientific theories, certain theories are just too important – too beautiful, one could say – to be discarded when the experiments don't go your way. Perhaps in the future beauty will provide an important criterion for selecting one theory over another, now that theories are emerging which cannot be verified by experimentation as we know it today.

Both art and science shift between symmetry and asymmetry. The skewed faces in Picasso's *Les Demoiselles d'Avignon* and the pleasing asymmetries in his *Les Trois Musiciens* break what cognitive scientists call laws of good form. These are the laws that enable us to organise perceptions into patterns that are reasonably understandable, to create order out of a chaos of sense perceptions.

Progressively throughout the 20th century, mathematics began to impinge on art. Most recently, scientists found that Jackson Pollock's repetitive yet complex drip paintings bore a striking similarity to chaotic systems. Without realising it, Pollock found a way to represent nature using fractal patterns, reflecting the very fingerprint of nature.

The past is peppered with true artist-scientists such as Albrecht Dürer and Leonardo da Vinci, whose studies of projective geometry and perspective led to the concept of infinity in western science. Today, art and science appear to be moving closer together again. Artists use scientific equipment and concepts, scientists employ aesthetics. Both deal with visual imagery and metaphor. And both have followed parallel paths of increasing abstraction as they have progressed.

Some hundred years from now, art and science may well share a common language. As technology advances, could a new visual language emerge to blur or even obliterate the distinction between art and science? ●

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