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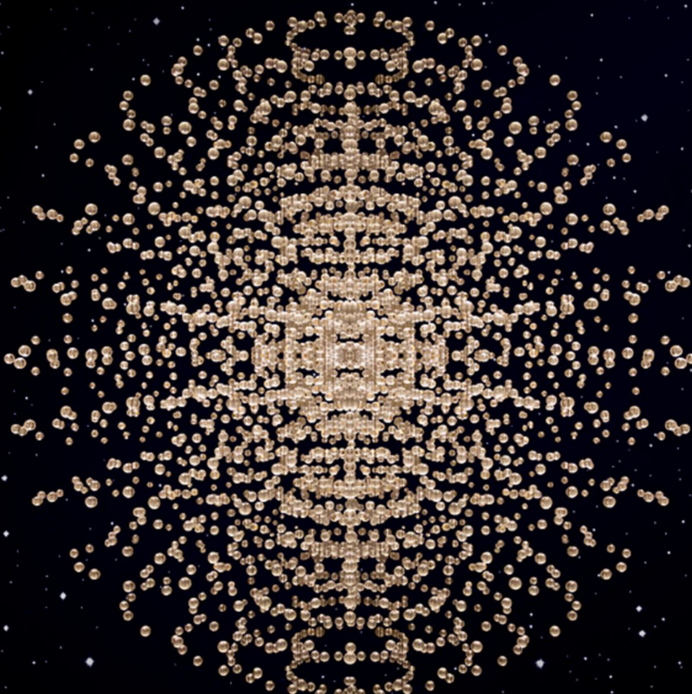
TOM McLEISH



THE POETRY AND MUSIC OF SCIENCE

Comparing Creativity in Science and Art

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Introduction

Creativity and Constraint

Art is limitation; the essence of every picture is the frame.

G. K. Chesterton

Creativity, Inspiration, Passion, Form, Imagination, Composition, Representation—this powerful list of words leads a reader's mind inevitably into the world of the arts. Perhaps it conjures up the shaping of a block of stone into the form of supple limbs and torso, or layering darkly tinted oil paints onto canvas to tease the eye into imagining a moonlit forest at night. Others may think of a composer scoring a symphony's climax—she summons the horns to descend as from a distant mountain peak to meet a harmonically ascending string bass-line in a satisfying resolution. A poet at his desk wrestles with meter and rhyme as he filters the streams of words, metaphors, and allusions that clamour for place on the page. The double miracle of art is not only that it allows humans to draw meaning from the world, but also that it reaches out to its listeners, viewers, and readers so that they may re-create for themselves something new and personal in response. Both by words and by images we are changed, troubled, made more aware as art enriches us in small ways or great. To engage in art by creation or reception and re-creation is to exercise one of the capacities that make us human. Indeed, the academic study of art's products and process falls under the class of disciplines we call the 'humanities'.

Experiment, Design, Formulation, Method, Theory, Observation, Hypothesis, Computation, Trial, Error—another list of words might lead to a different world of activity. These are more associated with disciplines we term 'the sciences'. Their energy seems to be of a different sort—we are not, perhaps, as emotionally moved by these terms; they do not suggest as much wild, unpredictable outcome. Are we encouraged to think, perhaps, of a laboratory setting—a careful mixing of liquids and a measuring of their temperature? Is the mental picture one of an observer carefully preparing a microscope, or calculating by computer the orbit of a distant planet? If the artistic associations are as likely to disturb as to excite, are the scientific associations more reassuring (the French cubist Georges Braque thought that, '*L'art est fait pour troubler, la science rassure*'[1])? Or do they disturb in a different way? Very likely this is a world that is unfamiliar and strange, less accommodating than the arts and, dare we admit it, less 'human' in some way (we do not class the sciences as 'humanities' after all).

But there are other voices that choose the same language to talk about art and science, and even in the same breath. Philosopher of science Karl Popper once wrote: 'A great work of music, like a great scientific theory, is a cosmos imposed upon chaos – in its tensions and harmonies inexhaustible even for its creator'[2]. This richly layered and dense commentary on music and science will need some background work to uncover Popper's meaning—its allusions immediately fail to intersect with the quite distinct word-lists that spring from usual talk of art and science. But it raises suspicions. Is a dualistic division into arts and science really faithful to our history, our capacities and needs? Does it spring from a deep understanding of what these twin human projects attempt to do—is it faithful, dare we ask, to their *purpose*? And if not, are we right to ask of our children, 'are they on the science-side or the arts-side?' or to reinforce the well-worn narrative of

[1] 'Art is made to disturb, science to reassure'.

[2] Karl Popper (1976 [2002]), *Unended Quest: An Intellectual Autobiography*. London and New York: Routledge.

C. P. Snow that there are 'Two Cultures'[3] at work in our late-modern world, non-overlapping, mutually incomprehensible, and doomed to conflict? If we are wrong to categorize culture, let alone people themselves in this way, then to make exclusive educational decisions based on such a dualistic assumption will be to trigger a process of atrophy in one or other aspect of those children's development, and in adult life to have closed off one or other world of expression, contemplation, creativity, enrichment—of complementary ways of being human.

Doubts intensify about a neat cultural divide if we take the all too unusual step of listening to an artist, or to a scientist, talk candidly about their journeys of labour from early ideas to a finished work. For now, the language-clouds of the arts and the sciences start to collide and overlap. I have an intense memory of my first lengthy conversation with an artist (also a professor of fine art at my then home university of Leeds) about our respective experiences of bringing to light new work in art and in science[4]. He spoke of his first experimental attempts to realize an original conception, of the confrontation of his ideas with the felt constraints of material—of paint and photographic print, of the necessary reformulation of the original concept, of the repeat of these frustrated assays not once but many times. I found that I could tell the story of almost any programme of scientific research I had experienced in almost precisely the same terms. The discovery was mutual: if I had been surprised by the element of experimentation and trial in his artistic project, then he had not expected my story of science to speak so vitally of the role of imagination. Not only that, it became clear to us that not only did the intellectual and technical histories of our projects map closely onto each other, but so also our emotional trajectories of excitement, hope, disappointment, rekindling of hope, and resolution found common expression. The more honest the story-telling in

[3] C. P. Snow (1959 [1998]), *The Two Cultures*. Cambridge: Cambridge University Press.

[4] Professor Ken Hay's project is discussed in detail in Chapter 3.

art or science, the more entangled and related became the experiences of emotion and cognition. Thinking and feeling are closer under the surface than in our public stories.

Why it is so much less common to discuss the long process of realization in art than to talk about the final article, composition, theory, or painting is hard to say. The famous exceptions (such as the evolution of Picasso's *Guernica*[5], or the candid reflections of Henry James' *Art of the Novel*[6]) underline the question. Maybe it has to do with the tradition of artisan and artist guarding carefully the 'secrets' of their trades, thereby to increase by mystique as well as by wonder the appeal of the finished article. Art has commercial value too—its finely honed techniques and formulae are secrets worth keeping, even though they are the vehicles, not the sources, of inspiration. Or perhaps there is less intention to weave a whimsical web of mystery around the production of art than a natural reluctance to admit too much of the false starts, errors, spilt ink, confused ideas, and dead ends that are the daily experience of any creative activity.

If art is shy about the sweat and tears of working out the form of an original idea, then science is almost silent about its epiphanies and moments of inspiration. Popper himself, celebrated for the most detailed modern outworking of a scientific method in his *Logic of Scientific Discovery*, wrote at length on how hypotheses may be refuted, but remained quiet on how they might be imagined in the first place. While acknowledging the vital necessity of such imaginative preconception, Popper declared that, as essentially non-methodological, he had nothing to say about it. There is some degree of logic and process in the testing and evaluating of a scientific idea, but there are no such recipes for conceiving them. Nobel Laureate Sir Peter Medawar lays some of the blame for our blindness to the role of imagination in science at the feet of John Stuart Mill's *System of Logic*, who writes as if he believed

[5] Rudolf Arnheim (1963) *The Genesis of a Painting: Picasso's Guernica* Berkeley: The University of California Press.

[6] H. James (1934), *The Art of the Novel*. Chicago: University of Chicago Press (2011).

'that a scientist would have already before him a neatly ordered pile of information ready-made—and to these he might quite often be able to apply his rules.'[7] If science gathers to itself a narrative more weighted towards method, and art is more vocal about creative origins, then these retellings of partial truths will conspire to drive an illusory distance between them.

Some considerable historical work will be necessary to trace the origins of buried commonalities of art and science. Even the words we use to discuss them bear hidden references. A good example to start with is 'theory'. Seventeenth-century puritan writer Thomas Browne was able to say in his 1643 *Religio Medici* that[8]

> *. . . nor can I thinke I have the true theory of death, when I contemplate a skull, . . .*

The ancient Greek Orphic priests seem to have used the word *theoria* to describe 'passionate, sympathetic contemplation'[9]. The explicitly visual, religious, and contemplative implications at the root of devising a theory will arise within a close examination of visual imagination in Chapter 3.

The contrasting traits of silence within the community of science on its imaginative energies, and of art on its workaday reckoning with material reality, is not restricted to our own times. William Blake, the eighteenth-century poet, artist, and engraver, famously inveighed against what he perceived was the destructive dehumanizing of 'natural philosophy', the term used for the quantified and experimental understanding of nature we would term 'science' today. He wrote of his own task:

> *'in the grandeur of Inspiration to cast off Rational Demonstration . . . to cast off Bacon, Locke and Newton'; 'I will not Reason and Compare – my business is to Create'.*[10]

[7] Peter Medawar (1984), An essay on scians, in *The Limits of Science*. Oxford: OUP.

[8] Kevin Killeen, ed. (2014), *Thomas Brown, Selected Writings*. Oxford: Oxford University Press, p. 47.

[9] Francis Cornford (1991), *From Religion to Philosophy: A Study in the Origins of Western Speculation.* Princeton: Princeton University Press.

[10] William Blake, *Milton* (1804), book 2, pl. 41; *Jerusalem*, ch 1, pl. 10.

For Blake, inspiration has no place in Newton's work, and reason none in his own. There is some buried personal dissonance here given what we know of his own painstaking technical developments in copper engraving. Yet he was not without cause for complaint against those early modern philosophers: John Locke, in his *Essays Concerning Human Understanding*[11] had identified 'the imagination' as the source of false and fantastical ideas, as opposed to experience, the reliable guide to the true.

I frequently find the same compartmentalized assignments of inspiration and rationality at work today when talking with high-school pupils. When visiting schools for 'general studies' discussions of science in society or the importance of interdisciplinary thinking, I like to ask advanced students who have not chosen to study science subjects (when from their intellectual engagement with the material it is clear that they could master anything they chose to) why they made that choice. Among the brightest of them, I never receive the complaint that the sciences seem too difficult, but rather that they appear to lack avenues for creativity and the exercise of imagination. The conversation sometimes also reflects the expectation of a more playful engagement with the humanities, contrasting with a notion of seriousness and narrowness in the sciences. I find this painful, doubly sad that these young people have been offered no insight into the immense fields for imagination offered by science, and that scientists have failed in communicating its call on creativity. As Sîan Ede[12] writes:

> *Compared with the cool rationalism of science with its material belief in wholeness, the theories employed by thinkers in the arts and humanities seem part of a playful circular game in which the truth is never to be privileged in one direction or another and is always out of reach.*

These echoes of Blake in the words of today's brightest young people are painful to hear. They speak to the urgency of a project

[11] John Locke (2015), *The Clarendon Edition of the Works of John Locke*, Oxford: Oxford University Press, *An Essay Concerning Human Understanding Book II*.

[12] Sîan Ede (2005), *Art and Science*. London I. B. Taurus.

that goes beyond the confrontational assumptions of the 'Two Cultures' to deeper levels of human motivation, desire, experience—one that recognizes the dual qualities of rationality and inspiration, of seriousness and playfulness, of imagination and constraint, but challenges their automatic alignment with the axes of humanities and sciences, exploring instead how they play out in both.

Admittedly it has never been easy to speak with clarity about moments of imaginative conception. When inspiration eventually comes, articulating the experience faithfully is fraught with difficulty. There is a wordlessness about those moments of vision that permit and initiate the necessary phase of craft within the creative process, that plant germs of energy and glimpse distant impressions of what might be accomplished and perceive the direction of the road ahead. We know how to desire the moments that William Whewell called 'felicitous strokes of inventive talent'[13], but not how to summon, and hardly to describe them. Here is Shakespeare struggling to do both (and succeeding) in his 100th Sonnet:

Where art thou Muse that thou forget'st so long,
To speak of that which gives thee all thy might?
Spend'st thou thy fury on some worthless song,
Darkening thy power to lend base subjects light?
Return forgetful Muse, and straight redeem,
In gentle numbers time so idly spent;
Sing to the ear that doth thy lays esteem
And gives thy pen both skill and argument.
Rise, resty Muse, my love's sweet face survey,
If Time have any wrinkle graven there;
If any, be a satire to decay,
And make Time's spoils despised every where.
Give my love fame faster than Time wastes life,
So thou prevent'st his scythe and crooked knife.

[13] William Whewell (1837), *History of the Inductive Sciences.* London: John W. Parker.

The poet longs for the return of his 'Muse', one of the ancient Greek mythological band of personified inspiration recorded as early as Hesiod (*c.* 600 BCE) and that Plato invokes to explain acts of creation[14]. Shakespeare pleads for his to sing him songs and guide his pen on the page before Time takes away all opportunity for further art. Yet, paradoxically he makes this 'time between inspirations', this ostensibly dry season of complaint—into a sublime sonnet. The actual song of the Muse is muffled, and the sight of her hidden, by the humorous complaint of her absence. Unnoticed, the poet's imagined sole source of inspiration, the face of his beloved, is replaced by his rising outrage that the Muse refuses to come at his beck and call. In the compressed lines of the sonnet, the first stage of creativity is conflated with the second; the visitation of inspiration itself is brought together with the 'skill and argument' of the pen. The long labour of writing must then do battle with Time itself. Ironically, it is the wasting erosion of time that becomes the topic of the final work of art. The poet knows that even if inspiration comes, time is not his friend during the long process of gestation before a poem lies completed upon the page. No scientist can read this sonnet without stirring frequent memories of dry days and weeks when ideas fail to come and fruitfulness all seems elsewhere.

After listening to Shakespeare on inspiration and labour in art, perhaps we ought then without delay turn to Einstein on creativity in science (why descend from the summit of Olympus before you have consulted all of its dwellers?). Here is the master and motivator of twentieth-century physics on the two components of creativity[15]:

> *The mere formulation of a problem is far more essential than its solution, which may be merely a matter of mathematical or experimental skills.*

[14] In most ancient sources there are nine: Calliope (epic poetry), Clio (history), Euterpe (flutes and lyric poetry), Thalia (comedy and pastoral poetry), Melpomene (tragedy), Terpsichore (dance), Erato (love poetry), Polyhymnia (sacred poetry), Urania (astronomy).

[15] Albert Einstein and Leopold Infeld (1938), *The Evolution of Physics.* London: Cambridge University Press.

To raise new questions, new possibilities,
to regard old problems from a new angle, requires creative imagination
and marks real advance in science.

~

I am enough of an artist to draw freely upon my imagination.
Imagination is more important than knowledge. Knowledge is limited.
Imagination encircles the world.

Both Shakespeare and Einstein, as they open the door into their workshops for us —albeit in very different forms, tell of two phases in the creative process. The first, 'the visit of the Muse', the 'creative imagination', or 'the mere formulation' is the inspiration, the genesis of an idea. The second is a longer, more directed process of developing the germ into its 'song' or 'solution'. It is intriguing that Einstein chooses to explain his knowledge of the wellspring of imagination—he 'draws' from it—by describing himself as an artist. He elevates 'imagination' as he demotes 'knowledge'. He wants to make clear that the greater task in science is the 'mere formulation' of the problem in the first place, rather than the application of methods to its solution (by 'mere' he means 'fundamental', 'elementary', or 'constitutive' rather than 'trivial' of course). The great scientist knows that we find our way to encircling the Earth, not principally by experiment, theory, deduction, falsification, or any of those important features of scientific method, but by imagination.

Thomas Kuhn famously coined the notion of 'paradigm shifts' to denote discontinuous changes in the scientific framework for understanding nature. They entail revolutions in entire sets of presuppositions and current mutually supporting scientific ideas. They typically witness the entry of new ideas not deducible from prior reasoning[16]. Classic examples are the Copernican revolution in cosmology and the shift from classical to quantum physics. Beyond identifying the growing dissatisfaction with the existing framework, Kuhn made no suggestions concerning the provenance

[16] Thomas Kuhn (1966), *The Structure of Scientific Revolutions.* Chicago: Chicago University Press.

of the new set of ideas—they are the protoplasm of his revolutions, but the seed of no methodology.

The formulation of the fruitful question, posed in the right way, constitutes the great imaginative act in science. It requires a developed sense of the current age of thought, of timing. Historian of science and chemist Lawrence Principe[17] has pointed out the appropriateness of asking the question about the structure of the solar system at the turn of the seventeenth century: when Tycho Brahe's meticulous observations of planetary motion and Copernicus' inspired partial solution to the new paradigm had opened up a field of potential progress. Kepler's deductions together with Thomas Harriot's and Galileo's assays in turning the new telescopes towards the heavens, made asking about the dynamical consequences of gravity among the sun and the planets fruitful in a sense that it had not in any previous century. If the scientific imagination is fed by the creative and timely question, it also needs the nourishment of the discontinuous, of leaps in thinking that receive their impulse from some other source than the worthy process of logical deduction. A generation on from the establishment of the orbits of the moon and planets within a heliocentric structure of the solar system, Newton's great imaginative conception was to contemplate a world in which the fall of an apple sprung from the same universal field of force as the monthly procession of the moon.

Einstein and Principe point us to the critical role of the well-formulated and timely question in science. Yet the silence of any formulation of 'scientific method' on this great creative act tends to mask its pivotal role, as well as to dull perception of scientific creativity. Sharpening and highlighting the role of creative imagination to a degree faithful to the way science actually works would deepen the level at which the fundamental motivation for science is recognized within human culture. An account of science that accords appropriate weight to divergent re-imagination

[17] Lawrence Principe (2013), *The Scientific Revolution: A Very Short Introduction*. Oxford: Oxford University Press.

of nature as much as to convergent deductive method also finds itself telling a much longer historical story than the exclusively post-enlightenment narratives that dominate at present. A literature-search for the question-form when addressed to the natural world, for example, lengthens the historical line over which we can map early stirrings of the desire to understand and contemplate nature. I have elsewhere written at length on the beautiful and profound ancient wisdom poem, the 'Lord's Answer' of the Old Testament Book of Job[18]. A work of over a hundred verses, it assumes the unusual poetic form of the repeated question—but in the light of this discussion appropriately so—since its subject matter is the human understanding of nature. The origin of light, the formation of the coastlines and mountains, the provenance of the hail and lightening, the ability of birds to navigate the Earth in their migrations—all appear in a grand cosmic sweep of its author's enquiry. One stanza from chapter 38 in particular would have impressed a Newton or an Einstein:

Can you bind the cluster of the Pleiades, or loose Orion's belt?
Can you bring out Mazzaroth in its season, or guide Aldebaran with its train?
Do you determine the laws of the heaven?
Can you establish its rule upon earth?

The poet looks at the motions of the stars and constellations across the sky, even noticing that some cluster together while others, though visually similar in brightness and hue, are separated. The lovely Pleiades is one of the very few 'open star clusters' resolvable to the human eye, with up to six or possibly seven members visible to keen-eyed northern hemisphere observers during autumn and winter nights. An outstretched hand-breadth to the south-west of them lie the linear triplet of bright blue-white stars in 'Orion's belt', far further from each other than the members of the cluster. The presence of a strange class of 'law', to be obeyed not by humans but by the stars themselves, that might contain the statutes binding some stars closely

[18] Tom McLeish (2014), *Faith and Wisdom in Science*. Oxford: Oxford University Press.

together while others are far-flung, that oversee their regular and irregular motions, is an impressive creation of the imagination even now. The conjecture, buried in such ancient philosophy, that heavenly and earthly laws might be connected is even more striking.

The presence of the creatively formulated question in as ancient a source as the Book of Job[19] (undatable other than to place it within the first half of the first millennium BCE) within the Semitic tradition, carries another salutary message to us late moderns. Alongside the complex history of ancient Hellenistic science from 500 BCE, it surely erodes any idea that science is in any way exclusively modern, beginning rootless at the enlightenment and blowing away the cobwebs of centuries of darkness, magic, superstition and alchemy. Sadly, much popular narrative of science history has it so, but claiming science as an exclusive property of the modern world removes the deep and slow cultural development of an imaginative and creative engagement with nature that develops, at least chronologically, alongside the story of art in its own multitude of forms[20].

The timely question is not the sole province of science. It is surely not coincidental that the literary genre of the novel arises, with Daniel Defoe, alongside early modern science, and that the genre of science fiction underwent an explosion in the last century. As Pat Waugh[21] has pointed out, the novel is the *experimental* medium of artistic creation par excellence. In the safe space of the novel, inhabited worlds can be summoned into existence and

[19] For a magisterial survey of the *Book of Job*, see the three-volume work by David Clines, Thomas Nelson pubs. We will encounter an explicit example of scientific inspiration drawn from reading it in the story of the rainbow, told in Chapter 7.

[20] For a more complete and integrated account of the history of science, see the now classic work by David Lindberg (2010), *The Beginnings of Western Science: The European Scientific Tradition in Philosophical, Religious, and Institutional Context, Prehistory to A.D. 1450, Second Edition*, Chicago: Chicago University Press.

[21] P. Waugh (2015), Beauty writes Literary History, in Corrine Saunders and Jane MacNaugten, eds., *The Recovery of Beauty*. London: Palgrave MacMillan.

their dangers and dark places explored. Questions of the relationship of human beings to time and space, to each other and to the Earth can be teased out in both internal and external worlds of their characters. The novelist does not experience unconstrained freedom, however, but discovers the multiple moral constraints of the experimental form. Crucially, novelistic writing forces a more intense outward gaze. For Iris Murdoch, novelistic writing enables an attention to '... the inexhaustible detail of the world, the endlessness of the task of understanding..., the connection of knowledge with love and of spiritual insight with the apprehension of the unique'[22]. Murdoch supplies us with another glimpse of commonality in the narrative that artists, creative writers, and scientists adopt when they are trying to articulate the deepest motivations for what they do. 'The endless task of understanding' and a focus on the 'inexhaustible detail of the world' are the shared delights and common labours of the physicist and biologist also. These novelistic hints are enough to tempt the much closer look at the relationship between experimental science and literature in Chapter 4.

Paying close attention to the stories of imagination and workmanship in the creation of art and science will be the first of this book's tasks in the project of reappraising science through the lens of the humanities. The second task must be a similar study of the way their creations are received by their respective audiences. Neither art nor science can exist in a solipsistic vacuum of their authors. Both must be listened to, observed, received, responded-to. If the current public narratives of creativity are artificially divided into the imagination of art and the logic of science, then the framing of their reception is just as polarized. 'Science is not with us an object of contemplation', complained social thinker Jacques Barzun[23]. The impression is that art appeals to the response of emotion and affect while science connects only to cerebral reason. Such a neat, Kantian, division appeals to a compartmentalized

[22] Iris Murdoch (1998), *Existentialists and Mystics.* New York: Penguin, p. 86.
[23] J. Barzun (1964), *Science that Glorious Entertainment*. London: Harper and Row.

and fragmented structural view of culture, but it reinforces the picture of artificial division of science and art into two realms. Perhaps this is where they do indeed divide—even if both draw at depth on a mysterious creative human energy in their production, it is conceivable that reading, listening, and hearing science and art nonetheless pursue distinct mental pathways.

On the other hand, if a distorted impression of creativity arises in part from selective silences on the part of their practitioners, then perhaps the same is true of their reception. Comment on the effect and the enjoyment of art is commonplace. It speaks of a healthy continuum from artist and performer to receiver and listener. We may not be able to paint or to sing like the great exponents of art and oratorio, but we are not silenced as a result from speaking, or even from critically appraising, paintings or performances. There is understood to be a 'ladder' of participation and reception in the arts. In music, for example, the lower rungs are occupied by those of us who enjoy concerts, who pick up instruments in the company of forgiving amateur friends. We would never presume to perform in public, but nevertheless can confidently express an opinion on which recording of a symphony we prefer. The upper rungs are occupied by the performers on those very recordings. Here is actor Simon Russell Beale[24] talking about his response to the music of the romantic composer Schubert:

> *Schubert can make time stand still. In the last, miraculous months of his life, he expanded his vision of what music could do. His most experimental work is the slow movement of his B flat Piano Sonata. It is as if he has distilled the process of music-making. He takes a harmonic progression, explores it, changes a single note, explores it again; he breaks down a simple melody until only the bones are left and the music is suspended. The result is a play of pure sound, without external reference, that gives us a glimpse of eternity.*

This is a piece of exceptionally high-quality comment, to be sure, but it is not unusual for someone who is not a professional

[24] Simon Russell Beale (2012), *Ferocious, Tender, Sublime*, *The Guardian*, 19th March.

musician to write at such serious critical depth about a piece of music. Beale's testimony is also an example of the narrative we met in the case of artistic creators, stories that map rather remarkably onto the rare but honest stories of science's own creative process. Schubert, is, as heard by Beale, experimental, exploratory, even reductionist and abstractionist. Yet he is also sublime. Beale describes an example of a deep property of music—its ability to reconcile us to the passage and structure of time by somehow suspending us from it. At the level of the abstract, music and mathematical science have long been compared, albeit inconclusively. Developing a comparison of their creative processes will be the concern of Chapter 5, but at this point the divergence in their apparent degree of communicability is stark.

It is harder to find comparable examples of reception and affect of scientific creation. But this is not because of a lack of inherent appeal to human desire and need. The 'ladder of access' that we identified in a creative art such as music is not (as observed by Barzun in different terms) present in our current culture in science. This was not always the case—Shelley, Coleridge, and Wordsworth all thought that science could, and would inspire poetry (though Shelley foresaw that the inspirational beauty of science would be a hidden one). So, for articulated contemporary reception of science, we must usually listen to the scientists themselves. Here cosmologist Subrahmanyan Chandrasekhar[25] describes in remarkable terms an example of the moments of transport for which science longs:

> *In my entire scientific life, extending over forty-five years, the most shattering experience has been the realization that an exact solution of Einstein's equations of general relativity, discovered by New Zealand mathematician Roy Kerr, provides the absolutely exact representation of untold numbers of massive black holes that populate the universe. This 'shuddering before the beautiful', this incredible fact that a discovery motivated by a search after the beautiful in mathematics should*

[25] Subrahmanyan Chandrasekhar (1987), *Truth and Beauty: Aesthetics and Motivations in Science*. Chicago: University of Chicago Press.

find its exact replica in Nature, persuades me to say that beauty is that to which the human mind responds at its deepest and most profound.

Chandrasekhar's 'shuddering before the beautiful' carries unmistakable resonance with Beale's 'glimpse of eternity'. It also, perhaps unwittingly, resonates with accounts of aesthetics that have been driven beyond the simply beautiful to the 'sublime'. The cosmologist is speaking of the extraordinarily simple yet utterly strange idea of a 'black hole'. For many years pure conjecture, observational evidence from stellar evolution and highly luminous galactic cores has pointed increasingly to the inevitable existence of these bizarre and terrible objects. Black holes are places in the cosmos where the local presence of matter is so great that gravity generates its runaway collapse towards a point where density becomes formally infinite, surrounded by a finite region of space in which the tug of gravity is so great that no light can escape. Possessing a terrifying and austere beauty, these objects are as near to instantiated mathematics as one could imagine. They can have no other properties than mass, spin and electric charge. All other attributes that their original matter once possessed are lost in its irreversible infall. The normal role of mathematics within theoretical physics is to provide approximate descriptions of natural objects, but in this case the attribution of a black hole's triplet of properties is complete.

The experience Chandrasekhar describes is a rarefied and extreme form of a precious wonder. Einstein put it thus: 'the most inexplicable thing about the universe is that it is explicable' and Eugene Wigner pointed towards it in the title of his celebrated essay *The Unreasonable Effectiveness of Mathematics in the Natural Sciences*[26]. The moment of connection of a constructed pattern of thought, mathematical, pictorial, or logical, with the deep structure of the natural world evokes an unparalleled experience of wonder. As Wigner pointed out, it also appeals through the inherent elegance of mathematics to the aesthetic sense. More than that, it seems to

[26] Eugene Wigner (1960), *Communications in Pure and Applied Mathematics*, **13**, No. I. New York: John Wiley & Sons, Inc.

satisfy a need for creative connectedness, the act of understanding, of re-creating an internalized world patterned on the external. Such reaching out into the world in abstract thought is perhaps a flowering of a human response to the ancient questions of the Book of Job[27]. Such long perspective suggests that there are deep and complex commonalities in both the motivation and imaginative act of creation, as well as in the role of aesthetics, in the sciences as much as in the arts.

All this is not to claim that there is no tradition of research and writing on the topic of creativity itself that includes scientific examples—far from it. A now-celebrated 1926 essay of Graham Wallas, *The Art of Thought*[28] introduced a four-stage abstract structure for 'the creative process' that we will make critical use of in the following chapters (finding it serviceable but wanting). Wallas himself draws deliberately on a genre of *The Art of . . .* works, initiated in modern times (it is an echo of Horace's ancient *Ars Poetica*) by writer Henry James in *The Art of the Novel* and taken up by William Beveridge in the early twentieth century in his *Art of Scientific Investigation*. We will be examining both of these works at close quarters in Chapter 4. Major edited collections of essays and research from psychologists[29] on creativity have recently spawned a subfield of cognitive neuroscience. The genre has even produced a 'Cambridge Handbook'[30]. The laboratory-scale essays into the close-study of the creative process and its context are informative, although by their nature cannot encompass the extended and unconstrained creative projects that characterize substantial works of art and science. At a more selective level, there are surveys of creative individuals, including those representing fields of science and art—Howard Gardner's *Creating*

[27] Tom McLeish, *Faith and Wisdom*.

[28] Graham Wallas (1926), *The Art of Thought.* Tunbridge Wells: Solis Press (2016).

[29] e.g. Robert J. Steinberg, ed. (1988), *The Nature of Creativity*. Cambridge: Cambridge University Press.

[30] James C. Kaufman and Robert J. Steinberg, eds. (2010), *The Cambridge Handbook of Creativity*. Cambridge: Cambridge University Press.

Minds[31] is an excellent example. Anthony Storr has begun to tease out conjectural psychological patterns in the minds of very creative thinkers[32]. Other contributions to the creativity literature are listed for convenience in the bibliography of the present work. But there is still a clear issue of misunderstanding in the perception of science within popular culture, as an activity that calls on minimal imagination. There is little discussion of the way that imagination plays out in the experience of the thousands of people engaged in the scientific and artistic work that adds colour to our communities and national lives. There is also almost total silence within the educational formation of scientists on the topic of imagination, of the creative formulation of questions and hypotheses, or of the experience of scientific ideation. There may not be a method for this most vital of all scientific processes, but there are accounts, practices, and a communal experience that ought to be more widely and openly shared both within and without the scientific community. Furthermore, as the explorations in this book of visual, textual, and abstract creativity in science and arts will show, the entanglements of experience between their artistic and scientific examples are so close that a renewed interdisciplinary dialogue promises a fruitful dividend for both cultural communities.

I have suggested elsewhere[33] that, because of the 'missing rungs' in scientific ladder of reception, it is lamentably less common for non-practitioners of science to experience the intensity of aesthetic response to a new understanding of nature, than for the scientists whose professional training has taken them to the ladder's higher footholds that still exist. But it is not impossible, and could be as common as the learning of a new tune or appreciating an unfamiliar painting for the first time. In a moving personal example, a friend told me of the moment when, gazing up at the moon one evening, he suddenly understood how its phases

[31] Howard Gardner (1993), *Creating Minds*. New York: Basic Books.

[32] Anthony Storr (1991), *The Dynamics of Creation*. London: Penguin Books.

[33] Tom McLeish, *Faith and Wisdom*.

worked. A life of familiarization with the monthly cycle of crescent, half, full, and gibbous moon was not equivalent to 'seeing' how these shapes served as the signature of an illuminated orb. On that moonlit night shortly after sunset he allowed the two-dimensional screen of the sky to become a three-dimensional space in his mind. The moon became a solid sphere, illuminated by a much more distant sun from different angles on different days, as seen from the centre of its orbit on the Earth. The celestial geometry and its circling dynamics found a home in his imagination—releasing an experience of pure joy. He described feeling present to the world in a deeper sense than before, and knowing that this stronger relationship was, once found, not going to be lost.

The genre of 'trade book' science writing has recently produced examples of exquisite care and intelligent communication that seem to be painstakingly replacing those removed rungs in the public latter of science-engagement, giving their readers some of the experience of personal revelation as my friend's personal reconstruction of lunar astronomy. Nobel Prize-winning physicist Frank Wilczek's lovingly articulated story of symmetry in art, philosophy, and physics authentically communicates a physicist's delight in the discovered layers of nature's patterned structure[34]. Former editor of the scientific journal *Nature*, and now science-writer, Philip Ball, has demonstrated how molecules make a story as human as it is material[35]. Television producer and writer Simon Singh's account of the three-century long search for a proof of Pierre de Fermat's famous 'last theorem' is a thing of beauty, emotion and an opening to the common gaze of a world of pure mathematics that engages without patronizing[36].

Experiences of such reception in science or in art, achieve at their most profound such an intensity of emotion and of felt transformation, that they must draw our exploration to a third

[34] Frank Wilczek (2015), *A Beautiful Question.* London: Allen Lane.
[35] Philip Ball (2001), *Stories of the Invisible: A Guided Tour of Molecules.* Oxford: OUP.
[36] Simon Singh (1997), *Fermat's Last Theorem.* London: Forth Estate Ltd.

level of parallel comparison—that of the human function of creative engagement with nature and, if we dare talk of it, of purpose. A nest of questions confronts us here: why do art, and early science, arise in pre-history? What do they achieve socially and psychologically today? Where do art and science appear, both explicitly and hidden, in the complex of cultural narratives? How do they receive, and provide, value and virtue? The humanities discipline of theology comes to aid here, for no other reason than that it is comfortable with the category and narrative of purpose. Recent writers have attempted to articulate a 'theology of' music (Begbie[37]), of art (Wolterstorff[38]), of science (the present writer[39]), and found that this trailhead leads to a fruitful landscape within which these questions of function can be attempted. Critic and literary scholar George Steiner's view of art in this regard elicits a striking reception when read from the perspective of science. In his moving critique of the humanities in late modernism *Real Presences*, he writes[40]

> *Only art can go some way towards making accessible, towards waking into some measure of communicability, the sheer inhuman otherness of matter*

speaking at the same time of deep need, and of powerful satisfaction. Writing in despair over a 'broken contract' of art with nature that he sees as vital to reverse, Steiner describes a human condition 'out of joint' with the world in which humans are immersed. There is a gulf of otherness, of strangeness, with which, for reasons we do not understand, we remain uncomfortable. The divorce is painful. The paradox is heightened when we reflect that the 'sheer inhuman otherness of matter' is the very stuff of which our bodies are composed. Art may indeed go some way towards a reconciliation of the human with the material. The

[37] Jeremy Begbie (2014), *Theology, Music and Time*. Cambridge: Cambridge University Press.

[38] Nicholas Wolterstorff (1987), *Art in Action Toward a Christian Aesthetic.* Grand Rapids: Eerdmans.

[39] Tom McLeish, *Faith and Wisdom*.

[40] George Steiner (1989), *Real Presences*. London: Faber and Faber.

creation by paint on canvas of a visual illusion, for example of standing before a riverbank picnic illuminated by mottled sunlight, is achieved only by a deep understanding of the received visual cues by which we reconstruct our surroundings. Or, if another contrast imposed by the 'inhuman otherness of matter' on the human is the appalling possibility of eternity in the face of our own temporality, then the 'glimpse of the eternal' afforded by a Schubert sonata is also doing some reconciliatory work. But so too, surely, is the science of the night sky, be it the humble reimagining of the illuminated moon or the severe simplicity of a mathematical black hole that finds connection with a myriad of unseen gravitational wells hidden within the whirling and immense galaxy overhead. Their utter inhuman otherness is to some degree woken into Steiner's 'some measure of communicability' by the conceived form of mathematical understanding. And if this is the role of art, then what other category remains for science?

Exploration of a possible parallel purpose at the deepest level for art and science will steer our trajectory into headlong collision with those who have perceived an irreconcilable antithesis between the two. To navigate these stormy waters will need some historical perspective, for an oppositional framing seems to reawaken, at least in the modern period, with each generation. Forty years previous to the late twentieth-century combatants of the 'Science Wars', public intellectuals engaged in angry words over the 'Two Cultures'. But half a century before C. P. Snow and F. R. Leavis locked horns, a gentler but equally incisive debate, anticipating some of the later rancour between the arts and the sciences, was engaged by Matthew Arnold and Thomas Henry Huxley[41]. Before them, romanticism drove home with force the charge that science does precisely the opposite of (at least narrative and poetic) art in the meeting of human creative need. We

[41] For a discussion of this debate see E. S. Schaeffer (1994), How many cultures had Lady MacBeth? in L. Gustafsson et al., eds., *Science and the Powers.* Hässelby Castle: Swedish Ministry of Science and Education, pp. 136–92.

have already met Blake's dismissal of reason as the antithesis of creation, but his voice was by no means a solitary one. In his long poem narrating the story of the mythical serpent *Lamia*, John Keats complains of science—for him 'cold philosophy':

> *Do not all charms fly*
> *At the mere touch of cold philosophy?*
> *There was an awful rainbow once in heaven:*
> *We know her woof, her texture; she is given*
> *In the dull catalogue of common things.*
> *Philosophy will clip an angel's wings,*
> *Conquer all mysteries by rule and line,*
> *Empty the haunted air, and gnomed mine*
> *Unweave a rainbow.*

In similar and surely commentary vein, Edgar Allan Poe called science the preying 'vulture of the heart' whose wings are 'dull realities', in his *Sonnet to Science*. We need to understand why Blake and Keats, Poe, and many others among their nineteenth-century contemporaries first perceived science to be the means of desiccation, of demystifying, of replacing wonder by measure, and then why they took up the tools of their trade at their highest energies to inveigh against it.

Historical locus is important. Retrospective projection of arguments from our own times, such as simplistic assurances that the romantic poets had nothing to worry about concerning the draining of wonder from the world, will not get to the root of their disquiet. In any case, the same concerns arise today in different forms. There are shifts in the role of science particular to the romantic period that may be significant. A change in nomenclature, for example—'natural philosophy' becomes 'science'—carries with it many etymological undercurrents of meaning. A Greek declaration of 'love of wisdom of natural things' (*philo—Sophia*) is slowly replaced by a Latinate claim to knowledge (*scio*) (Wordsworth's critique '*we murder to dissect*' uses the term 'science' where Keats and Poe retained 'philosophy'). Science departments and syllabuses began to appear in the universities. William

Whewell coined, around 1836, the term 'scientist', which gathered currency first in America and then Britain throughout the century. Although Faraday and Maxwell both refused the new term, insisting on the older 'natural philosopher', the final adoption of 'scientist' was complete by the end of the century. Momentously, the discoveries and theories of geology (Lyell's gradualist and ancient formation of geological strata) and of biology (Darwin's evolution by natural selection) were transforming utterly the understood relationships the human race in the time and space of our world, and with the other species on Earth. The period of romanticism swept in a fragmentation of disciplines and a further distancing of 'the inhuman otherness of matter' unprecedented in thought.

Writing within the stormy cultural change of a different cultural period to our own can easily be misread, however. In order to gauge the story of science's apparent offensiveness to the poetic in the nineteenth century, we will need to look harder at the context of the criticism. To taste just one example, Wordsworth's contrast of the scientist with the poet, explored in the preface to his *Lyrical Ballads*, centred on the solitude of science, its lack of communicability with others than the lonely investigator,

> *[Science] is a personal and individual acquisition, slow to come to us, and by no habitual and direct sympathy connecting us with our fellow-beings. The Man of Science seeks truth as a remote and unknown benefactor; he cherishes and loves it in his solitude; the Poet, singing a song in which all human beings join with him, rejoices in the presence of truth as our visible friend and hourly companion. Poetry is the breath and finer spirit of all knowledge; it is the impassioned expression which is in the countenance of all Science. Emphatically may it be said of the Poet, as Shakespeare hath said of man, 'that he looks before and after.' He is the rock of defence for human nature; an upholder and preserver, carrying everywhere with him relationship and love. Poetry is the first and last of all knowledge—it is as immortal as the heart of man. If the labours of Men of science should ever create any material revolution, direct or indirect, in our condition, and in the impressions which we habitually receive, the Poet will sleep then no more than at present; he will be ready to follow the steps of the Man of science, not only in those general indirect effects, but he will be at his side, carrying sensation into the midst of the*

> *objects of the science itself. The remotest discoveries of the Chemist, the Botanist, or Mineralogist, will be as proper objects of the Poet's art as any upon which it can be employed, if the time should ever come when these things shall be familiar to us, and the relations under which they are contemplated by the followers of these respective sciences shall be manifestly and palpably material to us as enjoying and suffering beings. If the time should ever come when what is now called science, thus familiarized to men, shall be ready to put on, as it were, a form of flesh and blood, the Poet will lend his divine spirit to aid the transfiguration, and will welcome the Being thus produced, as a dear and genuine inmate of the household of man.—It is not, then, to be supposed that any one, who holds that sublime notion of Poetry which I have attempted to convey, will break in upon the sanctity and truth of his pictures by transitory and accidental ornaments, and endeavour to excite admiration of himself by arts, the necessity of which must manifestly depend upon the assumed meanness of his subject.*

It is neither the practice nor the insights of science that Wordsworth sets apart as irrelevant to human sensation and sensibility, but their remoteness from common currency. In far richer language, he has identified the same missing lower echelons of science's ladder of access that still prevent all but the athletic practitioner from climbing it. Poetry has not been widely inspired by science, but only because it has no access to it at the level of contemplation that would make contact with its 'divine spirit'. Then, as now, only someone steeped in the learning of a scientific discipline might 'shudder before the beautiful', as we might all long to do as we read the cosmologist's account of the mathematical connection of black holes to the night sky above us.

A more optimistic nineteenth-century voice that can still be heard, albeit more quietly than the romantic poets, is that of John Ruskin. His Oxford lectures *The Eagle's Nest*[42] attempt a unified cultural view of art and science. Ruskin's frame is constructed from the cerebral and practical aspects of wisdom—*Sophia* and *phronesis*—that Aristotle conceived as complementary. He teases out the practical within the process of creating art from the mystical provenance of inspiration. He is writing as late as it is possible to do so without suffering from the loss of the vocabulary of

[42] John Ruskin (1905), *The Eagle's Nest.* London: George Allen.

Wisdom from resonances with science. 'Can anything be more simple, more evidently or indisputably natural and right, than such connection of the two powers?' Ruskin asks his student audience in the third lecture. We need to confront the reasons why, in the century in between then and now, his voice and Wordsworth's hopes have been lost in the clamour of Keats' and Poe's complaints.

If we have suffered from an arbitrary disciplinary set of divisions that blur our comprehension of creativity itself, then other, re-oriented ways of arranging our subject suggest themselves. The pictorial art that Steiner had partially in mind, the poetry and prose of Wordsworth, and the wordless wonder of a Schubert sonata, urge a categorization of creativity that recognizes stronger affiliations than structures within the vast domains of art and science themselves. Visual imagination is common to artist and scientist alike; the metaphor for understanding as 'seeing' is so ubiquitous and powerful that we fail now to notice its metaphorical status. The textual work of writing calls on a different, sequential and syntactical imagination, but again that is common to literature from the domain of science that invents, and that re-invents the natural. Finally, there is in both art and science wordless and picture-less domains of invention whose very existence we still strain to comprehend: the fields of music and of mathematics. Each of the three central chapters (Chapters 3–5) that follow will deal with one of these, experimenting with holding the artistic and scientific examples in close juxtaposition. Rather than construct parallel accounts of the creative narrative in art and science, experience suggests that they tell their stories together within these three realms of visual, textual, and abstract.

The cultural history of the nineteenth century also suggests reappraising the relationship of art and science through another lens: that of theology, among the other humanities. For there are close parallels between the strained relation of science and religion, and that between science and art. The divisive romantic period saw, for the first time, strident claims of conflict along both axes. Consider the critical language of the romantic poets alongside the later appearance of conflictual narratives such as Andrew Dickson White's *A History of the Warfare of Science with Theology in Christendom* (1896). Now recognized as polemic rather than history, of which it makes at best a highly selective reading, its constructed message still circulates today through chains of references, without the vulnerability of its own flimsy support. The drivers of the oppositional narratives for both art and religion to science, as received a century later, also bear similarities: both are served by presenting science as a cultural newcomer, and as a competitor for cultural territory occupied previously by art, the humanities or by religion. The story of conflict between science and religion is equally served by a superficial understanding of science itself and the scientific motivation, as much as by a distorted view of religion. Furthermore, the entire argument survives only by banishing all teleology, all talk of purpose.

I have attempted to subvert the three prior conditions for presenting the case for conflict in the book *Faith and Wisdom in Science*, where I traced the endeavour we now call 'science' back through the renaissance, medieval and late classical worlds into the wisdom writings of our Old Testament texts, in parallel to its philosophical roots in ancient Greece. That journey led to a recasting of the oppositional 'geometry' of theology *and* science to the mutually encompassing and twinned relationships described by a 'theology *of* science' and a 'science *of* theology'. In resonance with Ruskin's proposal that Wisdom frames art and science together, the narratives of ancient Wisdom appear as the very tributaries of science. The parallels of misconstrual, of mutual suspicion, and, in particular, of projection of science through a filter that removes its roots in longing, in creativity within the pain of distance from the world, strongly suggest that we play with equally fresh geometries of relationship between the humanities, arts, and the sciences. Such a more consonant perspective focuses on the teleology, cultural and theological, of both. We will resume a discussion of common purposes and ends in the final chapter, Chapter 7.

A journey into the purpose of science, and of art, must learn from the misunderstandings and the mutual pain of fragmented disciplines. It must, finally, move from talk about relationship into a practice of it. If we do find familial fellowship between science and art in a deeper reappraisal, then we will surely notice a structural imprint of their shared cultural DNA as we proceed. Returning to our first perspective—the comparative practice of creative imagination—suggests the lines of a possible framework. No art results from unconstrained exercise of imagination. The poet's vision and communicated emotion take shape within the constraining form of sonnet or quatrain. The composer lets thematic material expand, combine, and develop within sonata form or rondo. The painter conjures with light, colour, representation, but only successfully when she observes the material properties of oil on canvas, or of watercolour on board. It is the tension of imagination with constraint, of idea within form, which focusses creative energy into artistic creation itself. The greater the imaginative impulse, the tighter the form is needed to channel and shape it.

Seen in this light, science no longer looks quite so strange. For if its task is to re-conceive the universe, to create a mental map of its structure, the interrelationships of force and field, of the evolution of structure and complexity, to understand the patterns of matter from the earliest moments of time to its closing aeons, from the smallest fluctuation of space–time to the immensities of the cosmos, and to reconcile all this inhuman otherness to the finitude of our minds, then what task could possibly call on higher powers of imagination? What could demand a greater act of human creation? But what greater form, what more focussing constraint, could be supplied than the way we observe the universe to be? If writing a sonnet is the collision of creativity within constraint of expressing within a tight form and with new potency the human experience of the world, then science also becomes the conception of imagination within constraint. We re-create the universe by imagination within the constraint of its own form.

In this sense, science is not simply like poetry, it is construed as a form of poetry. Perhaps this is the sense in which Shelley claimed in his *Defence of Poetry*, that, 'poetry comprehends all science.' He knew, as did Einstein letting his mind wander through worlds of imagination, or as Shakespeare awaiting his Muse, that no-one can 'say I *will* write poetry . . . the greatest poet even cannot say it.'

Cousinly creativity with constraint—that is a starting hypothesis for a journey through art and science. It will be one with a listening ear. We need to spend time in the workshops of artists and of scientists, and look without prejudice at the way their work is, or could be, received emotionally as well as cerebrally. We will need to stand back from our own time and look at longer narratives, and at other ways of differentiating disciplines. Reflection from the high medieval centuries will join as a continuous conversation partner to contemporary voices. The journey will require some close, even technical, readings of great creative examples of art, music, mathematics, and science. The choice of which imaginative voices in all these avenues we listen to closely will be a personal one, but will be guided by the requirement that they should have written about the process of creativity itself. In such company, our journey will explore the hope that science might re-weave a rainbow in a way that Keats might have recognized as poetic, true, and constitutive of the human.

2

Creative Inspiration in Science

In the case of all discoveries, the results of previous labours that have been handed down from others have been advanced bit by bit by those who have taken them on, whereas the original discoveries generally make an advance that is small at first though much more useful than the development which later springs out of them. For it may be that in everything, as the saying is, 'the first start is the main part,' and for this reason also it is the most difficult; for in proportion as it is most potent in its influence, so it is smallest in its compass and most difficult to see; whereas this is once discovered, it is easier to add and develop the remainder in connexion with it[1].

ARISTOTLE

Where do new scientific ideas come from? Aristotle was thinking on a much wider canvas than the endeavours we call 'science' now—he later goes on to illustrate his point through examples in rhetorical technique. In contrast to the work of Plato's Muses, Aristotle defines the generative force of ideas, *poesis*, as an act of the innate imaginative mind, but did not solve the problem of 'the first start'. Our curiosity into the process of creation has not slackened since. Yet, as we saw in introduction, we understand almost nothing of it. To test a great idea in science is easier than to conceive of it in the first place. It is not simply easier—it is even possible to codify the practice of examination, modification, or refutation, once a new idea is grasped. Look up any popular definition of 'scientific method'—it is exclusively to this second stage that it refers. Such recipe-books for doing science describe something like this: ideas are sharpened into 'hypotheses' that

[1] Aristotle, *De sophisticis elenchis* **34**.183b17–184b9, trans. W. A. Pickard-Cumbridge (Oxford 1912).

have sufficient power to make predictions for the outcome of experiments. These are then performed and, depending on the results, the hypotheses are discarded or allowed to live to fight another day. In education, if not in more nuanced twentieth-century discussion of the philosophy of science, this pattern of *Conjectures and Refutations* described in methodological detail by Karl Popper is portrayed as the way that science proceeds. Yet even as a faithful account of the process of 'normal science', as Thomas Kuhn termed its daily work of incremental progress, it has severe drawbacks. Subsequent philosophers of science have pointed out that theories are not quite as easy to refute by a refusal at the first fence of experimental agreement. They have a way of circling around with minor modifications and trying the jump again.

But the greatest lacuna of any theory of scientific method is in its silence on where ideas come from in the first place. The small but vital 'first start' of Aristotle is the creative beginning of a new road that, once its potential geography is perceived, can be laid down mile by mile by the labourers. But how is the idea of the new start conceived in the first place? From where does the notion of possibility for a new road come? No one has written a method for the generation of new ideas. The 'scientific method' only tells half the story we need to complete the arc of new understanding. In its classic articulation by Popper[2], the 'logic of scientific discovery' explains in detail how we evaluate theories, construct critical experiments to test hypotheses, identify what adjustments or additions might be permissible without a complete overthrow of the theory. The 'scientific method' has never framed recommendations for the creation of hypotheses in the first place, however. Like the early internal combustion engine, it knows how to keep turning over but contains no means to self-start.

As we have already seen, the strange silence of science on its intellectual germinations, its sensitivity around talk of their conception, has damaging consequences. Once the results of science

[2] Karl Popper (2002 [1934]), *The Logic of Scientific Discovery*. London: Routledge.

are portrayed as de-humanizing in their effect, or as the enemy of the poetic impulse, the reluctance for creativity-talk does the other half of the work in portraying it as a recipe-based activity for lovers of logic and sceptics of wild imagination. In spite of the personal knowledge that the creative first step is as essential in natural philosophy as in art, and recognized as such from Aristotle to Einstein, there is still a false story circulating that imagination is not a strong requirement for the scientist. The distorted and dry narrative is as prevalent in public media as in education. What harm this does in all its ramifications is impossible to assess, but at the very least it must turn away some young people from enjoying a potentially fruitful and rewarding path in science. It contributes to the dualism of the 'Two Cultures' paradigm that still hangs so leadenly in our cultural skies.

The disappointment of the bright young people I encounter, who have not chosen to study science because they could not see, 'any channel for imagination' or any call on their 'creativity' were they to tread that path, condemns the generation that precedes them in two ways. We stand accused first for our public silence on the way that science draws so deeply from those essential wells of human energy. We are equally culpable for what we have said to those we educate—for our delineation of a science curriculum that manages to persuade most of those who follow it that science is about the accumulation and regurgitation of fact, when before us extends a universe of intricate structure and mystery. We have failed to communicate the adventure of re-imagination and learning, of nature's invitation to peer into the world's multiple levels of structure, to extend our sense of vision in manifold ways, think about matter and form in entirely new ways.

To persuade a scientist to recall and describe the moments when she or he realized that their imagination has been excited by a beautiful new idea is like unlocking a treasure chest. I enjoy these conversations immensely—the description of discovery is often reluctant at first, but the remembered moments of revelation are worth waiting for, even if some of these memories will have matured with age. A sparkling array of formerly hidden truth is open to a shared gaze, there is an immediate impression that as delights are plucked one by one, more will be found underneath—and overall a strong sense of personal discovery. More than that, there is an emotional as well as an intellectual appreciation, an aesthetic reward, and a sense of gift and privilege. These experiences are quite different from the 'logic of scientific discovery'—although they can be experienced even when immersed within the process of methodological work. The coming into shape of a radically new idea can occur in the routine of experiment, of calculation, of careful processing of data, in solving the myriad daily challenges of progressing a research project—they often seem to arrive unsought, and as from unconscious layers of the mind. They seem as much gifts as discoveries, and, although surely dependent on the extended labours of routine work, their own dynamic is special. This chapter will explore in more detail the creative experiences of scientists, some very well-known publicly, others only within their specific fields, but all attempt to articulate the scientific imagination. The continual question is of the origin of new ideas, especially those that radically transform our understanding of an aspect of nature.

A private moment of discovery

As we have noticed, there is less open a record of the experience of creative discovery in science than one might hope for, but there are a few candid and courageous counter-examples. One we have already met—indeed we were alerted in the introduction to explore imagination and affect in science by Chandrasekhar's emotional realization that black holes must proliferate in the universe in a mathematically exact way. Richard Feynman, Nobel Prize-winner for the quantum theory of light, describes a different but equally precious memory of creative conception, a culmination of a long period of thinking about the puzzling data from experiments on sub-atomic particles in the early 1950s. The recent developments in cyclotrons—machines that collide particles together at great energies—were providing enormous amounts of new data that indirectly indicated what the unknown forces between them might be. The problem was that no current mathematical law of force made sense of the measurements. As is normal in science, some of the experiments turned out in retrospect to be more trustworthy than others, but at the time it was unclear which should be granted greater weight.

Long before, Isaac Newton had been faced with data on the orbits of the moon, planets, and comets and realized that these might encode a general pattern of the gravitational forces between them. By the invention of new mathematical methods (the calculus) and the imaginative application of it to the mutual orbits of two bodies attracting each other with a force that depended on distance, he arrived at his celebrated 'inverse-square' law of gravity. The further two bodies were from each other, the weaker would be the force of attraction between them—and more: the way that the force dropped with distance would determine the geometrical form of the orbits the bodies would follow. The 'inverse-square' label simply describes this law of weakening attraction with distance: removing two bodies to twice their original distance reduces their attractive force by a quarter ($1/2^2$), to three times the distance by a ninth ($1/3^2$). Jupiter, five times further from the sun than the Earth, feels just one-twenty-fifth of the sun's gravity as does the Earth. A beautiful moment saw the astronomer Edward Halley calling on Newton to ask him if he knew of a law that would lead to elliptical orbits—for by 1684 observations had indicated that comets, as well as planets, followed just this geometry of paths around the sun. Newton had already calculated that elliptical orbits follow directly if gravity weakens with the inverse-square law of the separation of a planet from the sun[3]. The paths of planets in the sky that we are able to

[3] Although it seems that Newton had misplaced his earlier work, and had to repeat the calculation before he could reassure Halley of the link between elliptical orbits and the inverse square law of gravitational attraction, in the end a

see and measure were from that moment on signs of a universal field of force, entertained in the imagination, which we do not 'see' in any other way.

Nearly three full centuries later, Feynman had been searching similarly for the law of interaction between newly discovered particles called 'pions'. The essential data had only recently become available because the particles themselves required high energy collisions between the more familiar protons to be created, and existed stably for only a very short time before decaying to more stable particles. Both production and detection required technology developed in the 1950s. One of the pathways of disintegration called 'beta decay' was proving especially puzzling. Like the task of re-imagining gravity that had faced Newton long before, in this case too, a visual conception of a field of force subsisting in the space between the particles needed the accompaniment of a mathematical description (the analogy of the inverse-square law of gravity). Although the framework for this physics would have to be quantum mechanical rather than the classical paradigm in which Newton's gravity worked, the notion of a field of attractive force survives the transformation. Feynman writes of the night that he started seriously working with a theory that would, to his astonishment, predict a difference between left- and right-handed versions of the field of force:

> *That night I calculated all kinds of things with this theory. The first thing I calculated was the rate of disintegration of the mu and the neutron. They should be connected together, if this theory was right, by a certain relationship, and it was right to 9 percent . . . I went on and checked some other things, which fit, and new things fit, new things fit, and I was very excited. It was the first time, and the only time, in my career that I knew a law of nature that nobody else knew. (Of course it wasn't true, but finding out later that at least Murray Gell-Mann — and also Sudarshan and Marchak — had worked out the same theory didn't spoil my fun.)*
>
> *The other things I had done before were to take somebody else's theory and improve the method of calculating, or take an equation, such as the Schrödinger*

happy circumstance that led to the writing of his magisterial *Principia*. The tale is well-told by, e.g. Gale E. Christianson (2005), *Isaac Newton*. Oxford: OUP.

Equation, to explain a phenomenon, such as helium. We know the equation, and we know the phenomenon, but how does it work?

I thought about Dirac, who had his equation for a while—a new equation which told how an electron behaved—and I had this new equation for beta decay, which wasn't as vital as the Dirac Equation, but it was good. It's the only time I have discovered a new law.[4]

I have read this extraordinary piece of writing over and over again. Its explosive yet layered prose holds so much together. It communicates at once the thrill, the elevated pulse-rate, the fevered and sleepless labour of plucking one jewel after another from the chest that Feynman has just opened. He has imagined and made concrete an elegant law of force deep within the atom that itself provides a lens through which a mass of blurred and confused observations become suddenly clear. Yet at the heart of his first forays of exploration into this wonderful object there is a sense of contemplation beneath the excitement: 'I knew a law of nature'. *I knew a law of nature*—the bald statement carries the force of a focussed gaze across the divide between mind and the material world, and a sense of personal privilege that one more bridge has been constructed across it, and that this one was *mine* to build. Feynman is careful to distinguish the special nature of this work from the 'normal' science (in the case of a theoretical physicist) of 'calculating and explaining'. This is a moment of gift, and uniquely precious.

There is a solitary specialness to the instant, but his reflections are also drawn to the community of colleagues on which he depends. Dirac's famous mathematical representation of the electron comes to his mind, for it, too, constitutes a moment when the most common particle of all (the electron is responsible for all of chemistry, material properties, and the electrical conductivity of metals) was imagined with a much richer geometry than ever before. Dirac's creation was also a moment at which clarity replaced confusion and consistency contradiction—for the first

[4] Richard P. Feynman (1992), *Surely You're Joking Mr. Feynman?* London: Random House, p. 250.

if they could magically be cut and reformed (wonderfully, there exist proteins in bacteria that perform precisely this process on the bacterial DNA when it needs to disentangle itself into the two 'daughters' during cell-division). At first sight, such a massively complex system of entanglement and tortuosity would seem to be forever beyond comprehension or quantitative calculation. However could a human mind discern pattern or structure in such a mess?

An imaginative way to think about the problem simply was conceived by the French physicist (and later Nobel Laureate) Pierre-Gilles de Gennes, in 1972. He was thinking about the related system of a 'polymer network', in which the long-chain molecules possess occasional chemical attachments to each other, so that nothing flows at all, but forms a weak solid. This is, for example, the way to think of the molecular structure of rubber, or the weak solidity of a jelly. De Gennes then supposed one molecule *not* to be attached to the network of all the others, but instead free to wander through its random three-dimensional latticework. This special string-molecule would have only one way to move through the network, by sliding along its own contour—the tortuous path created by the neighbouring strings and their cross-links at every turn. To return to the noodle (or spaghetti analogy), this is the very motion that we generate when we eat them politely, winding up a few at a time with a fork. Each string of pasta is pulled out of the mess by one end, the rest of the string following its leader through the spaghetti-labyrinth along its original path, until it is wound up on the fork.

The difference between the macroscopic plate of noodles and the molecular-scale mess of polymer molecules is that, at the molecular scale, everything has a natural motion of its own—no external winding-forks are required. This is an example of the incessant random seething and wriggling known as 'Brownian motion', named after the Scottish botanist Robert Brown. He was first to investigate the phenomenon systematically, in the 1820s, through the effect it has on microscopic 'colloidal' particles.