CONVERGENCE

The Idea at the Heart of Science

How the Different Disciplines Are
Coming Together to Tell One Coherent,
Interlocking Story, and Making Science the
Basis for Other Forms of Knowledge

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CONTENTS

Part One

The Most Important Unifying Ideas of All Time

Part Two

The Long Arm of the Laws of Physics

Part Three

"The Friendly Invasion of the Biological Sciences by the Physical Sciences"

Part Four

The Continuum from Minerals to Man

Preface

CONVERGENCE: "THE DEEPEST IDEA IN THE UNIVERSE"

In early April 1912, the Danish physicist Niels Bohr arrived in the bustling city of Manchester in the north of England. When he had first stepped ashore from Denmark, some months previously, he had never imagined working in the industrial heartland of Britain, where the forest of factory chimneys billowed smoke and soot twenty-four hours a day, and where Market Street was said to be the most crowded in all Europe. Instead, his first destination had been the "mellow and stately" colleges and quadrangles of Cambridge. He had just completed his PhD, in Copenhagen, on the electron theory of metals, and he went to Cambridge to work with J. J. Thomson, the director of the Cavendish Laboratory and the man who, in 1897, had discovered the electron as a fundamental unit of matter, for which he had won the Nobel Prize.

But although Bohr was always very polite about Thomson in his letters home to his fiancée, Margrethe, Niels and "JJ"—as he was invariably known—didn't really hit it off. The Dane, a large-boned, heavyset man, had studied English at school, but his spoken syntax was rather stilted and formal and was hardly helped by the fact that he was trying to polish it by reading *David Copperfield.* Nor did he do himself any favors by attempting to advance his friendship with the director by pointing out several small errors in the other man's work. For his part, the notoriously absentminded JJ took weeks to read Bohr’s dissertation, which had been translated from the Danish but by someone who wasn’t a physicist. (The phrase “charged particles” had been rendered as “loaded particles.”) Thomson, who in fairness was very busy as director of the Cavendish, just didn’t seem overly interested in Bohr or his work.

And so when, shortly after Christmas, Ernest Rutherford came to Cambridge to speak at the annual Cavendish dinner—a riotous affair, mixing lectures and sing-alongs—Bohr was entranced. Rutherford was a down-to-earth, broad-shouldered man with a ruddy complexion and a reputation for swearing at experiments when they didn’t go according to plan. He was a New Zealander who had done postgraduate work at the Cavendish, and then worked at McGill University in Canada, before returning to Manchester, as professor. Rutherford, who had won the Nobel Prize in 1908, for his investigation of radioactivity, had astonished the world of physics for a second time by discovering the basic structure of the atom in May 1911. He showed that it was a bit like a miniature solar system, with a nucleus of positive charge, surrounded at a great distance by orbiting electrons of equal negative charge. (To put this into context, in the atom the proportions of the nucleus to the electron cloud surrounding it are of the order of a grain of sand in London’s Albert Hall. Put another way, if the nucleus were the size of a basketball, the electrons would be about three city blocks away. In real terms, the largest atom is that of caesium, a silvery-gold alkali metal, similar to potassium, discovered in 1860, which is just 0.0000005 millimeters—5×10^{-7}mm—across. It would take 10 million of these atoms laid out side by side to stretch between two points of the serrated edge of a postage stamp.)

After hearing Rutherford, Bohr seems to have decided there and then that he wanted to work with him. He arranged a face-to-face meeting via a friend of his father, who lived in Manchester but had worked in Copenhagen. This was a much more successful relationship than the one with JJ—Rutherford later said that Bohr was the most intelligent man he had ever met.

(number 40) and titanium (number 22), the two elements in the same column of the periodic table, rather than resemble the rare earths that occupied the places next to it. But in May 1922 the question of element 72 took a new and dramatic turn. Scientists in France claimed to have discovered a new rare-earth element, which they placed at number 72 in the periodic system.[2] The new element was named celtium, after France. If celtium *was* a rare earth, it would be a major embarrassment for Bohr's theory.

When he had departed his native Copenhagen to travel to Stockholm for the Nobel Prize ceremony he had left two colleagues working on the matter. They were investigating zircon-bearing minerals by X-ray spectrographic analysis. Showing a sense of timing that any theater director would be proud of, the two assistants wired Bohr on the evening immediately before the Nobel ceremony to say that the long-missing element had been found at last and that its chemical properties resembled nothing so much as those of zirconium. The new element was given the name hafnium, for Hafnia, the ancient name of Copenhagen. And so, when Bohr gave his Nobel lecture—as all prize-winners do, on the day after the awards ceremony—he was able to announce this latest result, which did indeed confirm that his theory had successfully unified physics and chemistry.

In the same year that Bohr began his work into the structure of the atom, 1913, Andrew Ellicott Douglass launched his researches, which he wouldn't feel confident enough about publishing until 1928–29. This was the science of dendrochronology, which exploited the links between astronomy, climatology, botany, and archaeology.

In the notebooks of Leonardo da Vinci there is a brief paragraph to the effect that wet years and dry years can be traced in tree rings. The same observation was repeated in 1837 by Charles Babbage—more famous as the man who designed the first mechanical calculators, ancestor of the computer. But Babbage added the notion that tree rings might also be related to other forms of dating. No one took this up for generations, but then Douglass, an American physicist and astronomer, and director of the University of Arizona's Steward Observatory, made a conceptual breakthrough.

His research interest was the effect of sunspots on the climate of the earth, and like other astronomers and climatologists, he knew that, crudely speaking, every eleven years or so, when sunspot activity is at its height, the earth is wracked by storms and rain—one consequence of which is that there is well above average moisture for plants and trees. In order to prove this link, Douglass needed to show that the pattern had been repeated far back into history. For such a project, the incomplete and occasional details about the weather reported in newspapers, say, were woefully inadequate. It was then that Douglass remembered something he had noticed as a boy, an observation familiar to everyone brought up in the countryside. When a tree is sawn through and the top part carried away, leaving just the stump, we see row upon row of concentric rings. All woodsmen, gardeners, and carpenters know, as part of the lore of their trade, that tree rings are annual rings. But what Douglass observed—which no one else had thought through—was that the rings are not of equal thickness. In some years there are narrow rings, in other years the rings are broader. Could it be, Douglass wondered, that broad rings represent what the Bible calls "fat years" (i.e., moist years) and the thin rings represent "lean years"—in other words, dry years?

It was a simple but inspired idea, not least because it could be tested fairly easily. Douglass set about comparing the outer rings of a newly cut tree with official weather records from recent years. To his satisfaction he discovered that his assumption fitted the facts. Next he moved further back. Some trees in Arizona, where he lived, were three hundred years old. If he followed the rings all the way into the pith of the trunk, he should be able to recreate climate fluctuations for his region in past centuries. And that is what he found. Every eleven years, coinciding with sunspot activity, there had been a "fat period," several years of broad rings. Douglass had proved his point: sunspot activity—astronomy—weather and tree growth are related.[3]

But now he saw other uses for his new technique. In Arizona, most of the trees were pine and didn't go back earlier than 1450, just before the European invasion of America. At first Douglass obtained samples of trees cut by Spaniards in the early sixteenth century to construct their missions. Later, he wrote to a number of archaeologists in the American Southwest, asking for core samples of the wood on their sites. Earl Morris, working amid the Aztec ruins fifty miles north of Pueblo Bonito, a prehistoric site in New Mexico, and Neil Judd, excavating at Pueblo Bonito itself, both sent samples. These Aztec "great houses" appeared to have been built at the same time, judging by their style and the objects excavated. But there had been no written calendar in ancient North America, and so no one had been able to place an exact date on the pueblos. Sometime after Douglass received his samples from Morris and Judd, he was able to thank them with a bombshell. "You might be interested to know," he said in a letter, "that the latest beam in the ceiling of the Aztec ruins was cut just nine years before the latest beam from Bonito."[4]

A new science, dendrochronology, had been born, and Pueblo Bonito was the first classical problem it helped to solve. At that point, by overlapping samples from trees of different ages felled at different times, Douglass had an unbroken sequence of rings in southwest America going back first to AD 1300, then to AD 700. Among other things, the sequence revealed that there had been a severe drought, which lasted from 1276 to 1299 and explained why there had been a vast migration at that time by Pueblo Indians, a puzzle that had baffled archaeologists for decades. Botany had resolved one of the prime problems of archaeology.

A third kind of unification took place in the wake of World War II. One of the prime problems in psychology at that time was the number of homeless children in postwar Europe. France, Holland, Germany, and Russia, in addition to Britain, had all suffered heavy bombing and the disruption of family life that went with it. John Bowlby, a child psychiatrist and psychoanalyst, and head of the Children's Department at the Tavistock Clinic in London, was commissioned in 1949 to write a report for the World Health Organization on the mental health of these homeless children. Preparation of the report gave Bowlby an opportunity to pick the brains of many practitioners, and he visited France, Holland, Sweden, Switzerland, and the United States.

Bowlby's international travels set him on a path that would before long result in the unification of pediatrics, psychoanalysis, ethology—in particular the study of animal behavior seen in an evolutionary context—and the hardening of the idea of the unconscious from a philosophical/psychological concept to a firmly based biological entity. His unification of these disciplines came under ferocious attack at the time from psychoanalysts determined to resist his "biologification" of their discipline. But Bowlby stuck to his guns, and history has vindicated him.

Bowlby's report was written in six months and published in 1951 as *Maternal Care and Mental Health* by the WHO. It was translated into fourteen languages and sold 400,000 copies in its English paperback edition. A second edition, entitled *Child Care and the Growth of Love*, was later published by Penguin.[5]

It was this report that first confirmed for many people the crucial nature of the early months of an infant's life, introducing the key phrase "maternal deprivation" to describe the source of a general pathology of development in children, the effects of which were found to be widespread. The very young infant who went without proper mothering was found to be "listless, quiet, unhappy, and unresponsive to a smile or a coo" and later to be less intelligent, bordering in some cases on the defective. No less important, Bowlby drew attention to a large number of studies which showed that victims of maternal deprivation failed to develop the ability to hold relationships with others, or to feel guilty about their failure. Such children either "craved affection" or were "affectless." Bowlby went on to show that delinquent groups were comprised of individuals who, more than their counterparts, were likely to have come from broken homes, where, by definition, there had been widespread maternal deprivation.

This was quite an achievement on Bowlby's part, but then, in 1951, through Julian Huxley, the eminent biologist, he was introduced to the work of the ethologist Konrad Lorenz, particularly his 1935 paper on imprinting. This is a well-known study now, famously showing that if, at a certain critical stage, young geese are exposed to a stimulus (Lorenz himself in the famous case), they will become "imprinted" on that stimulus. The photographs and film of Lorenz being followed wherever he went by a line of young goslings caught the imagination of everyone who saw it. From then on, Bowlby embraced ethology as a new discipline which could connect with and enrich pediatrics and psychoanalysis and would in time help refine the concept of the unconscious. He was joined at the Tavistock by Mary Ainsworth, a Canadian who moved to London for a time, following her husband's deployment there, and then on to Uganda and finally Baltimore. There she carried out parallel studies, using a variety of observational techniques, and ethological comparisons with other species (such as mother-child interaction in monkeys), to build up their notion of what became famous as "attachment theory."[6]

The significance of this was that it showed how linking one science with another could amplify understanding, different disciplines supporting each other, and lead to new methods of treatment. Bowlby and Ainsworth's alignment of pediatrics and ethology placed the mother-infant bond, and the unconscious motivation that results, on a firm and familiar biological basis and, no less important, situated it in an evolutionary context. According to the Bowlby-Ainsworth theory, attachment was an instinctual response (like imprinting) with the function of binding the infant at a critical period to the mother and vice versa, and in so doing promoting the evolutionary fitness of the offspring.[7]

biology, and genetics can help us reconstruct history. Importantly, the different dating mechanisms are consistent with one another, so that ancient history in particular is now an interdisciplinary branch of science.

But—and this is the underlying point—all the connections and overlaps, all the patterns and hierarchies that have been revealed, whether fundamental or otherwise, dovetail together conceptually. There are no exceptions, no important ones anyway. Scientific discoveries repeatedly come together, in all manner of ways, to support one another, to tell one coherent, interlocking story. In an important sense, and to use another analogy, it is as if this story has its own form of gravity as—like particles in cooling gases—the different chapters come together to form a solid narrative.

That narrative leads from the origins of the universe in a Big Bang 13.8 billion years ago, up through the creation of elementary particles, the formation of the lighter then the heavier chemical elements, the formation of the stars and planets, including our own sun, the evolution of the broad structure of the universe (the way the galaxies are laid out), of the gases that coalesced to comprise the rocks of the earth, how those rocks align in the way that they do, how the earth has aged, how the ice ages have come and gone, why the continents are arranged around the globe as they are, why the oceans circulate the planet in a particular pattern, where and when primitive forms of life developed, how ever more complex molecules and organisms came to be, how sex evolved, why trees and flowers take the form that they do, why leaves are green, why some animals have six limbs and others four, why the plants and animals (including people) are distributed across the earth in the way that they are, how major catastrophes have given rise to widespread myths and shape our beliefs, how accuracy developed and became important, how and why and where science itself emerged, culminating (so far) in humankind and the very different civilizations that populate the globe. Indeed, this one story shows *why* there are different civilizations that populate the globe where they do. The convergence of the sciences helps us explain the greatest single story there could be—Big History.

An Epic Detective Story and a New Dimension

I do not, however, tell the story by beginning at the beginning and ending at the end. It is much more revealing, more convincing, and altogether more thrilling to tell the story as it emerged; as it began to fall into place, piece by piece, chapter by chapter, converging tentatively at first, but then with increasing speed, vigor, and confidence. The overlaps and interdependence of the sciences, the patterns and hierarchies of the discoveries in different fields, the underlying order that they are gradually uncovering, is without question one of the most enthralling aspects—perhaps the most enthralling aspect—of modern science. It is in effect a collective detective story of epic dimensions. The convergence and the emerging order—even a kind of unity—between the sciences is one of the most important and satisfying elements in scientific knowledge, and all the more convincing because nobody went looking for it in the first place.

Nor do I begin, as many science histories do, in ancient Greece, the so-called Ionian Enchantment, or with the discoveries of Copernicus and Galileo, or with the scientific revolution of the seventeenth century. I begin much later, in the 1850s—a crucial decade as I show—because that is when the convergence began, when the interconnections and overlaps between the various disciplines first started to show themselves in two fundamental areas and so added a whole new dimension to science, one that hadn't been fully grasped until then.

It was in the 1850s that the idea of the conservation of energy was first aired, which brought together recent discoveries in the sciences of heat, optics, electricity, magnetism, food, and blood chemistry. Almost simultaneously, Darwin's theory of evolution by natural selection brought together the new sciences of deep-space astronomy, deep-time geology, paleontology, anthropology, geography, and biology. These two theories comprised the first great coming together, meaning that the 1850s was in many ways the most momentous decade in the annals of science, and possibly, as it has turned out, the years which saw the greatest intellectual breakthrough of all time: the realization of the way one science supports another, the beginning of a form of understanding like no other. This was in every way a new era intellectually.

I am not aware that anyone has told the history of science, or the history of the universe, in quite this way before. This is the distinctive twist that, I suggest, sets this science history apart.

I *am* aware that some historians of science, social scientists, and philosophers object to the very idea that there is unity or order in the sciences. But I argue that the story of convergence and the emerging order described in this book speaks for itself, and I address several of their objections in the Conclusion.

The idea that the sciences are linked in some hierarchical way is not new, of course, and is known as reductionism. Although reductionism has been criticized—especially in the last twenty to thirty years, even as the evidence in its favor has grown stronger than ever—for the most part, leading scientists themselves have overridden these objections. Such figures as George Gaylord Simpson, Philip Anderson, Ilya Prigogine, Abdus Salam, Steven Weinberg, and Robert Laughlin (the last five being Nobel Prize winners) have all described themselves as wholehearted reductionists. Edward O. Wilson, the noted sociobiologist, put it this way: "Reductionism is the primary cutting tool of science."

As this book was being finalized, there came the news that researchers had inserted two small silicon chips into the posterior parietal cortex of a tetraplegic individual, ninety-six microscopic electrodes that could record the activity of about a hundred nerve cells at the same time. Based on previous work with monkeys, which guided the researchers to a specific area of the human brain, they found that they could reliably read out where the patient *intended* to move his paralyzed arm by analyzing the differing patterns of these hundred cells. This information was then used—bypassing his damaged spinal cord—to enable him to direct a robot arm either to pick up a beer or move a cursor on a computer screen. The researchers could even predict how fast he wanted to move, and whether he wanted to move his left or right arm. In a related experiment, by showing the activity of a single nerve cell on a screen, the patient was able to modulate the cell activity. The experiment was very specific. One nerve cell, for example, would increase its activity when he imagined rotating his shoulder, and decrease its activity when he imagined touching his nose. The specificity of this experiment, and the fact that it could throw light on the man's *intentions*, not just his actual movements, offers great hope for the future, but from our point of view it takes reductionism to a new level, uniting still further psychology and physics.

The Beauty of Deep Order

That said, there is no final order yet, and there may never be. But the order that has emerged already is impressive enough. Order, in particular spontaneous order, is now a major interest of science (chapter 18).

And of course the story of this book is more than just a narrative—for there are two deeper implications of the order that convergence is producing.

The first is that alluded to earlier. Because the convergence—the emerging order—is so strong, and so coherent, science as a *form* of knowledge is beginning to invade other areas, other systems of knowledge traditionally different from or even opposed to science, and is starting to explain—and advance—*them.* Science is invading—and bringing order to—philosophy, to morality, to history, to culture in general, and even to politics (see chapters 14, 15, and 19). Critics object that this is a form of intellectual imperialism, but our newspapers are peppered every day with reports, for example, of the latest psychological research having a bearing on our honesty, generosity, trustworthiness, proneness to violence, and much else. This genie can’t be put back into its bottle.

It is not too much to say that the overall coherence and order revealed by the convergence of the sciences is ushering in a new phase of history. No other form of knowledge has the coherence and order that the converging sciences have brought about. The methods and infrastructure of science are invaluable, are indeed unrivaled aspects of modern democracy, and will shape society in all its manifestations even more in the future than they have in the past, and rightly so. This is a quintessentially contemporary story.

The second aspect of the order that is emerging relates to order itself. Order, the way even inanimate matter spontaneously organizes itself in nature (without, it should be said, any input from a supernatural power), has emerged in recent decades as one of the most important new topics. The very idea that there is a preexisting order *in* nature—a deep order underlying even “chaoplexity” (a mix of chaos and complexity), as appears to be the case—sounds itself very much like a philosophical conundrum as important as any other. Spontaneous order is being explored by physicists, chemists, biologists, and mathematicians and has been found to occur among elementary particles, among molecules, in complex systems, in living things, in the brain, in mathematics, even in traffic. All of which gives an idea of how central the subject now is (chapters 17 and 18). A breakthrough in this area could have breathtaking consequences, not least for our understanding of evolution (chapter 18).

And so there is no other story quite like the one told in this book. Convergence is, as Steven Weinberg says, and without exaggeration, the most fundamental story that could ever be imagined.

Nor, finally, should we overlook the fact that the way the sciences are coming together may offer comfort of a kind. Not quite a religious comfort perhaps, but the converging

Introduction

"THE UNITY OF THE OBSERVABLE WORLD"

We begin in the mid-nineteenth century, and in the most unlikely of places. Walking on a beach in Cornwall in 1852, a passerby chanced upon a length of driftwood that had been washed ashore following a recent storm. There was writing on the plank. It read: "*Mary Somerville.*" The ship of that name, which had been commissioned in 1834, had plied between Liverpool, India, and China, carrying cotton, tea, and flour. She had foundered on a return journey shortly before.

In that year, 1834, a wealthy Liverpool shipbuilder, William Potter, had asked the real-life Mary Somerville if he could name a merchant ship in her honor and, at the same time, obtain a copy of a bust that had been made of her for use as a figurehead of the ship. The original bust, recently completed, had been carved by Sir Francis Chantrey, the celebrated society portrait sculptor, whose other subjects included such eminences as King George III, King George IV, Prime Minister William Pitt the Younger, President George Washington, and scientists James Watt and John Dalton. The bust had been commissioned by the Fellows of the Royal Society of London and placed in the society's great hall.[1]

There was never any question that, as a woman, Mary Somerville would be *elected* to the Royal Society as a fellow—women were not allowed even to attend lectures there until 1876. But, as the commissioning of the bust and the dedication of the merchantman testify, she had nonetheless made her mark. And though it is unusual, it is by no means unsatisfactory to begin a book about science with an account of a remarkable *woman*, who so admirably introduces our theme.

She was born Mary Fairfax in Jedburgh, on the Scottish borders, in December 1780. Her mother had only just returned from waving off her husband—a naval officer—on a series of voyages from which he would not return until Mary was a girl of eight. During the intervening years, she received no formal education and was allowed "to run wild." When her father eventually returned home, he was alarmed to find that Mary had failed to master the skills of reading, writing, and account-keeping "that would make her a suitable wife" and so sent her away to boarding school, where she was taught dancing, painting, music, cookery, needlework, and "elementary geography."[2]

She had a more serious cast of mind, however, and taught herself algebra, using puzzles set in popular magazines as a way to begin. Mary found that she had a natural aptitude for mathematics. An avid book lover, she had no fortune to speak of but was fortunate in being beautiful, and at twenty-three, she married. She and her husband, Captain Samuel Greig, set up home in London, where he held a commission in the Russian Navy and was Russian consul. They had two sons, but Mary was lonely inside the marriage, and when her husband died suddenly, although she was inconsolable at first, she returned to Scotland.[3] Here, now having a small income deriving from her late husband's position, she was able to cultivate the kind of life she preferred. All the more so after she met her cousin, William Somerville, who soon proposed. This was a much better match. Both held liberal views on politics, religion, and education and both were interested in science. William, a military doctor, had done pioneering work on natural history and ethnological exploration in South Africa (plus some other, more secret, military duties).

"The Most Extraordinary Woman in Europe"

It was now that Mary's intellectual life really began to take off. The couple moved first to Edinburgh. This was the time of the Scottish Enlightenment; many of the men there had liberal views about the role of women, and among the individuals with whom she could share her interest in mathematics were the likes of James Hutton and John Stuart Mill. This was the heyday of the *Edinburgh Review*, one of the best periodicals in Britain, or anywhere, but in the early nineteenth century the reformers of British science had launched a new journal, which focused on mathematical challenges (this was a fashion of the times). The publication was entitled *New Series of the Mathematical Repository*, and in June 1811 Mary was delighted to learn that she had won the Prize Question, for which she received a silver medal with her name engraved on it.[4]

James Secord, the Cambridge-based historian of Victorian science, says that Mary felt "most intensely alive and completely herself" in mathematics. For her, he writes, "the practice of mathematics was a form of theological engagement. . . . For Somerville, the divine transcendence of God's power could most fully be experienced by those who—like herself—understood the language of mathematics." Or, as she herself put it, "These formulae, emblematic of Omniscience, condense into a few symbols the immutable laws of the universe. This mighty instrument of human power itself originates in the primitive constitution of the human mind, and rests upon a few fundamental axioms which have eternally existed in Him who implanted them in the breast of man when He created him after His own image." Mary was from the start interested in how the manifest diversity of the world could be reduced to those few fundamental axioms.

Then she and William moved to London, where they became well known among those with scientific interests: at least twenty-six of their regular friends were Fellows of the Royal Society, "possibly the most distinguished corps that any author ever commanded during a lifetime."[5] Mary Somerville took this in her stride. She was well connected socially but became famous, says Allan Chapman, in his biography, via her letters, by her conversation, and by the fact that everybody in intellectual London knew of this singular woman who had mastered the most abstruse mathematics of the age, and had acquired from her studies a sophisticated grasp of how physical science worked. Sir David Brewster, a physicist and mathematician who was principal of both St. Andrews and Edinburgh universities, described her as "the most extraordinary woman in Europe."[6]

In the long run, two things set her apart, in addition to that grasp of mathematics. Like other Grand Amateurs of the day, she took part in simple experiments, in her case into the connection between magnetism and sunlight.[7] This was in the excited wake of Hans Christian Ørsted's discovery of a connection between magnetism and electricity (see chapter 1), and the results she obtained were interesting enough for William, her husband, himself an FRS, to read her account of them before the Royal Society. The papers were subsequently published in the society's *Philosophical Transactions* and in that way were made available to a much wider range of readers. Offprints were sent to such figures as the astronomer Pierre-Simon Laplace and the chemist Joseph Louis Gay-Lussac in Paris, and to Ørsted himself in Copenhagen.

On the strength of her accomplishments, Henry Brougham suggested that Mary contribute an account of Newton's *Philosophiae Naturalis Principia Mathematica* and Laplace's famous book on the heavens, *Mécanique céleste*, to the publishing program of the Society for the Diffusion of Useful Knowledge. Brougham—an eccentric Scottish lawyer who was a guiding spirit behind the 1832 Reform Act, and was one of those individuals who had a finger in every pie—had founded the SDUK in 1826 with the aim of spreading knowledge until it "has become as plentiful and as universally diffused as the air we breathe." The SDUK published cheap books in weekly parts, topics ranging from brewing to hydraulics and from insects to Egyptian antiquities. Its most successful venture was the weekly illustrated *Penny Magazine*, which at its peak achieved a circulation of more than 200,000.[8]

The first books that Mary wrote were too detailed and too thorough for a penny magazine readership and so not at all suitable for the SDUK. She told Brougham along the way that her book would have to discuss the calculus, so that was bound to limit its appeal. But John Murray, the London publisher, who was himself a fixture on the intellectual scene in the capital, snapped it up, and so began Mary's successful writing career in science, the second thing that set her apart from other women. In all she wrote five books, *Mechanism of the Heavens* (1831), *On the Connexion of the Physical Sciences* (1834), *Physical Geography* (1848), *On Molecular and Microscopic Science* (1869), and *Personal Recollections* (1874, posthumous).

The book that concerns us is the second one, *On the Connexion of the Physical Sciences*, generally regarded as her most important work. She was preparing it at the peak of her renown, when the Chantrey bust for the Royal Society was being carved and when, a year later—to the envy of many—she was awarded an annual pension of £200 by the government for her services to science. (It was later increased to £300, the same as Michael Faraday and John Dalton received.)

The argument in *Connexion* was sharper then than it might seem now. Its aim was to reveal the common bonds—the links, the convergence—between the physical sciences at a time when they were otherwise being carved up into separate disciplines. Mary was very deliberately her own woman.

"Demonstrating the Unity of the Observable World"

The professed aim of her book, embodied in the title, was to *draw together* a range of subjects in the physical sciences that were undergoing unprecedented change. Secord again: "Through its wide readership, *Connexion* became a key work in transforming the 'natural philosophy' of the seventeenth and eighteenth source of ultimate unity, though she accepted that meant it would only ever be available to a very few. With this in mind, she therefore advanced her argument about mathematics without using a single equation.

She wrote most of the book in secret, uncertain of how its female authorship would be received, though she was already celebrated across Europe for her mathematical accomplishments (which is why Brougham had suggested the SDUK project in the first place). And, as Joanna Baillie, the Scottish poet and dramatist, pointedly remarked, Somerville had "done more to remove the light estimation in which the capacity of women is too often held, than all that has been accomplished by the whole sisterhood of poetic damsels and novel-writing authors."[11]

The first edition of two thousand copies was priced at seven shillings and sixpence and quickly sold out, the book remaining in print for over forty years, in ten editions. It was translated into German, French, and Italian, and publishers in Philadelphia and New York issued pirated editions. The *Athenaeum* conceded that the book was "at the same time a fit companion for the philosopher in his study and for the literary lady in her boudoir."

The Search for Meaningful Patterns and "Increasingly Higher Levels of Generalization"

The *Connexion* of the title was further explained in a preface: "The progress of modern science, especially within the last five years, has been remarkable for a tendency to simplify the laws of nature, and to unite detached branches by general principles. In some cases identity has been proved where there appeared to be nothing in common, as in the electric and magnetic influences; in others, as that of light and heat, such analogies have been pointed out as to justify the expectation, that they will ultimately be referred to the same agent; and in all there exists such a bond of union, that proficiency cannot be attained in any one without knowledge of the other." And she concluded: "Innumerable instances might be given in illustration of the immediate connexion of the physical sciences, most of which are united still more closely by the common bond of analysis which is daily extending its empire, and will ultimately embrace almost every subject in nature in its formulae."[12]

Kathryn Neeley reminds us that the aims of science then were not quite the same as they are now. One of the differences was that, since science was not yet professionalized, or as highly specialized as it would become, "omniscience prevailed as an intellectual ideal." She says that early Victorian intellectuals thrived on debate and controversy "but took a unitary approach to intellectual life." They saw culture as a whole and were ambivalent about specialization since it threatened that unity. People should know "something of everything and everything of something." John Herschel, a friend of Somerville, declined the presidency of the British Association for the Advancement of Science (BAAS) because he feared the organization would encourage the compartmentalization of science.

This was an essentially religious view, which held that science advanced by achieving increasingly higher levels of generalization, an approach that was first aired in Germany. "These higher levels of generalisation usually took the form of new laws with greater explanatory power . . . a desire for more and more widely applicable laws to interconnect the diverse phenomena. . . . Increasingly higher levels of generalisation could be achieved reliably only through the accumulation of increasingly large amounts of detailed information and the search for meaningful patterns and analogies."[13] Each early Victorian saw his work as part of an "intellectual totality."

Moreover, this unitary character of intellectual life was regarded as a form of the sublime. "The prevailing belief was that science could not be taught well without reference to the sublime truths of natural theology and that the scientific study of nature revealed God. . . . In the scientific sublime, the reader links with the great in the form of an encounter with the attributes of God revealed in nature by science." Unification was akin to an "enlarged power," a power of intellect embodied or made manifest in science. All this was certainly Mary Somerville's view—that coherence *was* a power.[14]

"United by the Discovery of General Principles"

The book was widely reviewed, almost always favorably.[15] Arguably the most interesting and influential comments were those in the March issue of the *Quarterly Review* by William Whewell, master of Trinity College, Cambridge, and himself the author of several books about the history of science. He acknowledged that "the tendency of the sciences has long been an increasing proclivity to separation and dismemberment. Formerly, the 'learned' embraced in their wide grasp all the branches of the tree of knowledge; the Scaligers and Vossiuses of former days were mathematicians as well as philologers, physical as well as antiquarian speculators.* But those days are past. . . . If a moralist, like Hobbes, ventures into the domain of mathematics, or a poet, like Goethe, wanders into the field of experimental science, he is received with contradictions and contempt . . . the disintegration goes on . . . physical science itself is endlessly subdivided, and subdivisions insulated. . . . The mathematician turns away from the chemist . . . the chemist is perhaps a chemist of electro-chemistry; if so, he leaves common chemical analysis to others. . . . And thus science, even mere physical science, loses all trace of unity."[16]

And then: "A curious illustration of this result may be observed in the want of any name by which we can designate the students of the knowledge of the material world collectively. We are informed that this difficulty was felt very oppressively by the members of the British Association for the Advancement of

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* Joseph Justus Scaliger (1540–1609) and Gerardus Vossius (1577–1649) both helped extend history and humanist scholarship beyond theology.

Science, at their meetings at York, Oxford, and Cambridge, in the last three summers [i.e., since the very inception of the BAAS]. There was no general term by which these gentlemen could describe themselves with reference to their pursuits. *Philosopher* was felt to be too wide and too lofty a term, and was very properly forbidden them by Mr. [Samuel Taylor] Coleridge, both in his capacity as philologer and metaphysician; *savants* was rather assuming, besides being French instead of English; some ingenious gentleman [in truth, this was Whewell himself, though he didn't say as much in the review] proposed that, by analogy with *artist*, they might form *scientist*, and added that there could be no scruple in making free with this termination when we have such words as *sciolist*, *economist*, and *atheist* but this was not generally palatable; others attempted to translate the term by which the members of similar associations in Germany have described themselves, but it was not found easy to discover an English equivalent for *natur-forscher.* The process of examination which it implies might suggest such undignified compounds as *nature-poker*, or *nature-peeper*, for these *naturæ curiosi*; but these were indignantly rejected."

This was thus the first public airing of the term "scientist," and Whewell, it should be noted, was fond of—and good at—neologisms. Besides "scientist," he is credited with coining the word "physicist" and with suggesting "ion," "anode," and "cathode" to Michael Faraday.

Having coined a word that would in time become commonplace, his review continued, "The inconveniences of this division of the soil of science into infinitely small allotments have been often felt and complained of. It was one object, we believe, of the British Association, to remedy these inconveniences by bringing together the cultivators of different departments. To remove the evil in another way is one object of Mrs. Somerville's book. If we apprehend her purpose rightly, this is to be done by showing how detached branches have, in the history of science, been united by the discovery of general principles."

One reason Whewell was sympathetic to Somerville was because, in his own way, in devising the neologism "scientist," he was engaged in a broadly similar thought process to hers—stressing the similarities between the sciences (including, in his case, their methods), rather than concentrating on the differences. In his 1840 synthesis, *The Philosophy of the Inductive Sciences*, Whewell was the first to use the word "consilience," to mean the "jumping together" of knowledge "by the linking of facts and fact-based theory across disciplines to create a common groundwork of explanation."[17]

But in fact this is as far as the connections of *Connexion* went. The book consisted of thirty-seven sections, over four hundred pages, and covered such topics as "Lunar Theory," "Perturbations to Planetary Orbits," "Tides and Currents," "Laws of Polarization," and "Electricity from Rotation and from Heat." There was no narrative structure, or any large-scale unfolding of logic, and most of the connections listed were those between two of these narrow topics, rather than any deeper underlying totalizing principles (apart from the mathematical ones which were closest to Mary Somerville's heart). Knowledge of the principle of matter, for example, she said, is needed for predicting its effect on light. She explained why we can look at the sun in the evening, when it is near the horizon, and not look at it at midday, high in the sky. Sound is capable of reflection from surfaces, according to the same laws as light. And so, given what was just around the corner—the great unifying theories of energy conservation and evolution by natural selection, which are the subjects of Part One of this book—the connections in *Connexion* were notable as an early attempt to construct such linkages. In the broader scheme of things, however, they were, in James Secord's verdict, "tame."[18]

Their significance lies in their broad argument, at a time when the sciences were fragmenting, and in their timing.[19] The tenth edition of *Connexion* appeared in 1877, and there were to be no more, for by then the two great unifying theories—arguably of all time—had been announced to the world in the same decade,

PART ONE

The Most Important Unifying Ideas of All Time

The world knows that in 1851 Victorian Britain held a Great Exhibition in London's Hyde Park, under a startling new construction, made almost entirely of glass: the Crystal Palace. Over five months, 6 million people from twenty-eight different countries visited the exhibition, the main theme of which, as one reviewer put it, in the London *Times*, was "The Gifts of Science to Industry." At that time, more people probably knew about science, and its practical possibilities, than ever before. This was no more than fitting because the decade around and following the Crystal Palace exhibition was arguably the most important in the history of science.

Most histories of science begin either with the Ionian Enchantment, in ancient Greece, with the observations and discoveries of Copernicus-Kepler-Galileo-Newtonian astronomy, or with the creation of the Royal Society in London and the Académie des Sciences in Paris in the 1660s, the so-called scientific revolution. Our theme—the coming together of the sciences, the great convergence—starts later, beginning in the 1850s. For, besides the Crystal Palace and all that it represented, that decade saw the emergence of the two most powerful unifying theories of all time.

The idea of the Conservation of Energy and the theory of Evolution by Natural Selection were both introduced to the world in the 1850s. Each was the fruit of the coming together of several sciences: the sciences of heat, optics, electricity, magnetism, food, and blood chemistry in the case of the conservation of energy; deep-space astronomy, deep-time geology, paleontology, anthropology, geography, and biology in the case of evolution. This was the first great coming together, meaning that the 1850s were in many ways the most momentous decade in the history of science, and possibly, as it has turned out, the years which saw the most exciting intellectual breakthrough of all time—the way one science supports and interconnects with another, the beginning of a form of understanding like no other in history. As a result, there was a massive increase in the authority of science, an authority that has gone on expanding as the emerging order of the overlapping and increasingly interlinked sciences has been progressively exposed. These interconnections have been there for all to see, but until now, they have scarcely received the attention they merit.

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"THE GREATEST OF ALL GENERALIZATIONS"

One morning in late August 1847, James Prescott Joule, a wealthy Manchester brewer but also a distinguished physicist, was walking in Switzerland, near Saint-Martin, beneath the Col de la Forclaz, in the south of the country, not too far from the Italian border. On the road between Saint-Martin and Saint-Gervais he was surprised to meet a colleague, William Thomson, a fellow physicist, later even more distinguished as Lord Kelvin. Thomson noted in a letter the next day to his father—a professor of mathematics—that Joule had with him some very sensitive thermometers and asked if Thomson would assist him in an unusual experiment: he wanted to measure the temperature of the water at the top and bottom of a local waterfall. The request was particularly unusual, Thomson suggested in his letter, because Joule was then on his honeymoon.

The experiment with waterfalls came to nothing. There was so much spray and splash at the foot of the local cataract that neither Joule nor Thomson could get close enough to the main body of water to make measurements. But the idea was ingenious and it was, moreover, very much a child of its time. Joule was homing in on a notion that, it is no exaggeration to say, would prove to be one of the two most important scientific ideas of all time, and a significant new view of nature.

He was not alone. Over the previous few years as many as fifteen scientists, working in Germany, Holland, and France as well as in Britain, were all thinking about the conservation of energy. The historian of science Thomas Kuhn says that there is "no more striking instance of the phenomenon known as simultaneous discovery than conservation of energy." Four of the men—Sadi Carnot in Paris in 1832, Marc Seguin in Lyon in 1839, Carl Holtzmann in Mannheim in 1845, and Gustave-Adolphe Hirn in Mulhouse in 1854—had all recorded their independent convictions that heat and work are quantitatively interchangeable. Between 1837 and 1844, Karl Mohr in Koblenz, William Grove and Michael Faraday in London, and Justus von Liebig in Giessen all described the world of phenomena "as manifesting but a single 'force,' one which could appear in electrical, thermal, dynamical, and many other forms but which could never, in all its transformations, be created or destroyed."[1] And between 1842 and 1847, the hypothesis of energy conservation was publicly announced, says Kuhn, by four "widely scattered" European scientists—Julius von Mayer in Tübingen, James Joule in Manchester, Ludwig Colding in Copenhagen, and Hermann von Helmholtz in Berlin, all but the last working in complete ignorance of the others.

Joule and his waterfalls apart, perhaps the most romantic of the different stories was that of Julius von Mayer. For the whole of 1840, starting in February, Julius Robert von Mayer served as a ship's physician on board a Dutch merchantman to the East Indies. The son of an apothecary from Heilbronn, Württemberg, he was a saturnine, bespectacled man who, in the fashion of his time, wore his beard under—but not actually *on*—his chin. Mayer's life and career interlocked in intellectually productive yet otherwise tragic ways. While a student he was arrested and briefly imprisoned for wearing the colors of a prohibited organization. He was also expelled for a year and spent the time traveling, notably to the Dutch East Indies, a lucky destination for him, as it turned out. Mayer graduated in medicine from the University of Tübingen in 1838, though physics was really his first love, and that was when he enlisted as a ship's doctor with the Dutch East India Company. The return to the East was to have momentous consequences.

On the way there, in the South Atlantic, off South Africa, he observed that the waves that were thrown about during some of the wild storms that the three-master encountered were warmer than the calm seas. That set him thinking about heat and motion. Then, during a stopover in Jakarta in the summer of 1840, he made his most famous observation. As was then common practice, he let the blood of several European sailors who had recently arrived in Java. He was surprised at how red their blood was—he took blood from their veins (blood returning to the heart) and found it was almost as red as arterial blood. Mayer inferred that the sailors' blood was more than usually red owing to the high temperatures in Indonesia, which meant their bodies required a lower rate of metabolic activity to maintain body heat. Their bodies had extracted less oxygen from their arterial blood, making the returning venous blood redder than it would otherwise have been.[2]

Heat and Motion Are the Same

Mayer was struck by this observation because it seemed to him to be self-evident support for the theory of his compatriot, the chemist and agricultural specialist Justus von Liebig, who argued that animal heat is produced by combustion—oxidation—of the chemicals in the food taken in by the body. In effect, Liebig was observing that chemical "force" (as the term was then used), which is latent in food, was being converted into (body) heat. Since the only "force" that enters animals is their food (their fuel) and the only form of force they display is activity and heat, then these two forces must always—by definition—be in balance. There was nowhere else for the force in the food to go.

Mayer originally tried to publish his work in the prestigious *Annalen der Physik und Chemie.* Founded in 1790, the *Annalen* had demonstrated a link between electricity and magnetism, and in Faraday's experiments, electricity and magnetism together produced movement. On top of this, the new technology of photography, invented in the 1830s, used light to produce chemical reactions. Above all, there was the steam engine, a machine for producing mechanical force from heat. Steam technology would lead to the most productive transformations of all, at least for a time. During the 1830s and 1840s the demand for motive power soared. In an age of colonial expansion, the appetite for railways and steamships was insatiable, and these needed to be made more efficient, with less and less leakage of power, of energy.

But Thomas Kuhn also observed that, of these twelve pioneers in the conservation of energy, five came from Germany itself, and a further two came from Alsace and Denmark—areas of German influence. He put this preponderance of Germans down to the fact that "many of the discoverers of energy conservation were deeply predisposed to see a single indestructible force at the root of all natural phenomena." He suggested that this root idea could be found in the literature of *Naturphilosophie.* "Schelling, for example [and in particular], maintained that magnetic, electrical, chemical and finally even organic phenomena would be interwoven into one great association." Liebig studied for two years with Schelling.[5]

A final factor, according to science historian Crosbie Smith, was the extreme practical-mindedness of physicists and engineers in Scotland and northern England, who were fascinated by the commercial possibilities of new machines. All of this comprised the "deep background" to the ideas of Mayer, Joule, and the others. But the final element, says John Theodore Merz (1840–1922) in his four-volume *History of European Thought in the Nineteenth Century* (1904–12), was that the unification of thought that was brought about by all those experiments and observations "needed a more general term . . . a still higher generalisation, a more complete unification of knowledge . . . this greatest of all exact generalisations [was] the conception of energy."[6]

Nature's Currency System: "Continual Conversion"

The other men who did most, at least to begin with, to explore the conservation of energy—Joule and William Thomson in Britain, Hermann von Helmholtz and Rudolf Clausius in Germany—fared better than Mayer, though there were interminable wrangles in the mid-nineteenth century as to who had discovered what first.

Joule (1818–89), born into a brewing family from Salford, had a Victorian—one might almost say imperial—mane, hair which reached almost as far down his back as his beard did down his front: his head was awash in hair. He is known for just one thing, but it was and is an important thing and was one for which he conducted experiments over a number of years to provide an ever more accurate explanation.

As a young man he had worked in the family's brewery, which may have ignited his interest in heat. This interest was no doubt fanned all the more when he was sent to study chemistry in Manchester with John Dalton. Dalton was famous for his atomic theory—the idea that each chemical element was made up of different kinds of atoms, and that the key difference between different atoms was their weight. Dalton thought that these "elementary elements" could be neither created nor destroyed, based on his observations which showed that different elements combined to produce substances which contained the elements in set proportions, with nothing left over.

With his commercial background, Joule was always interested in the practical end of science—in the possibility of electric motors, for instance, which might take over from steam. That didn't materialize, not then anyway, but his interest in the relation between heat, work, and energy did eventually pay off. "Eventually," because Joule's early reports, on the relationship between electricity and heat, were turned down by the Royal Society—just as Mayer's ideas had been turned down by Poggendorff—and Joule was forced to publish in the less prestigious *Philosophical*

Magazine. But he continued his experiments, which, by stirring a container of water with a paddle wheel, sought to show that work—movement—is converted into heat. Joule wrote that "we consider heat not as *substance* but as a state of *vibration.*" (This implicit reference to movement echoes his idea about the different temperatures of water at the top and bottom of waterfalls, and Mayer's observation that storm waves were warmer than calm seas.) Over his lifetime, Joule sought ever more accurate ways to calculate just how much work was needed to raise the temperature of a pound of water by one degree Fahrenheit (the traditional definition of "work"). Accuracy was vital if the conservation of energy was to be proved.[7]

And gradually people *were* won over. For example, Joule addressed several meetings of the British Association for the Advancement of Science, in 1842, and again in 1847. In between these meetings, Mayer published his observations, about body heat and blood color, but Joule had the momentum and, in the BAAS, the stage. The BAAS was well established then, having been founded in 1831, in York, modeled on the German *Gesellschaft Deutscher Naturforscher und Ärzte.* It held annual meetings in different British cities each year. But Joule needed only one individual in his BAAS audience to find what he had to say important, and that moment came in the 1847 meeting, when his ideas were picked up on by a young man of twenty-one. He was then named William Thomson but he would, in time, become better known as Lord Kelvin.

Just as Joule befriended the older Dalton, so he befriended the younger Thomson. In fact, he worked with Thomson on the theory of gases and how they cool and how all that related to Dalton's atomic theory. Joule was in particular interested in nailing the exact average speed at which molecules of gas move (movement that was of course related to their temperature). He focused on hydrogen and treated it as being made up of tiny particles bouncing off one another and off the walls of whatever container they were held in. By manipulating the temperature and the pressure, which affected the volume in predictable ways, he was able to calculate that, at a temperature of sixty degrees Fahrenheit and a pressure of thirty inches of mercury (more or less room temperature and pressure), the particles of gas move at 6,225.54 feet per second. Similarly, with oxygen, the molecules of which weigh sixteen times those of hydrogen, and since the inverse-square law* applies, in ordinary air the oxygen molecules move at a quarter of the speed of hydrogen molecules, or 1,556.39 feet per second. To pin down such infinitesimal activity was an amazing feat, and Joule was invited to address the Royal Society and elected a fellow, more than making up for his earlier rejection.

Joule shared a lot with Thomson, including his religious beliefs, which played an important part in the theory for some people. The principle of continual conversions or exchanges was established and maintained by God, he argued, as a basis for "nature's currency system," guaranteeing a dynamic stability in "nature's economy." "Indeed the phenomena of nature, whether mechanical, chemical, or vital, consist almost entirely in a continual conversion of attraction through space, living force, and heat into one another. Thus it is that order is maintained in the universe—nothing is deranged, nothing ever lost . . . the whole being governed by the sovereign will of God."[8]

Thomson followed on where Joule left off. Born in Belfast in June 1824, he spent almost all his life in university environments. His father was professor of mathematics at the Royal Belfast Academical Institution, a forerunner of Belfast University, and

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* The inverse-square law applies when some force or energy is radiated evenly from a point source into three-dimensional space, like a lightbulb, say. Since the surface area of a sphere is proportional to the square of the radius, the emitted radiation (light in this example) is spread out over an area that is increasing in proportion to the square of the distance from the source. When you sit next to a light to read by, the phenomenon shows itself. If you move your chair so that you are twice as distant from the source of light as you were initially, the light diminishes by the square of that—i.e., 2^2: it is four times as dim.

William and his brother were educated at home by their father (his brother James also became a physicist). Their mother died when William was six, and in 1832 their father moved to Glasgow, where again he became professor of mathematics. As a special dispensation, both his sons were allowed to attend lectures there, matriculating in 1834, when William was ten. After Glasgow, William was due to go to Cambridge, but there were concerns that graduating in Glasgow might "disadvantage" his prospects down south, so although he passed his finals and the MA exams a year later, he did not formally graduate. At the time, he therefore signed himself as William Thomson BATAIAP (Bachelor of Arts To All Intents And Purposes).

William transferred to Cambridge in 1841, graduating four years later, having won a number of prizes and publishing several papers in the *Cambridge Mathematical Journal.* He then worked for a while in Paris, familiarizing himself with the work of the brilliant French physicist Sadi Carnot (who had died tragically young), and then joined his father in Glasgow, as professor of natural philosophy. James Thomson Senior, who had worked tirelessly to bring his son to Glasgow, died shortly afterwards from cholera. But William remained at Glasgow from when he was appointed professor (in his mid-twenties) until he retired at seventy-five, when, "to keep his hand in," he enrolled as a student all over again. This, as historian John Gribbin rejoices in saying, made him "possibly both the youngest student and the oldest student ever to attend the University of Glasgow."[9]

Thomson was much more than a scientist. He had a hand in the first working transatlantic telegraph, between Great Britain and the USA (after other attempts had failed), which transformed communication almost as much as, and maybe more than, the Internet of today. He made money from his scientific and industrial patents, to such an extent that he was, first, knighted in 1866 and then made Baron Kelvin of Largs in 1892 (the River Largs runs through the campus of Glasgow University).

the University of Königsberg. In 1850 he invented the ophthalmoscope, which allows the far wall of the eye to be inspected, and contributed many papers on optics and the physiology of stereoscopic perception, as well as such subjects as fermentation. But von Helmholtz fits in here because of his 1847 pamphlet, "On the Conservation of Force."[12]

Like Mayer, he had sent his paper to Poggendorff at the *Annalen der Physik* but was rebuffed, and he chose to publish his pamphlet privately. And, like Mayer, von Helmholtz approached the problem of energy from a medical perspective. His previous physiological publications had all been designed to show how the heat of animal bodies and their muscular activity could be traced to the oxidation of food—that the human engine was little different from the steam engine. He did not think there were forces entirely peculiar to living things but insisted instead that organic life was the result of forces that were "modifications" of those operating in the inorganic realm. He had parallel ideas not just with Mayer and Kelvin, but with Liebig too.

In the purely mechanical universe envisaged by von Helmholtz there was an obvious connection between human and machine work. For him, *Lebenskraft*, as the Germans called the life force, was no more than an expression of "organisation" among related parts which carried no implication of a vital force.[13] "The idea of work is evidently transferred to machines from comparing their performances with those of men and animals, to replace which they were applied. We still reckon the work of steam engines according to horse power." Which led him to the principle of the conservation of force: "We cannot create mechanical force, but we may help ourselves from the general storehouse of Nature. . . . The possessor of a mill claims the gravity of the descending rivulet, or the living force of the moving wind, as his possession. These portions of the store of Nature are what give his property its chief value." His idea of the "store" of nature complemented Joule's notion of the "currency" of nature.

In making his case without any experimental evidence (which the members of the Berlin Academy noticed, while being impressed by his presentation), von Helmholtz "first established a clear distinction between theoretical and experimental physics."

The Tendency Toward Increasing Disorder

While Mayer and von Helmholtz, being doctors, came to the science of work through physiology, von Helmholtz's fellow Prussian Rudolf Clausius approached the phenomenon, like his British and French contemporaries, via the ubiquitous steam engine.

In later life Clausius had a rather forbidding appearance: a very high forehead, rather hard, piercing eyes, a thin, stern mouth, and a white beard fringing his cheeks and chin. In fairness to him, this sternness may have reflected nothing more than the pain he was in continuously after suffering a wound in the Franco-Prussian War of 1870–71. At the same time he was a fervent nationalist and that may also have been a factor.

He was born in January 1822, in Köslin, Prussia (now Koszalin, Poland), where his father was a pastor with his own private school. The sixth of his father's sons, Rudolf attended the family school for a few years, before transferring to the gymnasium at Stettin (now Szczecin, Poland) and then going on to the University of Berlin in 1840. To begin with he was drawn to history and studied under the great Leopold von Ranke, which may have had something to do with his subsequent nationalism. But Clausius switched to math and physics. In 1846, two years after graduating from Berlin, he entered August Böckh's seminar at Halle, and worked on explaining the blue color of the sky. The theory Clausius came up with about the blue of the sky, and its redness at night and morning, was based on faulty physics. He thought it was caused by reflection and refraction of light, whereas John Strutt, later Lord Rayleigh, was able to show it was due to the scattering of light.[14]

But Clausius's special contribution was to apply mathematics far more deeply than any of his predecessors, and his work was an important stage in the establishment of thermodynamics and theoretical physics. His first paper on the mechanical theory of heat was published in 1850. This was his most famous work and we shall return to it in just a moment. He advanced rapidly in his career, at least to begin with, being invited to the post of professor at the Royal Artillery and Engineering School at Berlin in September 1850 on the strength of his paper, then moving on to the Polytechnikum in Zurich, where he remained for some time despite being invited back to Germany more than once. He eventually accepted a chair at Würzburg in 1869, moving on to Bonn after only a year, when the Franco-Prussian War intervened. A "burning nationalist," as someone described him, Clausius volunteered, despite being just short of his fiftieth birthday, and was allowed to assume the leadership of an ambulance corps, which he formed from Bonn students, helping to carry the wounded at the great battles of Vionville and Gravelotte—the Germans suffered twenty thousand casualties at the latter battle. During the hostilities, Clausius was wounded in the leg, which caused him severe pain and disability for the rest of his life.[15] He was awarded the Iron Cross in 1871.

Unlike Mayer and von Helmholtz, Clausius did succeed in having his first important paper, "On the Moving Force of Heat, and the Laws Regarding the Nature of Heat That Are Deducible Therefrom," accepted by the *Annalen.* It appeared in 1850 and its importance was immediately recognized. In it he argued that the production of work resulted not only from a change in the *distribution* of heat, as Sadi Carnot—the French physicist and military engineer—had argued, but also from the *consumption* of heat: heat could be produced by the "expenditure" of work. "It is quite possible," he wrote, "that in the production of work . . . a certain portion of heat may be consumed, and a further portion transmitted from a warm body to a cold one: and both portions may stand in a certain definite relation to the quantity of work produced." In doing this he stated two fundamental principles, which would become known as the first and second laws of thermodynamics.

The first law may be illustrated by how it was later taught to Max Planck, the man who, at the turn of the twentieth century, would build on Clausius's work. Imagine a worker lifting a heavy stone onto the roof of a house. The stone will remain in position long after it has been left there, storing energy until at some point in the future it falls back to earth. Energy, says the first law, can be neither created nor destroyed. Clausius, however, pointed out in his second law that the first law does not give the total picture. In the example given, energy is expended by the worker as he lifts the stone into place, and is dissipated in the effort as heat, which among other things causes the worker to sweat. This *dissipation*, which Clausius was to term "entropy," was of fundamental importance, he said, because although it did not disappear from the universe, this energy could never be recovered in its original form. Clausius therefore concluded that the world (and the universe) must always tend towards increasing disorder, must always add to its entropy.[16]

Clausius never stopped refining his theories of heat, becoming in the process interested in the kinetic theory of gases, in particular the notion that the large-scale properties of gases were a function of the small-scale movements of the particles, or molecules, which comprised the gas. Heat, he came to think, was a function of the motion of such particles—hot gases were made up of fast-moving particles, colder gases of slower particles. Work was understood as "the alteration in some way or another of the arrangement of the constituent molecules of a body."

This idea that heat was a form of motion was not new. In addition to the ideas of Joule and Mayer, the American Benjamin Thompson had observed that heat was produced when a cannon barrel was bored, and in Britain Sir Humphry Davy had likewise noted that ice could be melted by friction. What attracted Clausius's interest was the exact form of motion that comprised heat. Was it the vibration of the internal particles, was it their "translational" motion as they moved from one position to another, or was it because they rotated on their own axes?

Clausius's second seminal paper, "On the Kind of Motion That We Call Heat," was published in the *Annalen* in 1857. He argued that the heat of a gas must be made up of all three types of movement and that therefore its total heat ought to be proportional to the sum of these motions. He assumed that the volume occupied by the particles themselves was vanishingly small and that all the particles moved with the same average velocity, which he calculated as being hundreds—if not thousands—of meters per second (building on Joule). This prompted the objection from several others that his assumptions and calculations could not be right, since otherwise gases would diffuse far more quickly than they were known to do. He therefore abandoned that approach, introducing instead the concept of the "mean free path"—the average distance that a particle could travel in a straight line before colliding with another one.[17]

The Unification of Electricity, Magnetism, and Light

Clausius was elected a fellow of the Royal Society in 1868, and awarded its Copley Medal in 1879. Others were attracted by his efforts, in particular James Clerk Maxwell in Britain, who published "Illustrations of the Dynamical Theory of Gases" in the *Philosophical Magazine* in 1860, making use of Clausius's idea of the mean free path.

According to one of his biographers, James Clerk Maxwell had a scientific idea "that was as profound as any work of philosophy, as beautiful as any painting, and more powerful than any act of politics or war. Nothing would be the same again." These are big things to say, but, in a nutshell, Maxwell conceived four equations that, at a stroke, united electricity, magnetism, and light and in so doing showed that visible light was only a small band in a vast range of possible waves, "which all travelled at the same speed but vibrated at different frequencies."[18] Physicists, says the same and studied their mathematical relationships, coming up with some formulas to describe what he had found. Some of this had been worked out earlier by no less a figure than René Descartes, but Maxwell's system was simpler and was judged good enough to be read before the Royal Society of Edinburgh. Because he was so young, the paper had to be read for him.

He was a devout Christian, of the austere Presbyterian kind, something that paid off when he visited other Presbyterian relatives in Glasgow. One of his cousins, Jemima, had married Hugh Blackburn, professor of mathematics at Glasgow and a great friend of William Thomson, the new professor of natural philosophy there. Maxwell and Thomson struck up a friendship that would continue for years.

As mentioned in the Introduction, in mid-nineteenth-century Britain the word "scientist" had not yet come into common use. Physicists and chemists called themselves "natural philosophers" and biologists called themselves "natural historians." Maxwell decided to enroll at Edinburgh University, to study mathematics, natural philosophy, and logic. He matriculated at sixteen.

This was when Maxwell himself began to experiment, aided by the practice of the Scottish universities of closing from late April to early November to allow students home to help with the farming. He read and read and read and carried out his first experiments at Glenlair, developing an interest in electromagnetism and polarized light. These DIY adventures did more than develop his experimental skill, though that was important. They helped give him a deep feeling for nature's materials and processes that later pervaded his theoretical work. While in Edinburgh he produced two more papers for the Royal Society there. So, when he left for Cambridge at the age of nineteen, he had a solid body of knowledge, a handful of publications to his name, and some valuable and potentially influential friends in the world of academia and science.

He started at Peterhouse but found it dull and moved to Trinity, which was more congenial and much more mathematically minded (the master at the time being William Whewell). In Cambridge Maxwell joined the class of the famous (in mathematical circles) "senior wrangler maker," William Hopkins—wranglers being those who gained first-class degrees in the mathematical tripos, which all had to take. The reward for wranglers was lifelong recognition in whatever field they chose. The tripos was an arduous seven-day affair, six hours a day, and James came second, after E. J. Routh, who went on to be a remarkable mathematician, with a function named after him, the routhian. (P. G. Tait, Maxwell's erstwhile Edinburgh Academy friend, had been senior wrangler two years before.)[21]

With the tripos out of the way, Maxwell was now free to give rein to the ideas that had been brewing in his mind over his two stints as an undergraduate. There were two aspects of the physical world he wanted to explore. One was the process of vision, particularly the way we see colors, and the other was electricity and magnetism.

In his color research he had an early breakthrough, finding that there is a fundamental difference between mixing pigments, as one does with paints or dyes, and mixing lights, as one does when spinning a multicolored disc. Pigments act as extractors of color, so that the light you see after mixing two paints is whatever color the paints have failed to absorb. In other words, mixing pigments is a subtractive process, whereas mixing lights is additive—so that, for instance, blue and yellow do not make green, as they do with pigments, but *pink.* And by experiment he was able to show that there are, in light terms, three primary colors—red, blue, and green—and that it is possible to mix them in different proportions to obtain all the colors of the rainbow. This was a major advance and is the theory behind the colors in color television, for example.

At the same time, he was getting to grips with electricity and magnetism, and in 1855 the first of his three great papers appeared. Michael Faraday had thought of lines of force as discrete tentacles (analogous to the lines of iron filings that form around a magnet). Maxwell now conceived them as merged into one continuous essence, which he called “flux”—the higher the density of flux at any particular location, the stronger the electrical or magnetic force there. And he grasped moreover that the electric and magnetic forces between bodies vary inversely as the square of their distance apart—much as Newton had said of gravity.[22]

In this way, lines of force became the “field,” and *this* was the concept that set Maxwell apart and put him on a par with Newton and Einstein. More than that, he would build on it six years later with his concept of *electromagnetic waves.*

In between times, his father fell ill, and James was forced to spend time nursing him. But it wasn’t enough: he needed a post nearer home. This cropped up when he was offered the position as professor of natural philosophy at Marischal College in Aberdeen, one of the colleges that would, not much later, become Aberdeen University. The post buoyed both father and son, but it had its drawbacks. James later wrote to a friend, “No jokes of any kind are understood here. I have not made one for 2 months, and if I feel one coming on I shall bite my tongue.” But it wasn’t all hopeless, as James found the daughter of the college principal exactly to his taste, proposed, and was accepted.[23]

In June 1858 he and Katherine were married and then, a few months later, he read the paper by Clausius about the diffusion of gases. The problem, which several people had pointed out, was that, to explain the pressure of gases at normal temperatures, the molecules would have to move very fast—several hundred meters a second, as Joule had calculated. Why then do smells—of perfume, say—spread relatively slowly about a room? Clausius proposed that each molecule undergoes an enormous number of collisions, so that it is forever changing direction—to carry a smell across a room the molecule(s) would actually have to travel several kilometers.

Clausius had assumed that, at any given moment, all the molecules would travel at the same speed. He knew that couldn’t be the correct answer, but he couldn't think of anything better. Maxwell was also stymied at first, but then he had a brain wave. At a stroke, says Basil Mahon, it "opened the way to huge advances in our understanding of how the world works."

Maxwell saw that what was needed was a way of representing many motions in a single equation, a *statistical* law. He devised one that said nothing about individual molecules but accounted for the *proportion* that had the velocities within any given range. This was the first-ever statistical law in physics, and the distribution of velocities turned out to be bell-shaped, the familiar normal distribution of populations about a mean. But its shape varied with the temperature—the hotter the gas, the flatter the curve and the wider the bell.

This was a discovery of the first magnitude, which would in time lead to statistical mechanics, a proper understanding of thermodynamics, and to the use of probability distributions in quantum mechanics. This alone was enough to put Maxwell in the first rank of scientists. The Royal Society certainly thought so, awarding him the Rumford Medal, its highest award for physics. No less important in the long run, King's College London was looking for a professor of natural philosophy—James entered his name and was appointed. And he still had more than one breakthrough in him.

King's, in the Strand, just north of the Thames, had been founded in 1829 as an Anglican alternative to the nonsectarian University College, a mile further north, which was itself intended as an alternative to the strictly Church of England Oxbridge universities. Unlike the traditional courses, to be found at Aberdeen and Cambridge, King's' courses were much more modern.

Being in London meant that Maxwell could attend the meetings of the Royal Society, and the Royal Institution, where he was able to cement his friendship with Faraday. They had corresponded a great deal, but now at last met and struck up a genial friendship. And Maxwell homed in on his final great insight.

In his paper, "On Faraday's Lines of Force," he showed how he had found a way of representing the lines of force mathematically as continuous fields, and had made a start towards forming a set of equations governing the way electrical and magnetic fields interact with one another. But that was still only part of the picture. Picture is in fact the wrong word here, because it is at this point that physics began to enter a world where the familiar visual analogies break down. The image of a "field" is easy enough to imagine in itself, but what Maxwell was struggling to explain, in his equations, could only be explained with difficulty in ordinary language, and this came home to him—and then to everyone—in his 1862 paper, where he concluded, dramatically, and using the mathematics that he had himself created, that light is also a form of electromagnetic disturbance and, moreover, could be understood as both a wave and a beam of particles. This was unheard of, inexplicable when put into language, but made sense in mathematics.[24]

In fact, Maxwell derived four equations that between them "summed up everything that it is possible to say about classical electricity and magnetism." Which is why, among physicists, if not yet the general public, Maxwell is placed on a par with Newton. "Between them, Newton's laws and his theory of gravity and Maxwell's equations explained everything known to physics at the end of the 1860s." Maxwell's achievement was the greatest breakthrough since Newton's *Principia Mathematica* in 1687.[25]

As if all this were not enough, Maxwell's equations contained within them the implication that there must be other forms of electromagnetic waves with much longer wavelengths than those of visible light. Their discovery would not be long in coming.

The final chapter in Maxwell's extraordinary career arrived when he was invited to accept an important new professorship at Cambridge. The duke of Devonshire, who was chancellor of the University, had offered a large sum of money to build a new laboratory for teaching and research, which was to compete with the best of what then existed on the Continent, especially in Germany. Cambridge was being left behind in experimental at Graz before moving to Heidelberg and afterward Berlin, where he studied under Bunsen, Kirchhoff, and von Helmholtz. In 1869, at the age of twenty-five, he was appointed to the chair of theoretical physics in Graz. After that, Boltzmann had a very unsettled career—he changed professorships numerous times, more than once because he couldn't get on with colleagues. The constant arguments depressed Boltzmann and he attempted suicide for the first time.

Finally, in 1901, after all this chopping and changing, Boltzmann returned to Vienna to the chair he had vacated in one of his arguments with colleagues and which had not been filled in the meantime. In addition he was given a course to teach on the philosophy of science, which quickly became very popular, so much so that he was invited to the palace of Emperor Franz Joseph.

This was impressive, but Boltzmann's main achievement lay in two famous papers that described in mathematical terms the velocities, spatial distribution, and collision probabilities of molecules in a gas, all of which determined its temperature (heat and motion again). The mathematics were statistical, showing that—whatever the initial state of a gas—Maxwell's velocity distribution law would describe its equilibrium state. This became known as the Maxwell-Boltzmann distribution. Boltzmann also produced a statistical description of entropy.[29]

In 1904 Boltzmann went to the United States and visited the World's Fair at St. Louis, where he gave some lectures before going on to visit Berkeley and Stanford. While there he behaved oddly—people couldn't make out whether his elevated manner was an illness or pretentiousness. He returned home and went on vacation with his family to Duino, near Trieste. While his wife and daughter were swimming he hanged himself. No one can be certain whether his general instability was the cause of his suicide, or the continual attacks on his ideas. What is certain, unfortunately, is that he couldn't have been aware, at the time of his death, that his ideas would very soon receive experimental confirmation.

What is important about the work of Mayer, Joule, and von Helmholtz, and in particular Clausius, Maxwell, and Boltzmann, is that—whether one can follow the mathematics or not—they brought *probability* into physics. How can that be? Matter definitely exists, transformations (as when water freezes, say) obey invariant laws. What can probability have to do with it? This was the first appearance of “strangeness” in physics, heralding the increasingly weird twentieth-century quantum world. These early physicists also made “particles” (atoms, molecules, or something else, not yet clearly understood) integral to the behavior of substances.[30]

The understanding of thermodynamics was the high point of nineteenth-century physics, and of the early marriage between physics and mathematics, building richly on Mary Somerville’s previous ideas. It signaled an end to the strictly mechanical Newtonian view of nature. It would prove decisive in leading to a spectacular new form of energy: nuclear power. This all stemmed, ultimately, from the concept of the conservation of energy.

2

“A SINGLE STROKE UNIFIES LIFE, MEANING, PURPOSE, AND PHYSICAL LAW”

It may be difficult for us to understand now but, in the late eighteenth and early nineteenth centuries, when the philologists were attacking the very basics of Christianity—seeking to pillory the absurdities and inconsistencies of the Bible, for instance—the men of science did not for the most part join in. For the most part, biologists, chemists, and physiologists remained devoutly religious. That even applied, again for the most part, to the practitioners of the two sciences that were to produce the most convincing evidence that the biblical chronology had to be wrong: astronomy and geology.

Astronomy underwent its greatest change since Copernicus and Newton thanks to an unlikely couple who might never have achieved what they did had not the British powers that be decided to invite a German to be their king.

The way Richard Holmes tells the story, Joseph Banks—botanist and explorer, who accompanied James Cook on his first great voyage—shortly after he was elected president of the Royal Society in 1778, began to hear stories about a gifted amateur astronomer “working away on his own” in the West Country. This news reached Banks via the secretary to the Royal Society, Sir William Watson, whose son lived in Somerset and was a central member of the Bath Philosophical Society. According to these accounts, this maverick was a German who built his own (very powerful) telescopes and was making extravagant claims about the moon.

The man's name was Wilhelm, or William, Herschel. Though tall and well dressed, "and wearing his hair powdered," he spoke with a thick German accent (he was from Hanover) and had no manservant with him when Watson's son encountered him, in a cobbled backstreet of Bath, looking at the moon.[1] Watson's son had asked if he might look through the telescope, which he was smart enough to note was a reflecting instrument, not the usual refracting type used by amateurs. And he found that though the whole seven-feet-long contraption was evidently homemade, it nonetheless offered a better resolution than he had ever seen and he observed the moon more clearly than ever before.

Watson's son formed a friendship with Herschel, finding him to be in fact the organist at Bath's Octagon Chapel, who made ends meet by giving music lessons. He also composed, had a house full of astronomical and other books, and lived with his sister, who looked after him but whom he also described as his "astronomical assistant."

On the strength of this, Watson's son invited Herschel to join the Bath Philosophical Society, where he began sending papers. These were so unconventional, but so striking, that Watson sent them on to his father, and some of the more surprising were published in the Royal Society's *Philosophical Transactions.* The first of them, "Observations on the Mountains of the Moon," claimed that, with his homemade telescope, he had observed "forests" on the surface of the moon and concluded that it was, "in all probability," inhabited. This outraged the more established types in the Royal Society, some of whom decided to visit Herschel in Bath. Nothing much came out of this meeting, other than the fact that they were impressed by his telescopes and intrigued by his diminutive sister, Caroline, who seemed as mad about astronomy as he was.[2]

All that changed a year later when Herschel announced that he had discovered a new planet, something that hadn't happened since the days of Pythagoras. Moreover, Herschel's new planet had important implications for the nature of the solar system.

But first some background. Herschel had been born in Hanover on November 15, 1738, twelve years before his sister. They had been deeply attached since childhood and what we know about their life is drawn from the journal Caroline kept. William and Caroline's parents produced ten children—one every two years—of whom six survived.[3] William's father made him a tiny violin, which he learned to play as soon as he could hold it—this seems to be where he got his facility for working with wood, and making instruments. On winter nights, the children were taken outside to view the stars. In those days before widespread light pollution, the night skies were much more vivid than now.

But not everything was rosy. The eldest child in the family, Jacob, the apple of his mother's eye, soon became spoiled and a bully, who whipped Caroline and teased Wilhelm when he did well at school, as he often did. Jacob was a virtuoso musician and thought nothing else mattered in life. When he was fourteen, William joined the regimental band, alongside his father and brother, and learned in time to play the oboe, the violin, the harpsichord, the guitar, and, eventually, the organ.

In the spring of 1756, when William was seventeen and Caroline six, the Hanover Foot Guard was posted to England, to serve under their ally, the Hanoverian King George II. The three men of the family were stationed in Maidstone, Kent, returning home a year later. Richard Holmes tells us that Jacob took with him "a beautifully tailored English suit," while Wilhelm took a copy of John Locke's *An Essay Concerning Human Understanding.* But the family now became embroiled in the French-German wars, even to the extent of having French troops billeted in their home. Jacob and Wilhelm escaped, fleeing back to England, where they arrived together in London, penniless.

They obtained employment as musicians—playing or and had no trail. That could only mean a new "wanderer"—a new planet—and indeed that is what he had found, the seventh planet in the solar system, beyond Jupiter and Saturn: the first new planet to be discovered since the days of Ptolemy (c. AD 90–c. AD 168). Herschel at first named it for the Hanoverian king, "Georgium Sidus" (George's Star), but it eventually became known as Uranus, "Urania" being the goddess of astronomy.[8]

For some time, however, no one could agree on what, exactly, Herschel had found. He eventually communicated his observations to Watson, who conveyed them to the Royal Society, who asked Messier in Paris for an opinion. Given Herschel's earlier faux pas over life on the moon, not everyone was immediately convinced.

Nevil Maskelyne, the astronomer royal at the time, was in an especial quandary. There were dangers to his credibility in acceding too quickly to what Herschel was claiming. On the other hand, it had the potential to be a feather in the cap of British science (albeit one produced by a German), which otherwise the predatory French might appropriate for their own, by recognizing Herschel first (and maybe even naming the star). Moreover, Banks was pressing: the Royal Society needed to cement its relations with the new king, who was known to be keen on stars. Maskelyne observed the object himself, and confirmed its existence, though he refrained from saying at that moment whether it was a planet or a comet. Later he changed his mind, and opted to support Herschel. Messier agreed, writing from Paris that, having himself discovered no fewer than eighteen comets, Herschel's discovery resembled none of them. The result was that Herschel gave a paper before the Royal Society in late April. The paper, entitled "An Account of a Comet," said plainly that Herschel had discovered a new planet. He was elected a fellow of the Royal Society immediately.[9]

The Order of the Heavens

The discovery began a revolution in the popular conception of cosmology. Astronomers from all over Europe wrote to Herschel, asking for details of his equipment, though there were still skeptics in the Royal Society who doubted what they could actually achieve. One who wasn't skeptical was the king, George III, who was fascinated by the heavens himself, and invited Herschel to court at Windsor to congratulate him. When they met, in May 1782, with both Hanoverians speaking English, the encounter was a great success.

This rubbed off on Banks, ever mindful to promote the interests of science, and he now sought to obtain for Herschel a salary and a better place to live. The post of astronomer royal was filled, so Banks convinced the king to create a new position, the king's personal astronomer, on a salary of £200 per annum, with a house near Windsor, at Datchet, thrown in.[10] Caroline continued to keep her journal so that the chronology of their joint careers is well attested.

Between 1784 and 1785, Herschel began to draw together his new and very radical ideas about the cosmos, which were published in two "revolutionary papers" in the Royal Society's *Philosophical Transactions.* In "An Investigation of the Construction of the Heavens," published in June 1784, Herschel identified 466 new nebulae (four times the number identified by Messier) and for the first time raised the possibility that many of them, if not all, must be huge, independent star clusters or galaxies that were *outside* the Milky Way. This led him to propose that the Milky Way wasn't flat but three-dimensional, that we are in effect *inside* it, part of it, and that it is discus-shaped with arms extending out into deep space.

In his second paper, a year later, and headed "On the Construction of the Heavens," he began by saying that astronomy needed a "delicate balance" of observation and speculation if it were to proceed by induction—mere observation was not enough. And he went on to observe that the universe was not static, that the heavens far away were constantly changing, that all gaseous nebulae were "resolvable" into stars, and were in reality enormous star clusters far beyond the Milky Way. In so doing he immeasurably increased the size of the cosmos—by this time his nebulae count had risen to well over nine hundred, many of which, he insisted, were larger than the Milky Way.[11] And he estimated that deep space was "not less than 6 or 8 thousand times the distance of Sirius." He conceded that these were coarse estimates, and they are, certainly, much less than we now know, though thoroughly outlandish for their time.

In this paper, incidentally, he credited his sister with discovering one of the nebulae clusters. This mention, though brief, probably did wonders for Caroline's self-confidence, for she went on to make a name for herself as an astronomer in her own right, discovering no fewer than eight comets.

For his part, William also observed that the many nebulae he had identified varied in systematic ways—some were more "compressed" than others; others appeared to be "condensing." He advanced the idea that some nebulae were older than others, more *evolved*—that nebulae aged, matured, and climaxed. The fundamental force was gravity, gradually compressing nebulous gas into huge, bright galactic systems, which eventually condensed into individual stars.

It was in this paper that astronomy changed its character, fundamentally, from a mathematical science concerned primarily with navigation, to a cosmological science concerned with the evolution of stars and the origins of the universe.[12]

Although the implications of this were slow to be absorbed (perhaps because people didn't *want* to absorb them), one of the first to follow up Herschel's ideas was the French mathematician and astronomer (and, perhaps significantly, atheist) Pierre-Simon Laplace, who published a paper on "the nebular hypothesis" in 1796.

Laplace drew on Herschel's ideas and applied them to the formation of the solar system. He is sometimes known as the French Newton, being as much a mathematician as a physicist and astronomer. Many details of his early life went up in smoke, literally, when the family château burned down in 1925. But we know he was born in Beaumont-en-Auge, in Normandy, in 1749, into an agricultural background. We know too that Laplace was schooled in a Benedictine priory, his father intending him for the church, before he was sent to the University of Caen to read theology.

Laplace's adaptation of Herschel's ideas to the solar system was published in his *Exposition du système du monde* (1796) and the first volume of his classic *Mécanique céleste* (1799), in which he argued that the sun had slowly condensed out of a nebulous cloud of stardust and then spun off our entire planetary system, in exactly the same way as other planetary systems across the universe.* He also came close to predicting the existence of black holes when he pointed out that there could be massive stars in the universe where gravity was so great that not even light could escape from their surface. The significance of all this, of course, was as much theological as scientific. He was saying there had been no special Creation, that instead there had been a purely material origin of the earth with no divine intention needed, no Genesis. Nor was divine creation visible in any other part of the universe.

Herschel was made a baronet in May 1838, in time to attend Queen Victoria's coronation in Westminster Abbey, and was elected president of the Royal Society in the same year. By the 1850s he was the leading public scientist of Victorian England and was photographed by Julia Margaret Cameron, using a process that he himself had partly invented. But, without belittling all this in any way, his real achievement was to reveal the philosophical significance of astronomy. He calculated that the light rays that

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* It was this title that Mary Somerville wrote about in her first effort for the Society for the Dissemination of Useful Knowledge, and which John Murray eventually published (see the Introduction).

reached his telescopes from faraway nebulae must have been, in some cases, "two million years on their way."[13] In other words, the universe was almost unimaginably bigger and older than anyone had previously thought. Without Herschel, Charles Darwin would not have been plausible.

The First Geological Synthesis

Alongside cosmology another discipline matured that would put prehistory onto a different footing and further prepare the way for Darwin. Geology differed fundamentally from all the other sciences, and from philosophy. It was, as Charles Gillispie has said, the first science to be concerned with the history of nature rather than its order.

In the seventeenth century Descartes had been the first to link the new astronomy and the new physics to form a coherent view of the universe, in which even the sun—let alone the earth—was just another star. He speculated that the earth might have formed from a ball of cooling ash and become trapped in the sun's "vortex." The idea that physics operated on the same principles throughout the universe was a major change in thinking that could not have occurred to the medieval mind. The basic ideas of heaven and earth, as understood in the West at least, were Aristotelian and were held to be fundamentally different: one could not give rise to the other. Eventually, Descartes's physics were replaced by Newton's, and the "vortex" by gravity. In 1691 Thomas Burnet published his *Sacred Theory of the Earth*, in which he argued that various materials had coalesced to form the earth, with dense rock at the center, then less dense water, then a light crust, on which we live. A few years later, in 1696, William Whiston, Newton's successor at Cambridge, proposed that the earth could have been formed from the cloud of dust left by a comet, which coalesced to form a solid body, and was then deluged with water from a second passing comet. This idea, that the earth was once covered by a vast ocean, which then retreated, proved soon after, Hutton found he had fathered an illegitimate child, no small thing in Presbyterian Edinburgh. He fled Scotland, continuing his studies in Paris, Leiden, and London, and did not return to Edinburgh until 1767. But when he did go back, he returned to live in the family home with his three sisters.

And what a homecoming it was. The Edinburgh Enlightenment was in full flood and he quickly formed lasting friendships with Joseph Black, James Watt, and Adam Smith. Alongside the presence of three sisters, the Edinburgh house soon became Hutton’s laboratory as well as his home. One visitor wrote, “His study is so full of fossils and chemical apparatus of various kinds that there is barely room to sit down.”[18]

Fossils formed part of the picture for Hutton, but not the main part. He looked around him at the geological changes he could see occurring in his own day and adopted the view that these processes had always been going on. In this way he observed that the crust of the earth, its outermost, most accessible layer, is formed by two types of rock, one of igneous origin (formed by heat), and the other of aqueous origin. He further observed that the main igneous rocks (granite, porphyry, basalt) usually lie beneath the aqueous ones, except where subterranean upheavals have thrust the igneous rocks upward. He also observed what anyone else could see, that weathering and erosion are even today laying down a fine silt of sandstone, limestone, clay, and pebbles on the bed of the ocean near river estuaries. He then asked what could have transformed these silts into the solid rock that is everywhere about us. He concluded that it could only have been heat. Water was ruled out—an important breakthrough—because so many of these rocks are clearly insoluble. And so where did this heat come from? Hutton concluded that it came from inside the earth, and that it was expressed by volcanic action. This would explain the convoluted and angled strata that could be observed at many places all over the world. He pointed out that volcanic action was still occurring, and that the rivers—again as anyone could see—were still carrying silt to the sea.

Hutton first published his theories in the *Transactions* of the Royal Society of Edinburgh in 1788. (The Royal Society of Edinburgh was created in 1783 but grew out of the earlier Edinburgh Philosophical Society. It was and is more broadly based than the Royal Society in London, including literary figures and historians among its interests and fellows.) This first Hutton publication was followed by the two-volume *Theory of the Earth* in 1795, "the earliest treatise which can be considered a geological synthesis rather than an imaginative exercise."[19]

At the time Hutton's book appeared, the historical reality of the Flood was beyond question. Just as the Flood was undisputed, so the biblical narrative of the Creation of the world, as revealed in Genesis, was also beyond question. On this account, the length of time since Creation was still believed to be about six thousand years (based on the wording in Genesis that it took God six days to create the world and, elsewhere, that to God one day is like a thousand years). And though some people were beginning to wonder whether this was long enough, hardly anyone thought the earth *very* much older.

There was no question but that Hutton's Vulcanism fitted many of the facts better than Werner's Neptunism. Many critics resisted it, however, because Vulcanism implied vast tracts of geological time, "inconceivable ages that went far beyond what anyone had envisaged before." And so there were many eminent men of science in the early nineteenth century who, despite Hutton's theories, still subscribed to Neptunism: Sir Joseph Banks, Humphry Davy, not to mention Hutton's friend James Watt. Hutton's theory did not really begin to catch on—his books weren't very well written—until John Playfair published a popular version in 1802 (this was the same John Playfair who had tried to bring "the elementary truths of Natural Philosophy into a small compass"—see the Introduction).[20]

But Hutton (a deist) was not alone in believing that the observation of processes still going on would triumph. In 1815, William Smith, a canal builder often called the "father" of British geology, pointed out that similar forms of rock, scattered across the globe, contained similar fossils. Many of these species no longer existed. This, in itself, implied that species came into existence, flourished, and then became extinct, over the vast periods of time that it took the rocks to be laid down and harden. This was significant in two ways. In the first place, it supported the idea that successive layers of rock were not formed all at once, but over time. And second, it reinforced the notion that there had been separate and numerous creations and extinctions, quite at variance with what it said in the Bible.[21]

The Biological Order in the Rocks

Objections to the biblical account were growing. Nevertheless, it was still the case that hardly anyone at the beginning of the nineteenth century questioned the Flood. Peter Bowler says that at this time geological texts sometimes outsold popular novels, but that science "was respectable only so long as it did not appear to disturb religious and social conventions of the day." Neptunism did, however, receive a significant twist in 1811 when Georges Cuvier published his *Recherches sur les ossemens fossiles* ("Researches on Fossil Bones"). With his book going through four editions in ten years, Cuvier argued that there had been not one but several cataclysms—including floods—in the history of the earth. Looking about him, in the Huttonian manner, he concluded that, because entire mammoths and other sizeable vertebrates had been "encased whole" in the ice in mountain regions, these cataclysms must have been very sudden indeed. He also argued that if whole mountains had been lifted high above the seas, these cataclysms could only have been—by definition—unimaginably violent, so violent that entire species had been exterminated and, conceivably, earlier forms of humanity.[22]

Cuvier also observed, and this was important, that in the rocks the deeper the fossils, the more different they were from life forms in existence today and that, moreover, fossils occur in a