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ATOMS OF COGNITION: METAPHYSICS IN THE ROYAL SOCIETY, 1715–2010

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THE LOOSENING OF THE MOORINGS OF THOUGHT WHICH CAN BE SENSED IN THESE EARLY DAYS OF THE SOCIETY HELPED SUSTAIN SOME VAST INTELLECTUAL DISPUTES. AS NEAL STEPHENSON EXPLAINS, ONE OF THE SHARPEST, BETWEEN THE TWO GIANTS NEWTON AND LEIBNIZ, INVOLVED SOME VERY STRANGE METAPHYSICS – NEARLY AS STRANGE, IT TURNS OUT, AS TWENTY-FIRST-CENTURY PHYSICS.

> This philosophy is a gift of God to this old world, to serve as the only plank, as it were, which pious and prudent people may use to escape the shipwreck of atheism which now threatens us.
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> – Leibniz, in a 1669 letter to Thomasius

Isaac Newton was slow to join the Royal Society – in the Charter Book that lives in the Society's vault, his signature does not appear until the ninth page – but by the second decade of the eighteenth century he had become its President. His unquestioned status as the greatest mind of his generation, combined with his political connections as Master of the Mint and his ruthlessness toward those he perceived as rivals, had given him an unusual degree of power. This he brought to bear against the only living person who could even hope to challenge his intellectual supremacy: Gottfried Wilhelm Leibniz, who despite being a foreigner (he was Hanoverian) had been made a Fellow of the Royal Society in 1673, largely in recognition for his invention of the Stepped Reckoner, a mechanical computer.

The contrasts between Newton and Leibniz were lavish. Newton seems to have had an entirely accurate sense of just how he compared to his contemporaries, and acted accordingly without concern for dusty precedents or the personal feelings of those who clung to them. When confronted with anything less than uncritical acceptance of his work, he lashed out and then secluded himself. He published rarely but ex cathedra, handing down nearly flawless treatises over which he had toiled for years or decades, perfectly organised into definitions, axioms, lemmas and laws, framing a mathematical physics that could be used to explain past observations and to make verifiable predictions.

Isaac Newton's signature.

Is. Newton.

Leibniz was an accomplished courtier who maintained long friendships with the Electress of Hanover, the first Queen of Prussia, the sister-in-law of Louis XIV, and the future Queen Consort of England, while moonlighting, late in his career, for Peter the Great. He corresponded so heavily that scholars are still sorting through his unpublished papers. In his philosophy he practised an ecumenicism that in a lesser mind would strike us as suspicious or even craven. Leibniz seems never to have met a philosopher or a theologian he didn't like, and his metaphysics developed out of an effort to harmonise the ancient thinking of (both) Plato and Aristotle with tenets of

Christian and Jewish theology and with the 'mechanical philosophy' the Royal Society had been created to champion. It is impossible to know precisely what he was thinking without perusing his vast legacy of papers. In effect, Leibniz's philosophy ceased to exist at the moment he died. Since then, anyone who has wanted to know it has first had to reconstruct it, which is only possible for forensically inclined scholars, fluent in Latin, French and German, and well versed in the history of Western philosophy, Christian theology and Enlightenment science.

Given Leibniz's stature as one of the great thinkers of Western history, one might expect that, as of the 350th anniversary of the founding of the Royal Society, all of his writings would long since have been published, and that everything would be known about his philosophy. But the question of 'what did Leibniz believe, and when did he believe it?' is unsettled and is the topic of current research and debate.

A squalid row over the origins of the calculus, which these two men had independently invented decades earlier, became the public face of the conflict, which is regrettable since it is not very interesting and since it reflects dreadfully on the combatants. Much more significant in the long run was a debate on topics that reach so deeply into the foundations of science that they are still discussed in our times. This broke the surface in the last year of Leibniz's life, in an exchange of letters that has come to be known as the Leibniz–Clarke correspondence.

The year was 1715, and because of two royal deaths (in England, Queen Anne; in Hanover, Electress Sophie), Princess Caroline of Brandenburg-Ansbach had just become the Princess of Wales. To the modern reader, Caroline seems less like a real historical personage than a plucky, clever, independent-minded heroine from some post-feminist historical novel. A noble but poor orphan, raised as a ward of the Prussian court, she was conversant with scientific topics of the day, largely because she had been tutored in them by Leibniz. She had married into the Hanoverian dynasty and had moved with it to London, where her father-

Opposite:
Portrait of Gottfried Wilhelm Leibniz, by an unknown artist.

Opposite:
Portrait of Isaac Newton by Charles Jervas.

in-law had been crowned King George I. The sixty-nine-year-old Leibniz, who had become unfashionable and, because of the dispute over the calculus, something of a political problem, had been left behind in Germany. He wrote a short letter to Caroline, warning her that religion was declining in England; that John Locke did not believe in the immortality of the soul; and that Sir Isaac Newton held to some strange views about the relationship between God and the physical universe.

Anyone who has blithely forwarded a private email to a corporate mailing list, with incalculable consequences, will recognise what happened next: Caroline made Leibniz's letter known, and one Samuel Clarke stepped forward to rebut Leibniz's charges. The result was a series of letters (five each by Leibniz and Clarke) over the course of a year, at which point Leibniz died. Clarke, though he had serious credentials in his own right both as theologian and scientist, was acting as a spokesman for Newton, and so the correspondence can fairly be read as a debate between Leibniz and Newton.

In the opening round, the combatants practically trip over each other in their eagerness to remind the Princess that atheism is bad and that true natural philosophy in no way conflicts with religion. There is no reason to think that either of them is being disingenuous. The scientific revolution had created doubts about the existence of God, or at least the veracity of religious dogma, in the minds of many; but not Newton or Leibniz.

These concerns are dispensed with in a few paragraphs. The bulk of the correspondence, which runs to about eighty pages, resembles an email exchange that devolves, as it goes on, into several distinct threads, each concerning a specific sub-topic. The correspondents begin to number their paragraphs (Leibniz's fifth letter contains 130 of them), the better to keep track of all the rebuttals and counter-rebuttals. The over-arching theme is the relationship of God to the universe, and more specifically the universe as perceived, measured and understood by scientists. Leibniz, in the universal manner of authors promoting their latest work, finds frequent occasion to mention his books *Theodicy* and *Monadology*. Even when he isn't mentioning them by name, he is presenting arguments, and using terminology, derived from them.

My theme is the legacy of Leibniz's metaphysics from the time of his death down to the present day, and so a direct summary of that system, based on the scholarship of latter-day researchers, will do better service than any attempt to untangle the points and counter-points in the correspondence. The account presented below is patterned after the work of Christia Mercer of Columbia University. Her book *Leibniz's Metaphysics: Its Origins and Development*, published in 2001 by Cambridge University Press, is a formidable work of forensic scholarship that can in no way be improved by my attempts to summarise it.

In 1661, at the age of fourteen, Leibniz had formed a resolution to embrace the new mechanical philosophy. For most natural philosophers of the era, this meant rejecting the Aristotelian worldview of the medieval schoolmen. As mentioned, though, Leibniz was an ecumenicist and a conciliator, and so for him it meant, rather, the beginning of a lifelong quest to reconcile certain select, precisely defined tenets of Aristotelian and Platonic thought with modern science.

In his metaphysical reasoning, Leibniz is at least as meticulous as is Newton in his mathematical physics. Bertrand Russell called Leibniz's system 'profound, coherent, largely Spinozistic, and amazingly logical'. Newton, however, can verify his results by comparing them to observations, while Leibniz is beholden to no one except Leibniz. By pure thinking, Leibniz fabricated a metaphysical system that could hardly be more at odds with that of Newton, or indeed any other person who attempts to think in a commonsensical way about how the world might work.

Where Newton's work is grounded in Euclidean geometry, Leibniz begins with certain precepts that he takes to be axiomatic, such as the Principle of Sufficient Reason (nothing exists without a reason; there is no effect without a cause) and the Identity of Indiscernibles (two individual things cannot differ in number alone; it must be possible to explain why they are distinct based on some intrinsic difference). Newton developed calculus because it enabled him to solve problems in his theory of gravitation; Leibniz developed it as an outgrowth of his fascination with the problem of the Continuum, which asks how a line can be made up out of points, a span of time from instants, or a thought from the minute perceptions and endeavours of a mind. Just as Newton would not bother developing a physics that could not explain the fact that planets move in elliptical orbits, Leibniz had no time for any metaphysics that was incompatible with the transubstantiation of the Eucharist (both the Protestant and the Catholic versions!) and the incarnation of God in Christ. Much of the pick-and-shovel work of his *Monadology* came from a 1671 tract about the Incarnation of God.*

The modern reader, following the development of Leibniz's ideas over the years between 1661 and his death in 1716, veers between finding it all quite reasonable and feeling as though it must have come from an alien planet. Just when one is about to judge Leibniz as having the strangest mind of anyone who ever lived, one remembers Newton and his lifelong obsession with alchemy and his strenuous efforts to predict the exact date of the End Times by ransacking the Book of Revelation for encrypted clues.

It takes an entire book such as Mercer's to explain Leibniz's full chain of reasoning, so there is not room here to attempt any such thing. The end point – Leibniz's mature system, as described in *Monadology* – may be summarised as follows:

Matter, assumed by most to be the primary stuff of the universe, extended in space and time, is, in fact, unreal. Atomism in its conventional form – the idea that physical objects can be divided and subdivided up to a certain point, but (for some, usually unspecified, reason) no further, and that the result is a collection of tiny indivisible matter-bits moving around in empty space and banging into one another – is all wrong. The true atoms – the fundamental, indivisible units that make up the universe

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* This perennial theological chestnut seems to have occasioned some soul-searching for Newton as well, since he risked serious trouble by semi-openly espousing the Arian heresy, which denies the Trinity.

– are not spatiotemporal and so are not bound by spatial and temporal constraints; rather, space and time are epiphenomena of their activities, which are mental (today we might say computational) rather than physical. Leibniz calls these mind-atoms by the name of monads.

Use of 'mind' and 'mental' is apt to give modern readers the wrong idea. Many translators of Leibniz (including Russell) choose the word 'soul' instead of 'mind', which is even more confusing. A word about those words is, therefore, in order. Extension (occupying physical space) and duration (persisting through time) are obvious properties of matter that had long been of interest to natural philosophers. Beginning around 1671, Leibniz added a third element, namely *cognitio*, which can be translated as 'thought' or 'knowledge'. In his metaphysics, *cognitio* is a property that things can possess and that makes them different from inert matter. Early in his career, it is as fundamental as extension. Later, it becomes more so. Previously, he had admitted God and the human mind as the only two incorporeal principles in his system; the key move he now made was to admit the possibility of cogitating entities ('minds' or 'souls') that were neither divine nor human, and to make them and 'endeavour' – the smallest possible unit of cogitation, which is to *cognitio* as a point is to a line or an instant is to time – as fundamental as space and time. Later, he goes on to deny the primary reality of space and time altogether and to assert that the created world consists entirely of these unextended monads and that the universe is created from moment to moment as a result of their cognition. In this he breaks from the metaphysics assumed by Newton (and almost anyone else who has thought in a commonsensical way about space, time and atoms) in which space and time have an absolute reality, and form a sort of lattice on which the laws of physics are enacted, and, indeed, without which they cannot even be written down.

Because the monads do not exist in space and time, they are free to take on certain powers and properties that would otherwise be implausible: (1) each monad perceives the state of every other monad in the universe, and

(2) each exists in a certain state, and is capable of changing that state. This process of continual internal state-change is the cogitation that is the raison d'être of the monad and the fundamental process of the universe.

Internal and intrinsic to each monad is a rule (dubbed by Mercer the Production Rule) that governs how it changes its state in response to its current state and the perceived state of all of the other monads. And just as the constraints of space and time are inapplicable to monads, so cause and effect work differently, for each monad is causally independent of all other monads. It makes its own decisions by its own lights, obeying its intrinsic rule.

This raises the obvious objection that if the states of the other monads serve as inputs to the production rule, then there would seem to be a cause-and-effect relationship at work, but Leibniz doggedly maintains that no such relationship exists and that coordination among monads comes about, not through causal linkages, but as the result of a divinely ordained pre-established harmony that brings all of the monads into a kind of synchronisation without encroaching on their independence. For minds and cogitation are, to Leibniz, the ultimate reality, and unless the minds have free will, they are not minds at all but physical mechanisms numbly obeying deterministic rules.

This is the one feature of the Monadology that might (I speculate) have aroused some competitive anxiety in Newton's mind. The Leibniz–Clarke correspondence probably would not have drawn the attention of so many important people were it not that traditional (spatiotemporal) atomism, combined with the then-new science of mathematical physics, seems to lead ineluctably to what was later called Laplacian determinism. If the behaviour of all objects can be explained in terms of spatiotemporal atoms, and if the atoms' behaviour, in turn, is subject to Newton's deterministic mathematical laws, then there is no room for free will. Humans are robots and religion is a fraud.

Newton was aware of this problem. He had no intention of promulgating a philosophy that stripped humans of free will. He seems to have got around it by positing supernatural intervention, i.e., by recourse to entities and powers that lay outside the system described by his science. Leibniz's approach, bizarre as it might be in many respects, was, in a sense, more scientific; free will was no longer a problem that needed to be explained away, but an intrinsic feature of every monad.

Monadology spent the next two centuries on the ash-heap of intellectual history. After Leibniz's death, a faulty version was published by one of his disciples, and its errors laid at Leibniz's feet. Then it swam into the gunsights of Immanuel Kant. In his *Critique of Pure Reason,* Kant begins by saying a few complimentary things about Leibniz. Three hundred pages later, having carefully set his pieces out on the board, he annihilates Leibniz's metaphysics in a few sentences. According to Kant's philosophy, Leibniz is correct in thinking that space and time, cause and effect, are not ultimate realities, but rather constructs of mental activity. But by the same token, Kant says, the human mind is powerless to think in any useful or productive way about anything that is outside space and time, cause and effect, and so Leibniz's entire Monadology – or any thinking that attempts to transcend spatiotemporality – is rubbish.

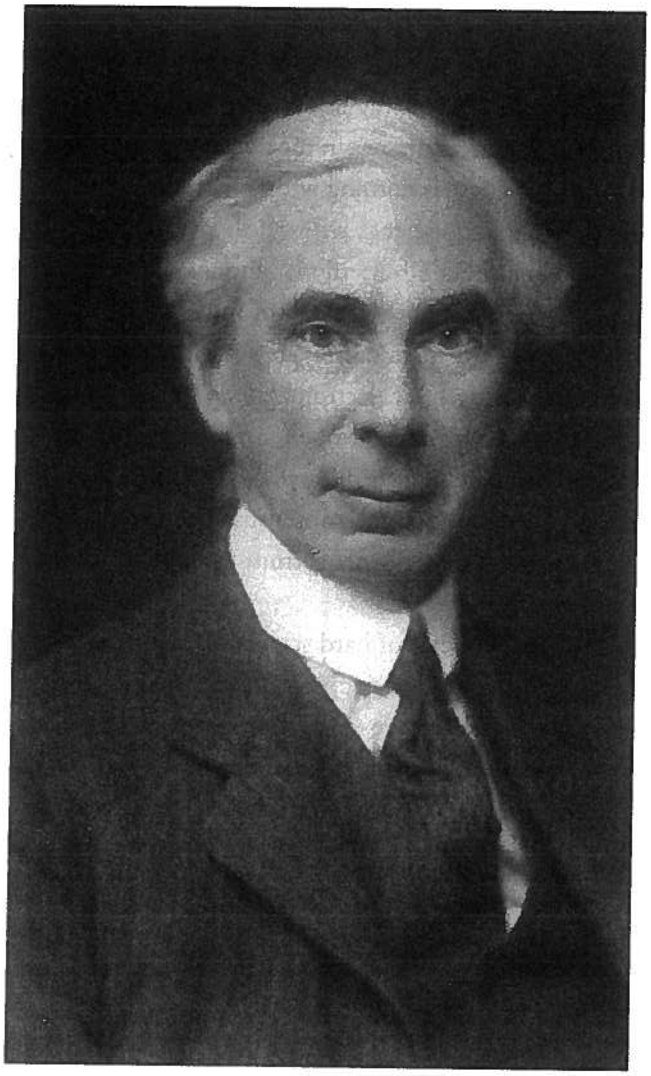
In the day of Newton and Leibniz, metaphysics had been as respectable as mathematics, but the hard-headed empiricists of the scientific world began to kick dirt on it during the nineteenth century and, in the first half of the twentieth, the logical positivists buried it. And indeed, Leibniz's work seems unsound at best, ludicrous at worst, by the scientific standards of the era before relativity, quantum mechanics and Gödel's proof.

Today, metaphysics in general has regained much of its former respectability among philosophers. For almost everyone else, though, it retains the connotations of woolliness that it picked up during that century or so of rough treatment at the hands of empiricists and positivists. Many hard scientists still use 'metaphysics' as a byword for undisciplined, conjectural thinking. Nevertheless, metaphysics is still being practised today: by philosophers openly, by physicists under other names.

A straightforward way of defining metaphysics is as the set of assumptions and practices present in the scientist's mind before he or she begins to do science. There is nothing wrong with making such assumptions, as it is not possible to do science without them. The lepidopterist who records in her notebook that a butterfly is blue may not stop to consider that this is true only because the giant ball of nuclear fuel ninety-three million miles away happens to maintain a surface temperature just right for shedding certain wavelengths of electromagnetic radiation on the Earth; that the eyes of humans have evolved to be sensitive to those wavelengths; that the eye can discriminate slightly different wavelengths as colours; that one of those colours has, by cultural consensus, been defined as 'blue', and so on. Nevertheless, science benefits from the lepidopterist's note that the butterfly is blue.

Even the hardest of hard sciences is replete with assumptions that may fairly be classified as metaphysical. Almost all mathematicians, for example, presume that they are discovering, rather than creating, mathematical truths. Ask a roomful of mathematicians whether three was a prime number a billion years ago (i.e. before there were humans to define it as such) and every hand will go up. And yet to say so is to espouse the metaphysical position that primeness and all the other subject matter of mathematics have a reality independent of the human mind. This assumption goes under various names, one of which is Mathematical Platonism. Likewise, physicists can hardly go about their work without assuming that the physical world answers to laws that may be expressed and proved mathematically – an assumption for which there is plenty of empirical evidence, dating back (at least) to Galileo, but no proof as such.

The revival of Leibniz's fortunes may be dated to approximately 1900, when Bertrand Russell began to publish his studies of Leibniz's unpublished work. While unsparing in his criticisms of Leibniz's character and of his more popular writings, Russell had a high opinion of Leibniz's work on mathematical logic and was fascinated by some of the ramifications of the



Bertrand Russell.

Monadology. In his *History of Western Philosophy* (1945) he ends his chapter on Leibniz as follows: 'What I ... think best in his theory of monads is his two kinds of space, one subjective, in the perceptions of each monad, and one objective, consisting of the assemblage of points of view of the various monads. This, I believe, is still useful in relating perception to physics.'

Leibniz then came to the attention of a wide range of thinkers. To tell the story in chronological order, including all of the requisite details about those who have knowingly or unknowingly echoed Leibniz's views, would require a substantial book in itself, of which the following might serve as a brief sketch or outline.

1. The debate on free will vs. determinism is no more settled today than it was at the time of the Leibniz–Clarke correspondence, and so in that sense (at least) Monadology is still interesting as a gambit, which different observers might see as heroic, ingenious, or desperate, to cut that Gordian knot by making free minds or souls into the fundamental components of the universe.

2. Leibniz's interpreters made use of the vocabulary at their disposal to translate his terminology into words such as 'mind', 'soul', 'cognition', 'endeavour', etc. This, however, was before the era of information theory, Turing machines and digital computers, which have supplied us with a new set of concepts, a lexicon, and a rigorous science pertaining to things that, like monads, perform a sort of cogitation but are neither divine nor human. A translator of Leibniz's work, beginning in AD 2010 from a blank sheet of paper, would, I submit, be more likely to use words like 'computer' and 'computation' than 'soul' and 'cognition'. During Leibniz's era, the only person who had thought seriously about such machines was Leibniz himself; building on earlier work by Blaise Pascal, he designed, and caused to be built, a mechanical computer, and envisioned coupling it to a formal logical system called the *Characteristica Universalis*. He invented binary arithmetic, and, according to no less an authority than Norbert Wiener, pioneered the idea of feedback.

3. In particular, the monads' production rule scheme clearly presages the modern concept of cellular automata. Quoting from Mercer's work:

> The Production Rule of F is a rule for the continuous production of the discrete states of F so that it instructs F about exactly what to think at every moment of F's existence. Following Leibniz's suggestion, if F exists from t_1 to t_n and has a different thought at each moment of its existence, then at every moment, there will be an instruction about what to think next. The present thought occurring at t_1, together with the Production Rule, will determine what F will think at t_2.

Combined with the monadic property of being able to perceive the states of all other monads, this comes close to being a mathematically formal definition of cellular automata, a branch of mathematics generally agreed to have been invented by Stanislaw Ulam and John von Neumann during the 1940s as an outgrowth of work at Los Alamos. The impressive capabilities of such systems have, in subsequent decades, drawn the attention of many luminaries from the worlds of mathematics and physics, some of whom have proposed that the physical universe might, in fact, consist of cellular automata carrying out a calculation – a hypothesis known as Digital Physics, or It from Bit.

4. Leibniz insisted that each monad perceived the states of all of the others, a premise that runs counter to intuition, given that this would seem to require that an infinite amount of information be transmitted to and stored in each monad. Of all the claims of Monadology, this must have seemed the easiest to refute a hundred years ago. Since then, however, it has been given a new lease on life by quantum mechanics. Consider, for example, the Pauli exclusion principle, which states (for example) that in a helium atom with two electrons in the same orbital, the two must have opposite spins. It is not possible for both of them to possess exactly the same state. Each of the two electrons somehow 'knows' the direction of the other's spin and 'obeys' the rule that its spin must be different. The Pauli exclusion principle is Leibniz's identity of indiscernibles principle translated directly

into physics. Moreover, the ability of an electron to 'know' the state of another electron, without any physical explanation as to how this information is transmitted and stored, is strongly reminiscent of Monadology. Elementary descriptions of quantum mechanics tend to limit themselves to extremely simple systems, such as individual particles or atoms, since beyond there the mathematics becomes intractable. But the same principles apply, albeit in vastly more complex form, in larger systems: the quantum state of each particle is dependent upon the states of all the other particles in the system.

5. Leibniz's notion that the ultimate entities in the universe were non-spatiotemporal received a kind of weak boost from general relativity, which called into question the idea of absolute space and time as a fixed lattice on which the laws of physics were enacted. More recently, absolute space and time have come under more concerted attack as some physicists have sought to develop so-called background-independent theories. The idea of background independence is explained in more detail in Lee Smolin's *The Trouble with Physics*, and the history of the concept of absolute space and time, from the Babylonians forwards, is told by Julian Barbour in his magisterial *The Discovery of Dynamics*. That space and time have an absolute reality, and that the laws of physics must be hung on a fixed spatiotemporal lattice, are metaphysical assumptions. Very reasonable, empirically grounded assumptions to be sure, but assumptions nonetheless. Resulting theories are called background-dependent. Various efforts have been made to derive background-independent theories that make no assumptions as to the fundamental reality of space and time. Barbour in particular has done seminal work along these lines, showing that general relativity is a realisation of a relational, i.e. Leibnizian, view of space and time. More recently, other researchers, notably Smolin, have sought to unify Barbour's formulation of general relativity with quantum mechanics, the aim being to develop a background-independent theory of quantum gravity according to which space

and time are emergent properties resulting from interactions of more fundamental entities joined together in a graph of connections. This theory, which is called loop quantum gravity, is proposed as an alternative to string theory, which is background-dependent.

6. The Leibnizian concept of pre-established harmony was viciously mocked by Voltaire in *Candide*, and has become no easier for sophisticated people to accept since then. Stripped of its theological overtones and saccharine connotations, though, the concept has a reasonably clear analogue in modern physics.

> a) Newtonian mechanics exactly describes the behaviour of individual bodies (provided, as Einstein later discovered, that they are reasonably large and slow-moving). Its laws are expressed in terms of individual particles: a particle moves in a straight line unless acted upon by a force. The force acting on a particle is equal to the product of its mass and acceleration (F = ma). As any first-year physics student learns the hard way, naïvely using the F = ma approach to describe systems comprising many independent parts soon becomes mathematically intractable.
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> b) Leibniz is credited with having written down the law now known as conservation of energy (which he denoted *vis viva*). In any system of particles, the product of the mass and the square of the velocity of each particle, summed over all of the particles in the system, remains constant. When this, and the law of conservation of momentum, are imposed as constraints on a system, the mathematics frequently gets easier, to the point where it becomes possible to produce results not obtainable otherwise. Conservation of energy does not contradict Newton's laws, and, in fact, is derivable from them, and so from a strictly mathematical point of view it adds nothing to Newtonian physics. It does, however, introduce a different way of thinking about

physical systems. The naïve reductionist strategy of the first-year physics student gives way to a global approach in which the system as a whole must obey certain rules, to which the detailed movements and interactions of its components are seen as subordinate.

c) The physicists of the late eighteenth and early nineteenth century developed new tools based on the notion of state or configuration spaces framed not of spatial dimensions but of all the generalised coordinates and momenta needed to specify the state of the system. Any possible state can be represented as a point in that space, and its evolution over time as a trajectory. The behaviour of such trajectories is governed by an 'action principle' that encodes all of the applicable physical laws, such as conservation of momentum and of energy. Action principles in classical state space are a mathematical reformulation of Newton's laws, not an alternative to them. The change in point of view from physical trajectories in Cartesian space to action in state space is nonetheless significant. It is a further step away from the reductionist and toward the global approach. It seems to inject a teleological aspect that is not present in the older formulation, and so has occasioned some introspection among philosophically inclined scientists. In his *Lectures on Physics*, Richard Feynman interpolated a single, anomalous chapter on the topic, simply because of his abiding fascination with it. It allows the physicist to predict the behaviour of a complex system without having to work out the detailed interactions among its physical atoms. It leads to important results from thermodynamics and it is directly applicable to quantum mechanics. It is a way of thinking, systematically and rigorously, about compossibility, a concept important to Leibniz. Many possible states of affairs might exist or, to put it another way, there are an infinite number of possible worlds. But not all states of affairs are *compossible*; some are mutually contradictory, and while it is possible to imagine a universe in which contradictory states of affairs coexist, it is not possible for such a universe to come into practical being. The configuration space that describes the universe contains an infinity of points, each of which represents a different state of affairs, but most of these are incoherent. Only certain points – certain universes – make sense internally, and those points lie on trajectories that describe the logical evolution, according to physical law, of those universes over time. If one adopts this frame of reference for considering Leibniz's concept of the pre-established harmony, and excludes (or at least adopts an agnostic stance toward) the notion that it was all set up at the beginning by God, it is easier to come to grips with Leibniz's idea that the monads act in a coherent way somehow transcending detailed cause-and-effect interactions.

d) That much is true of classical (i.e. pre-quantum) state space theory, even though it adds nothing beyond Newton's original laws. The quantum version of the theory, on the other hand, requires that actions over all possible worlds be brought together in a calculation yielding the probability that any one state of affairs will eventuate. As Feynman puts it, 'It isn't that a particle takes the path of least action but that it smells all the paths in the neighbourhood and chooses the one that has the least action …' The picture is reminiscent of Leibniz's 'best of all possible worlds'.

7. Possible-world theory has come in for serious study in recent decades both by philosophers and physicists. For impressively technical reasons that are likely to leave lay readers nonplussed, David Lewis (*Plurality of Worlds*) posited that all possible worlds really exist and are no less real than the one we live in. Such notions are the subject of current philosophical research, under the rubrics of modal realism and actualist realism. Among physicists, Hugh Everett launched the many-worlds interpretation of quantum

mechanics in the late 1950s, since which time it has slowly but steadily garnered support. A particularly eloquent latter-day treatment can be found in David Deutsch's *The Fabric of Reality*.

8. Kurt Gödel (1906–1978) who early in his life became known as 'the greatest logician since Aristotle' because of his astonishingly original work on the foundations of mathematics, devoted much of the second half of his life to the development of a rigorous metaphysical system that was to be based upon the work of Leibniz, with whom he had a fascination that became notorious.

Kurt Gödel.

Gödel was a strong mathematical Platonist who thought in a serious way about the notion that the entities that are the subject matter of mathematics really exist, though not in our physical universe, and that when we do mathematics we in some sense perceive those entities. An almost painfully meticulous scholar, he was well aware of Kant's objections to Leibniz's metaphysics, and understood that those objections would have to be dealt with in order for him to make any progress. According to his friend and biographer Hao Wang, Gödel discovered the works of Edmund Husserl (1859–1938) in the late 1950s and devoted much of the remainder of his life to studying them. He felt that Husserl had solved many, if not all, of the metaphysical problems that Gödel had set for himself, including doing away with Kant's objections to Leibniz's work. Husserl is prolix, prolific and infamously difficult to read (even Gödel complained of this) and so a reader of sub-Gödel IQ, eyeing a heap of Husserl translations on a table, might despair of ever putting his finger on the passages that Gödel is thinking of. Fortunately, Hao Wang did us the favour of listing the specific Husserl books that Gödel most admired. One of them is *Cartesian Meditations*, based on a series of lectures that Husserl delivered late in his career. In the fifth and last of these, Husserl gets around to mentioning, in an approving way, Leibniz and monads. Husserl has come round to Leibniz's way of thinking, but he has got there by taking a different route, pioneered by Husserl, through phenomenology – the premises and development of which I'll spare the reader. Since Gödel's death, mathematical Platonism has come in for serious study both by philosophers such as Edward N. Zalta, a metaphysician at Stanford University, and scientists such as Max Tegmark, an MIT cosmologist. Zalta and Tegmark (like Deutsch) have been influenced by David Lewis' work on modal realism. Beginning from different premises, they have arrived at markedly similar approaches.

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None of these latter-day echoes of Leibnizian thinking has generated traceable, exact results in the same way that, for example, Newtonian mechanics was able to predict the orbit of the Moon. If such a thing happens in the future – if, for example, the practitioners of loop quantum gravity use their theory to make predictions that are verified by experiment – then credit will have to go to them and not to Leibniz, who could never have imagined such a science. It's not the point of this chapter, in other words, to argue that Leibniz was right, much less that Newton was wrong. Leibniz was not even doing science as we now define the term. My conclusions are two. First of all, that the infamous duel between Newton and Leibniz – which was only superficially about who had invented the calculus – came back from the dead a hundred years ago to exert remarkable influence over the course of modern science. Secondly, that Leibniz's most fundamental assumption, namely that the universe makes sense and that the human has the power to make sense of it and that, consequently, pure metaphysics is no waste of time, remains perhaps the central question of all science. In 1960, Eugene Wigner wrote a paper, *The Unreasonable Effectiveness of Mathematics in the Physical Sciences*, in which he addressed the nearly miraculous way in which pure mathematics – seemingly a product of human cognition, and nothing else – predicts the behaviour of the physical world. The examples cited by Wigner would have made sense to Leibniz. Leibniz, however, would have been baffled by Wigner's use of the adjective 'unreasonable' in the title of his paper. Wigner was a modern: a product of a sceptical age. He was uneasy (or felt obliged to pretend to be uneasy) with the philosophical implications of the way in which the physical world answered to mathematics. This unease could not have been more alien to Leibniz, who, during his long philosophical career, questioned many things that would have been easier to leave alone, but believed, with a kind of medieval serenity, in the reasonableness of Creation.