CHAOS BEYOND ORDER:

OVERCOMING THE QUEST FOR CERTAINTY AND CONSERVATION IN MODERN WESTERN SCIENCES

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ABSTRACT: Chaos theory not only stretched the concept of chaos well beyond its traditional semantic boundaries, but it also challenged fundamental tenets of physics and science in general. Hence, its present and potential impact on the Western worldview cannot be underestimated. I will illustrate the relevance of chaos theory in regard to modern Western thought by tracing the concept of order, which modern thinkers emphasised as chaos' dichotomic counterpart. In particular, I will underline how the concern of seventeenth-century natural philosophers with order and conservation oriented the production of their concept of nature. Moreover, I will match this resulting world of natural facts with both the classical construction of the *cosmos*, and the nineteenth-century physico-chemical structure of conservation laws. Furthermore, I will recall the challenges to the deterministic and determinable modern scientific framework. These challenges arose from within the hard sciences, and they were often understood as a temporary lack of knowledge. I will argue that scientists long failed to acknowledge results that were at odds with their expectations, which were deeply engrained in modern Western thought, and which even harked back to the classical theoretical framework. Finally, I will suggest a link between the cultural earthquake that shook Western societies during the 'long sixties,' and the questioning of scientific expectations, which chaos theory defied.

KEYWORDS: Chaos Theory; Conservation Laws; Poincaré; Order; Modern Western Sciences; Long Sixties; Toulmin

INTRODUCTION

The aim of this paper is to emphasise the originality of chaos theory as compared with the whole modern scientific tradition. To this end, I will not simply summarize scientific theories, but I will trace their development in time. Hence, my construction will not follow the synchronic model of scientific textbooks. And yet, I will not repeat the teleological formulation of many a text of history of science. On the contrary, I will construct a brief genealogical account of modern scientific thought, in order to show that some of the fundamental features of modern scientific discourse are no longer compatible with its more recent developments. In particular, I will depict modern sciences as developing from a more general Western conceptual matrix, which they continued both to reconfirm and to reconfigure. My narration will repeatedly step back in time to underline such a double relation with the past. Therefore, my narrative line will proceed through loops that will take it back to the past, from where it will begin following another historical thread. Given the linearity of writing, this narrative technique is an attempt to provide a more articulated account of the complexity of historical transformations. In particular, this paper is structured around two major loops, the first ending at the threshold of the formulation of chaos theory, and the second following again the path of Western scientific knowledge until contemporary times.

THE QUEST FOR CERTAIN KNOWLEDGE IN THE MODERN WESTERN WORLD

The modern Western framework was constructed as a theoretical answer to a demand for certain and universal knowledge.[1] Since Descartes, this answer took the shape of a natural order of things, whose objective structure had to be revealed by discarding local, oral, particular and time-bound knowledge.[2] Actually, also in classical times Western philosophers generally affirmed the priority of universal and immutable knowledge.[3] Moreover, later on Christian thinkers restated such a priority in theological terms. In particular, since the twelfth-century renaissance the new theological and juridical rationalism even emphasised the derivation of knowledge from universal truths.[4] However, writers from the emerging European urban civilization also struggled to work out a self-centred and autonomous culture, which was increasingly engaged with specificity and change as proper objects of knowledge. This engagement abruptly narrowed down to factual analysis in the wake of the religious wars that followed the Reformation. Between 1590 and 1640, Western thought was dramatically reoriented by a quest for certainty, which became the touchstone for the new natural philosophy.

The founders of modern science reacted to the clash of Christianities, which opposed irreconcilable theological certainties, by building another absolute certainty,

[1] Stephen Toulmin, *Cosmopolis: The Hidden Agenda of Modernity*, Chicago, University of Chicago Press, 1990.
[2] René Descartes, *Descartes: Selected Philosophical Writings*, trans. John Cottingham, Dugald Murdoch and Robert Stoothoff, Cambridge, Cambridge University Press, 1988.
[3] John Dewey, *The later works 1925-1953, vol.4: The Quest for Certainty*, Carbondale, Southern Illinois University Press, 1988.
[4] Harold Berman, *The Formation of Western Legal Tradition*, Cambridge, Harvard University Press, 1983.

which was the objective natural world.[5] In other terms, as the religious wars crushed the belief in the same one god, natural philosophers appealed to the supposed objective commonality of god's product, i.e. nature. The order of nature, which was supposed to mirror the perfection of its maker, in turn would have guaranteed the political order that, after the horrors of the civil wars, natural philosophers praised more than civil liberties and personal freedom. Moreover, Galileo restated that the natural order relied on mathematical language, which after Descartes became both the main example and the model for certain knowledge.[6]

A MODEL FOR MODERN SCIENCE: THE SEVENTEENTH-CENTURY FASCINATION WITH GEOMETRY[7]

The concept of order as opposed to chaos was a common feature of seventeenth-century epistemic oriented writings. Whilst it was given the shape of a system in taxonomical researches, it was intended as ordered procedures in heuristic oriented ones. In particular, the Cartesian method was both a set of general procedures to be applied and a project for devising a systematic order of nature yet to be revealed. Within this project, the explanatory power of mathematics was less important than the compelling power of mathematical rules. This power was acknowledged also by Roman Inquisitors, who condemned Galileo's ideas as an explanation of planetary motion, but did not attempt to refute them as mathematical theories, whose soundness they understood and recognised.

This acknowledgement should not be surprising, because the *Elements* of Euclid were studied in European universities since the twelfth century. In particular, Euclidean geometry was one of the four subjects of the *quadrivium*, a course that was considered preparatory work for the study of philosophy and theology. Moreover, the *Elements* were one of the first books to go to press, and since 1482 printed copies of the treatise spread over Europe. The fortuitous reading of one of these copies caused Hobbes to fall in love with geometry.[8] Hobbes learned from the *Elements* to deduce a not obvious proposition by following a series of precise steps. These steps were linked by geometrical procedures that appeared to be incontrovertible. Also other readers of the *Elements* such as Descartes, Pascal, Leibniz and Spinoza felt compelled to accept Euclid's demonstrations. Moreover, because they supposed that everyone else would

[5] Toulmin, *Cosmopolis*.

[6] Galileo Galilei, *Il Saggiatore*, Torino, Einaudi, 1977.

[7] 'which is the onely Science that it hath pleased God hitherto to bestow on mankind', in Thomas Hobbes, *Leviathan*, Cambridge, Cambridge University Press, 1904, p.17.

[8] John Aubrey, 'A Brief Life of Thomas Hobbes, 1588-1679', in O. L. Dick ed., *Aubrey's Brief Lives*, London, Secker and Warburg, 1949, pp. 147-159.

have submitted to this compulsion, they felt they found in mathematics the royal road to unanimous and indisputable knowledge.

Thanks to their apparent indisputability, geometric and algebraic procedures became the viable answer to seventeenth-century natural philosophers' quest for certainty.[9] The concern of natural philosophers with founding knowledge on a sure ground followed a track already beaten by Plato, who deemed the mastery of geometrical reasoning as necessary to obtain philosophical knowledge. Nevertheless, despite Plato's interest in geometry, in the Greek world mathematics never attained a status of general model for knowledge. Only in seventeenth-century Europe, the fascination with the compelling power of mathematical reasoning gave rise to what we now call modern science.

A RENEWED UNIVERSAL: THE NATURAL ORDER OF THINGS

Seventeenth-century natural philosophers held mathematics as the language of nature. In their view, geometric, arithmetic and algebraic objects and procedures were not conventions. On the contrary, they considered the certainty of the results obtained by mathematical operations as mirroring the certainty of the divine order. With few notable exceptions, the founders of modern science never questioned the divine origin of the natural order, which was a legitimate heir of 'the medieval insistence on the rationality of God, conceived as with the personal energy of Jehovah and with the rationality of a Greek philosopher.'[10] In other terms, seventeenth-century natural philosophers' faith in the order of nature was a derivative of medieval theology. In particular, it answered to natural philosophers' demand for certain knowledge, which in the wake of the clash of Christianities was for them an absolute theoretical priority. The natural world appeared to natural philosophers as the objective and universal expression of the divine order, which conflicting theologies could no longer univocally represent.

For natural philosophers nature was the *opus* of god. Hence nature, as the product of a perfect maker, must have been perfectly ordered. The objective and univocal order of nature could in turn warrant the possibility of human communication and reciprocal understanding, which religious conflicts had severely undermined. In this perspective, the study of nature was conceived as the process of theoretical reconstruction of the pre-existing order of things. Therefore, though the new sciences were challenging several tenets of Greek-inspired medieval thought, they reaffirmed

[9] Dewey, *The Quest for Certainty*.
[10] Alfred North Whitehead, *Science and the Modern World*, Cambridge, Cambridge University Press, 1953, p.15.

the Greek presumption of a well-ordered *cosmos*. And yet, in the Greek world the cosmic order was both factual and ethical, so that human knowledge could not be pursued without limits. Moreover, though the Christian eschatological perspective broke the Greek cyclic order, it even emphasised the Greek ethical overtone. On the contrary, seventeenth-century natural philosophers built the natural order on the pretension to separate facts from values. In particular, they stressed the indisputability of mathematical procedures as an example and a model of immediate evidence, which demanded immediate consensus regardless of values and opinions.

CRACKS IN THE MODERN DREAM: THE UNEXPECTED MULTIPLICITY OF THE NEW MATHEMATICS

The seventeenth-century mathematization of nature was a unique blend of different cultural strains, whose combination was shaped by the contemporary demand for certainty. The success of physico-mathematical models in representing physical objects gave then further momentum to the mathematizing approach to knowledge, so that physics became the paradigm of science until the late twentieth century. In the meantime, it underwent several transformations.

At the end of the eighteenth century, the divine maker began to evacuate physical theory, as witnessed by its definition as an 'unnecessary hypothesis' attributed to Laplace.[11] Later on, by the irony of history nineteenth-century positivist narratives built the image of Science as a worldview alternative to the religious ones. Shortly after, the early twentieth-century debate on the foundations of mathematics sought to clarify the ultimate principles of the whole scientific structure. In particular, following Frege, Russell and Whitehead attempted to reduce mathematics to logic.[12] The logicist approach to the foundation of mathematics led to the formulation of several paradoxes, which exposed the internal limits of logical theories. Whilst Russell's paradox could be avoided by imposing a hierarchical structure to the space of logical possibilities, no *ad hoc* solution could outflank Gödel's and Tarsky's theorems.[13] In particular, Gödel's incompleteness theorems stated that formal languages defining natural numbers have inherent limitations as their own proof systems. In other words, there are statements within any such language that are neither provably true nor false. In turn, Tarsky's indefinability theorem affirmed that arithmetical truth is not

[11] Laplace was probably denying the necessity of god's intervention in his celestial mechanics, rather than god's existence, but the popularity of the dictum is evidence of the change of perspective.
[12] Bertrand Russell and Alfred North Whitehead, *Principia Mathematica*, Cambridge, Cambridge University Press, 1910.
[13] Kurt Gödel, *Collected Works*, Oxford, Oxford University Press, 1986.

definable within arithmetic. All these theorems dealt with the limits to formal languages' ability of self-representation. They recognised that these limits could only be overcome by recurring to a metalanguage.

Though the renderings of logical theorems in ordinary language are not logically rigorous, the influence of these results went well beyond the field of logic. Galileo's vision of numbers and figures as the language of nature, which revived in the quest for the foundations of mathematics, was about to strand on the non-self-sufficiency of the historical core of mathematics, namely the natural numbers. As a matter of fact, the concept of mathematics as the very structure of reality was already questioned in the nineteenth century by the invention of non-Euclidean geometries. In the 1820s, Bolyai and Lobacevskij, though being unaware of both the eighteenth-century investigations by Saccheri on the fifth postulate of Euclid's Elements and of each other's research, devised a geometry alternative to the Euclidean one.[14] Few years later, in 1854 Riemann developed a third geometry, which he called elliptic. Mathematicians soon associated these geometries with models that could be represented in space. And yet, non-Euclidean geometries do not require an experiential counterpart. Philosophers of science such as Reichenbach even termed the new geometries as mathematical geometry, as opposed to physical geometry that was supposed to deal with the physical world, and therefore to pertain to physics.[15] However, as since the early twentieth century physics was left the burden of representing the supposed objective reality, the crisis that invested the foundations of mathematics could no longer strike a fatal blow to modern objectivism. A much more threatening crack in the dream of the modern natural order opened instead when Heisenberg stated his uncertainty principle.

OF GOD AND DICE: UNCERTAINTY COMES FROM THE NEW PHYSICS

The physicist Werner Heisenberg formalized in 1927 a relation between specifically related pairs of variables describing the behaviour of subatomic particles.[16] Such formalization, which is known as the uncertainty principle, stated that the more precisely the value of one variable is determined, the more uncertain is the value of the other one. Therefore, it is not possible to ascertain at the same time, for instance, both the speed and the position of an electron.[17] According to this principle, the

[14] Morris Kline, *Mathematics: The Loss of Certainty*, Oxford, Oxford University Press, 1980.
[15] Hans Reichenbach, *The Philosophy of Space and Time*, trans. John Freund and Maria Reichenbach, New York, Dover Publications, 1958.
[16] Werner Heisenberg, *Physics and Philosophy: The Revolution in Modern Science*, New York, Harper, 1958.
[17] More precisely, the two variables at stake would be the position vector and the momentum vector, which is the product of mass and velocity.

uncertainty is not dependant on measurement procedures. Moreover, it was later recognised that the uncertainty is not a result of the interference with the measurement tools, as Heisenberg himself at first suggested.

Not all physicists fully accepted the uncertainty principle and the new mechanics that entailed it. For example, Einstein famously wrote about the new quantum mechanics: 'the theory yields a lot, but it hardly brings us any closer to the secret of the Old One. In any case I am convinced that He does not throw dice.'[18] Einstein went on looking for hidden variables, which would have filled what he believed to be a lack of knowledge about a completely determined reality. On the contrary, his efforts only helped to exclude interference as a cause for uncertainty, and they ultimately led Bell to state in 1966 his theorem of inequality. Bell's theorem affirmed that no theory of local hidden variables could provide the same amount of prediction of quantum physics. Therefore, the theorem implied that though within quantum mechanics rendering of subatomic particles 'it is not possible to arrive at an accurate and detailed prediction and description of the particular process resulting in a particular event,'[19] quantum theory should not be regarded, *pace* Einstein, as incomplete.

However, the theorem of inequality left undecided the issue of the relations between quantum mechanics and relativity theory, which generally was used by physicists to deal with non-subatomic objects. Moreover, the debate among physicists showed that any definition of such relations was entangled with the issue of the relations between physical theories and the so-called physical world. For example, Einstein's profession of faith in the deterministic order of things was perfectly in line with seventeenth-century natural philosophers' theological underpinning. In particular, Einstein's unplayful god was more akin to Spinoza's ordered nature, rather than to Newton's personified ruler. On the contrary Bohr, who was Heisenberg's mentor and inspirer, invited Einstein not to tell god what to do. Bohr accepted uncertainty as a feature of 'a novel situation unforeseen in classical physics and irreconcilable with conventional ideas suited for our orientation and adjustment to ordinary experience.'[20] This novel situation demanded that gathered data should not be detached from measuring activities. To put it in Bohr's terms, nothing existed until

[18] Albert Einstein, Letter to Max Born, 4 December 1926, in *The Born-Einstein Letters*, New York, Walker, p. 91.
[19] Anton Zeilinger, 'On the Interpretation and Philosophical Foundation of Quantum Mechanics', in *Vastakohtien todellisuus*, Festschrift for K.V. Laurikainen, U. Ketvel et al. eds, Helsinki, Helsinki University Press, 1996.
[20] Niels Bohr, 'Discussion with Einstein', in Schilpp ed., *Albert Einstein: Philosopher-Scientist*, La Salle, Open Court, 1970, p.235.

it was measured. Within the modern theoretical framework, which assigned physics the task of mirroring the physical world, this statement expressed quite a strong ontological stance. In particular, it recalled eighteenth-century Bishop Berkeley's dictum *esse est percipi*, i.e. to be is to be perceived, with not even Berkeley's faith in the constant intervention of god to warrant the continuity of the world.[21] It is fair to recall that Bohr was attempting to transcend the modern dichotomy between subjects and objects, and hence also the Berkeleyan reduction of objects to subjects. However, the theoretical position of Bohr, which is known as the Copenhagen interpretation of quantum physics, came to be accepted by most physicists. This interpretation definitively rejected, at least within subatomic physics, the seventeenth-century ideal of detached observation. Nonetheless, as the Copenhagen interpretation was justified by the specific behaviour of subatomic particles, it did not immediately challenge seventeenth-century natural philosophers' pretension to describe the behaviour of macroscopic objects through mathematical means. And yet, such challenge was in place from within physics since the late nineteenth century, when Poincaré presented his paper on the three body problem.[22] Just like Poe's purloined letter,[23] Poincaré's challenge to Newtonian mechanics was since then hidden in plain sight. It had to wait until the late twentieth century, when it came to be recognised as a forerunner of chaos theory.

IDEAL MODELS, IDEAL NATURE: THE PLATONISM OF MODERN SCIENCE

In 1997, Prigogine and Stengers boldly stated that 'we have come to the end of the road paved by Galileo and Newton, which presented us with an image of a time-reversible, deterministic universe.'[24] This road certainly did not start from scratch. As Whitehead reminded us, the modern faith in the natural order of things was inherited from classical thinkers.[25] In this regard, modern science simply recast the Aristotelian doctrine of natural places and forms into that one of a natural and timeless order. For example, in Aristotelian physics bodies fell on earth as their natural place, which was also the centre of the universe. After Copernicus displaced the earth from its privileged position, terrestrial attraction was instead explained by Newton as an

[21] George Berkeley, *A Treatise Concerning the Principles of Human Knowledge*, La Salle, Open Court, 1946.
[22] June Barrow-Green, *Poincaré and the Three Body Problem*, Providence, American Mathematical Society, 1997.
[23] Edgar Allan Poe, *Tales of Mystery and Imagination*, Ware, Wordsworth, 1993.
[24] Ilya Prigogine and Isabelle Stengers, *The End of Certainty: Time, Chaos, and the New Laws of Nature*, New York, Free Press, 1997, p. VIII.
[25] Whitehead, *Science and the Modern World.*

instance of a generalized gravitational force, which was supposed to affect every astronomical body.

Prigogine and Stengers also emphasised the technical outcomes of 'the desire to achieve a quasi-divine point of view in our description of nature.'[26] In particular, they underlined that the very scientific tools were devised according to a supposed stable and deterministic order of things. As a consequence, seventeenth-century natural philosophers built nature as the object of science by purifying observation from any aspect that could not fit such order. For example, in describing objects Galileo carefully distinguished qualities that could be measured, as those defining sizes, shapes, numbers, and slow and fast movements, from qualities as odours, tastes and sounds.[27] According to Galileo, only measurable qualities pertained to external bodies and they were thus worth of scientific investigation by mathematical means.

Already in classical antiquity, mathematical tools were intended to tackle a stable *cosmos*, whose order was confirmed by cyclical transformations. Later on, Christian theology kept recognising with Augustine the mathematical order of things, and it held arithmetical and geometrical evidence as an instance and a model of knowable truth. However, during the middle ages computing techniques were also driven by commercial activities, and they profited from adopting the Arab notation for numbers and the Indian symbol for zero. Moreover, specific calculation tools were part of the professional knowledge of builders, sculptors, painters and artillerists among others. In the fourteenth century, Oresme even attempted to reconcile practical measurements and mathematical speculations, so that he introduced what is subject to change[28] into the intellectual world inherited from the Greeks. In particular, Oresme suggested that phenomena could be represented as *formae fluentes*, i.e. flowing forms, which could be obtained by describing variations over three distinct parameters with geometrical diagrams, thus forerunning Descartes' analytical geometry.

Only in the seventeenth century a more comprehensive synthesis than Oresme's was brought forth by Galileo, who laid the foundations of modern physics. Galileo did not improve mathematical theory, but he made use of then current mathematical tools in order to describe motion. With his quantitative theory of motion Galileo rejected the objection to the possibility of representing change through mathematical means. Such objection was inherited by scholastic thinkers from Aristotle, who considered motion as a kind of change.

[26] Prigogine and Stengers, *The End of Certainty*, p. 38.
[27] Galilei, *Il Saggiatore*.
[28] Hugo Dingler, *Storia Filosofica della Scienza*, Milano, Longanesi, 1979.

Whilst Galileo refused Aristotelian physics, he endorsed other aspects of the classical Greek worldview.[29] For example, he followed in Plato's footsteps by declaring mathematics as the core of reality. Moreover, he even iterated Plato's rhetorical strategy, by letting the characters of his dialogues deduce the law of physics, just like the character of the slave in Plato's dialogue *Meno* did with a mathematical demonstration.[30] More important, he restated the Greek longing for stability by constructing his new theory upon the principle of inertia. Though this principle was explicitly formalized by Newton, it was already thoroughly implied by Galileo's physical theory. The principle of inertia affirmed the fundamental stability of both states of rest and motion, which Galileo intended as a rectilinear movement at constant velocity. In other words, whatever body, left to itself, was to remain in its state of rest or motion unless subjected to an external force. Of course, no physical body can be left to itself, i.e. free from interaction. Hence, uniform motion is utterly impossible, and it is to be considered as a purely ideal state. Therefore, Galileo literally put in ideal motion the Euclidean-Archimedean model of ideal shapes, and he obtained an equally ideal model of moving objects.

MODERN SCIENCE'S SEARCH FOR IMMUTABILITY IN CHANGE: THE DYNAMICAL ORDER OF CONSERVATION LAWS

Modern narratives of science credited Galileo's physics as being closer to phenomena than the traditional Aristotelian one. Nevertheless, 'on certain points, including even the description of mechanical motion, it was in fact Aristotelian physics that was more easily brought into contact with empirical facts.'[31] In general, the new Galilean dynamics saved the phenomena only as mutable expressions of immutable physical laws. More precisely, Galileo shifted physical theory from a static or, better, localized order towards a more abstract, systematic and dynamical one. In particular, he conceived of physical bodies as accidental bearers of measurable qualities, whose conservation was the essential feature of the observed system. Such conservation was later given mathematical expression by Newton's laws, which defined the inertial mass of any particular body as its resistance to dynamical change.

The conservation of motion as expressed by the principle of inertia opened the way for conservation laws, which described invariants within closed systems, i.e. systems that were supposedly non-interacting with the outer world. Equations expressed in mathematical form these and other invariances, by stating ratios between

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[29] Alexandre Koyré, 'Galileo and Plato', *Journal of the History of Ideas*, vol. 4, no. 4, Oct. 1943, pp. 400-428.
[30] Plato, *Plato's Meno*, ed. R. S. Bluck, Cambridge, Cambridge University Press, 1961.
[31] Ilya Prigogine and Isabelle Stengers, *Order Out of Chaos*, London, Fontana, 1985, p. 41.

the values of the variables that defined the considered system. For example, in the seventeenth century Mariotte and Boyle elaborated an equation that linked the values of the variables that were supposed to describe the ideal behaviour of gases. These and other equations devised with the same aim were still reference formulas in 1834, when Clapeyron put them together in his ideal gas law. Only in 1873 Van der Waals introduced in his equation of state parameters that were taking account of the behaviour of actual gases.

A more general conservation law came from the application of the Newtonian principle of conservation of mass to chemical reactions. In the 1780s Lavoisier weighed reactants and products of chemical transformations in order to demonstrate a general law of conservation of matter. It is worth recalling that the French researcher included in the definition of matter also light and heat or caloric, which he considered material substances. However, in 1811 Fourier stated his law of propagation of heat, which was independent from Newtonian mechanics. Moreover, nineteenth-century researchers came to deal with a whole range of new physical interactions, and they looked for a new theoretical synthesis. In particular, in 1837 Mohr enlisted motion together with light, chemical affinity, cohesion, electricity and magnetism in that which is considered as an earlier statement of the principle of conservation of energy. In the original German text, Mohr used the word *kraft*, which is better translated as force or power rather than energy.[32] The same term *kraft* (also associated with the word *arbeit*, i.e. work) was deployed by Helmholtz in his paper *On the Conservation of Force*, which was published in 1847. The concept of *kraft* included also heat, which was deemed by Mayer and Joule as interchangeable with motion. We may notice that in the meantime, nineteenth-century classical economists were developing a law of global equilibrium of value and labour, which is better known as labour theory of value. In the most sophisticated formulation of the economic equivalence of value and labor, Marx defined the second term of the conservation law as *Arbeitskraft*, i.e. labour power or force.[33]

Within the physical domain, the principle of conservation of energy generalized the Newtonian program, because it reduced phenomena to local accidental variations of a globally invariant sum of forces. However, in this perspective, phenomenally different energies should have been mutually interchangeable, regardless of time direction. In other words, it should have been possible to reverse any transformation from a form of energy to another. On the contrary, already in 1824 Carnot realized a

[32] D. S. L. Cardwell, *From Watt to Clausius*, Heinemann, London, 1971.
[33] Karl Marx, *Capital: a Critique of Political Economy*, trans. E. Aveling and S. Moore, Moscow, Foreign Languages Publishing House, 1954.

limitation of the convertibility of heat into mechanical work.[34] In 1850, such limitation was affirmed by Clausius in a statement that is now regarded as an expression of the second law of thermodynamics, the principle of conservation of energy being the first one.[35]

The word thermodynamic, which combines the Greek terms 'hot' (*thermós*) and 'force' (*dýnamis*), was first used by Thompson in 1849 to describe engines that exchanged and transformed heat. It was soon to label the branch of physics dealing with processes of heat exchange and transformation. These processes were framed by the two laws stating respectively the absolute limitations to the exchange of heat and work, and the conservation of energy. Both laws were independent from Newtonian mechanics. Following Thomson's insight, thermodynamic laws were reformulated in 1865 by Clausius as cosmological statements.[36] They asserted that the energy of the universe is constant, and that the entropy of the universe strives to attain a maximum value. Clausius invented the concept of entropy in order to take account of that which Thomson called dissipated energy, i.e. the energy that is transformed through such irreversible processes as conduction, friction, percussion etc., and which cannot be transformed back.[37] Entropy was also significantly referred to as a measure of disorder, and thus it had within thermodynamics the same role that undesired frictions had within the inertial dynamical model. Both entropy and frictions represented as a disturbance to the idealized world of physical theories the timely, irreversible and irredeemably chaotic experiential world.

UNACCEPTABLE BEHAVIOUR: THE PHYSICISTS' RELUCTANT RENUNCIATION OF PREDICTABILITY

Despite the physicists' will to reduce thermodynamic systems to the Newtonian model, all along the nineteenth century, dynamic and thermodynamic approaches to physical objects coexisted with no encompassing framework to bridge the theoretical gap. In the 1870s, an attempt in this direction was made by Boltzmann. The Austrian physicist proposed an interpretation of the thermodynamic behaviour of gases as a

[34] Joseph Kestin, *The Second Law of Thermodynamics*, Stroudsburg, Dowden, Hutchinson & Ross, 1976.

[35] R. J. E. Clausius, 'Ueber die bewegende Kraft der Wärme', *Annalen der Physik und Chemie*, 79, 1850, pp. 368-397 [translated and excerpted in William Francis Magie, *A Source Book in Physics*, New York, McGraw-Hill, 1935].

[36] R. J. E. Clausius, 'Ueber verschiedene für die Anwendung bequeme Formen der Hauptgleichungen der mechanischen Wärmetheorie', *Annalen der Physik und Chemie*, 125, 1865, pp. 353-379 [translated and excerpted in William Francis Magie, *A Source Book in Physics,* New York, McGraw-Hill,1935].

[37] William Thomson, 'On a Universal Tendency in Nature to the Dissipation of Mechanical Energy', in *Mathematical and Physical Papers*, Cambridge, Cambridge University Press, 1882, p. 511.

statistic result of mechanical interaction between molecules. Therefore, Boltzmann's hypothesis at least related dynamics and thermodynamics as describing in mechanical terms the behaviour of physical objects at the level of individuals and populations respectively. The latter term echoed both the Darwinian approach to biological evolution and Quetelet's statistical attempt to build a social physics. However, Boltzmann did not conceive of his statistical approach as an approximate description, but rather as a proper explanation of physical processes involving huge amounts of particles. His contemporary critics instead considered the inability of Boltzmann's statistical mechanic to describe the trajectories of single molecules as a subjective limit of his approach. In other terms, they held that only deterministic dynamic trajectories could fully represent the objective physical reality.

Boltzmann's critics regarded thermodynamic concepts as a measure of the ignorance of the observer. Nevertheless, in 1888 a paper by Poincaré on the so-called three body problem showed that a complete description of the trajectories of even just three interacting objects could not be reached. The problem was not new, as it was addressed already in the seventeenth century by Newton, in order to demonstrate the stability of the solar system. To his surprise, Newton was unable to solve the problem, and so did all the other would-be solvers down to Poincaré. The French scientist illustrated how the motions of three bodies that followed the laws of Newton could not be described by completely determined trajectories. On the contrary, in some portions of space Newtonian dynamic equations would provide more than one possible trajectory. Moreover, Poincaré noticed that very small changes in the initial conditions of the system could lead to enormous differences in the final phenomena, so that prediction became impossible. These were shocking results, as they directly questioned the stability of planetary motion, which long represented the very symbol of eternity.[38] Most of all, they revealed the limits of the Newtonian idealization, which assumed that not only planets, but all physical bodies could interact with other bodies while maintaining their completely predictable individual behaviour.

Poincaré's paper on the three body problem did not provide a solution. And yet, it was recognised as being so brilliant that it won the international mathematical competition to which it was submitted in 1888. Unfortunately, Poincaré's findings were at odds with the scientists' belief in the certainty of physical prediction, which was the touchstone for Newtonian science. Moreover, as previously recalled, even Einstein shared the belief in complete predictability, which hence survived the relativity revolution unlike Newtonian space and time. Furthermore, when quantum

[38] Prigogine and Stengers, *Order out of Chaos.*

physics presented evidence of the unpredictability of the behaviour of subatomic particles, the same Bohr was keen to limit indeterminacy to the subatomic realm.

TIMES ARE A-CHANGING[39] AND READY TO ACCEPT THE NEVER REPEATING STATES OF CHAOTIC SYSTEMS

Poincaré's opening to uncertainty remained unnoticed for seventy years, until its relevance came to be acknowledged by researchers who were dealing with meteorological and chemical predictability. In particular, in the early 1960s Lorenz suggested that weather predictability was hindered by the sensitivity of meteorological systems to initial conditions.[40] This sensitivity was already detected within dynamical systems by Poincaré. Lorenz described it as the butterfly effect, which hinted to the possibility that a cause as tiny as the flapping wings of a butterfly could ultimately have large-scale effects such as a tornado. The butterfly effect was to become a popular representation of the surprising link between minuscule initial changes and huge long-term variations.

Lorenz looked for a generalization of the non-periodic and unpredictable behaviour of meteorological systems. To this aim, he produced a mathematical model which was intended to describe a convective process, i.e. a movement caused by heat within a fluid, through a system of three differential equations.[41] He plotted the solutions of these equations into a graph, which was to attain the status of an iconic emblem for future chaos researchers. The image showed a line that never intersected itself, meaning that the system never repeated its state. This was the graphical representation of a behaviour that seemed impossible, because it coupled the supposed incompatible properties of stableness and non-recurrence. In other words, the graph represented a system that neither tended towards a steady state, i.e. a state in which the values of the variables no longer change, nor it tended to settle into a pattern of periodic repetition. In 1975, twelve years later, Yorke gave to the behaviour of this system the name it was to retain: chaos.[42]

Yorke labelled as chaotic a system's behaviour that would always stay within certain bounds, but which would neither tend to rest nor to periodical repetition. To mark the contrast with these latter ordered states, Yorke utilized the word 'chaos' as

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[39] Robert Zimmermann (Bob Dylan), *Times are a-changing*, audio recording, Columbia, 1964.

[40] Edward N. Lorenz, 'Deterministic Nonperiodic Flow', *Journal of the Atmospheric Sciences* no. 20, 1963, pp. 130-141.

[41] Edward N. Lorenz, 'The predictability of hydrodynamic flow', *Transactions of the New York Academy of Sciences,* ser. II, vol.25, no. 4, 1963, pp. 409-432.

[42] Tien Yien Li and James A. Yorke, 'Period Three Implies Chaos', *American Mathematical Monthly* vol. 82, no. 10, Dec 1975, pp. 985-992.

an evocative synonym for disorder. Nonetheless, he was dealing with disorder occurring within deterministic processes. These processes were described by deterministic mathematical models, which did not allow randomness. In other terms, within these models the state of the described system was determined uniquely by past states. As previously recalled, scientists from Newton to Einstein and beyond presumed that such a deterministic link should have warranted the possibility of predicting the behaviour of the system with absolute certainty. From this perspective, Yorke's definition of deterministic systems as chaotic might have appeared as a kind of oxymoron, i.e. a contradiction in terms. Nevertheless, Yorke's association of determinism and chaos could rely on Poincaré, who showed that even fairly simple deterministic systems could produce uncertainty. More important, it relied on the work of Lorenz, who even visualized a system's behaviour that scientific common sense had just ruled out.

QUESTIONING MODERNITIES: FAREWELL TO THE SEVENTEENTH CENTURY

The findings of Poincaré and Lorenz had to wait seventy and ten years respectively, until the path of Western thought allowed at least some researchers to fully appreciate them. This happened because the results of these researches were at odds with expectations that were deeply engrained in modern Western thought, and even harked back to the classical theoretical framework. Only during the 'long sixties' such expectations began to be widely questioned. Contemporary events such as the process of political decolonization, the second feminist movement, the spreading of phenomena of mass protest and the emerging of a counterculture[43] produced a political, social and cultural earthquake. The shaking of the foundations of the modern world helped to reopen issues such as the concepts of the individual, of nature and of the state, which seventeenth-century natural philosophers strove to settle once and for all.[44] In particular, many researchers began to be aware from within their disciplines of the theoretical limitations imposed by the modern conceptual framework. It is arguable that the contemporary emergence of chaos theory was no coincidence. The new concept of chaos welcomes us to the way out of the seventeenth century.

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[43] Theodore Roszak, *The Making of a Counter Culture: Reflections on the Technocratic Society and its Youthful Opposition*, New York, Doubleday, 1968.
[44] Toulmin, *Cosmopolis*.