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THE END OF CERTAINTY: THE TIME PARADOX AND THE CONSTRUCTION OF A NEW SCIENTIFIC RATIONALITY IN ILYA PRIGOGINE

O FIM DAS CERTEZAS: O PARADOXO DO TEMPO E A CONSTRUÇÃO DE UMA NOVA RACIONALIDADE CIENTÍFICA EM ILYA PRIGOGINE

EL FIN DE LAS CERTIDUMBRES: LA PARADOJA DEL TIEMPO Y LA CONSTRUCCIÓN DE UNA NUEVA RACIONALIDAD CIENTÍFICA EN ILYA PRIGOGINE

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ABSTRACT

This theoretical essay examines Ilya Prigogine's epistemological proposal in *The End of Certainty: Time, Chaos and the New Laws of Nature* (1996), aiming to reconstruct the argument by which the author shifts the laws of nature from the register of certainty to that of possibility. This is a theoretical-bibliographical study, qualitative in approach and hermeneutic-interpretative in character, taking the book as a primary source and examining it in dialogue with the literature of philosophy of science and non-equilibrium thermodynamics. The analysis unfolds in eight movements: the formulation of Epicurus' dilemma and the historical genealogy of the ideal of certainty; the time paradox and the anthropocentric reading of irreversibility inherited from Boltzmann's defeat; the constructive role of irreversible processes, evidenced by dissipative structures and bifurcations; the breakdown of the equivalence between individual and statistical description in unstable dynamical systems; the extension of classical and quantum dynamics based on Poincaré resonances; the cosmological unfolding of the thesis that time precedes existence; the ethical and epistemological implications of science conceived as a dialogue with nature; and finally the transposition of the argument to the examination of artificial intelligence as a bifurcation of twenty-first-century society. It is argued that Prigogine's decisive contribution lies not in adding a clause of uncertainty to a preserved deterministic edifice, but in inscribing instability within the very structure of fundamental laws, so that the arrow of time ceases to be a subjective appearance and becomes a property of nature. It is concluded that the Prigoginian programme offers contemporary science a third way — the “narrow path” between determinism and pure chance — whose fruitfulness exceeds physics and reaches the way in which the sciences, including the human and social sciences, conceive prediction, explanation and responsibility — and, most acutely, the way twenty-first-century society positions itself in relation to artificial intelligence.

KEYWORDS: Ilya Prigogine. Time paradox. Irreversibility. Dissipative structures. Artificial intelligence. Epistemology of complexity.

RESUMO

Este ensaio teórico examina a proposta epistemológica de Ilya Prigogine em *O fim das certezas: tempo, caos e as leis da natureza* (1996), com o objetivo de reconstituir o argumento pelo qual o autor desloca as leis da natureza do registro da certeza para o registro da possibilidade. Trata-se de pesquisa de natureza teórico-bibliográfica, de abordagem qualitativa e caráter hermenêutico-interpretativo, que toma a obra como fonte primária e a examina em diálogo com a literatura da filosofia da ciência e da termodinâmica de não-equilíbrio. O percurso analítico organiza-se em oito movimentos: a formulação do dilema de Epicuro e a genealogia histórica do ideal de certeza; o paradoxo do tempo e a leitura antropocêntrica da irreversibilidade herdada da derrota de Boltzmann; o papel construtivo dos processos irreversíveis, evidenciado pelas estruturas dissipativas e pelas bifurcações; a ruptura da equivalência entre a descrição individual

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e a descrição estatística nos sistemas dinâmicos instáveis; a extensão da dinâmica clássica e quântica a partir das ressonâncias de Poincaré; o desdobramento cosmológico da tese de que o tempo precede a existência; as implicações éticas e epistemológicas da ciência concebida como diálogo com a natureza; e, por fim, a transposição do argumento para o exame da inteligência artificial como bifurcação da sociedade do século XXI. Argumenta-se que a contribuição decisiva de Prigogine não reside em acrescentar uma cláusula de incerteza a um edifício determinista preservado, mas em inscrever a instabilidade na estrutura mesma das leis fundamentais, de modo que a flecha do tempo deixe de ser aparência subjetiva e se torne propriedade da natureza. Conclui-se que o programa prigoginiano oferece à comunidade científica contemporânea uma terceira via — o "caminho estreito" entre o determinismo e o acaso puro — cuja fecundidade excede a física e alcança o modo como as ciências, inclusive as humanas e sociais, concebem previsão, explicação e responsabilidade — e, de modo particularmente agudo, o modo como a sociedade do século XXI se posiciona diante da inteligência artificial.

PALAVRAS-CHAVE: Ilya Prigogine. Paradoxo do tempo. Irreversibilidade. Estruturas dissipativas. Inteligência artificial. Epistemologia da complexidade.

RESUMEN

Este ensayo teórico examina la propuesta epistemológica de Ilya Prigogine en *El fin de las certidumbres: tiempo, caos y las leyes de la naturaleza* (1996), con el objetivo de reconstituir el argumento mediante el cual el autor desplaza las leyes de la naturaleza del registro de la certeza al de la posibilidad. Se trata de una investigación teórico-bibliográfica, de enfoque cualitativo y carácter hermenéutico-interpretativo, que toma la obra como fuente primaria y la examina en diálogo con la literatura de la filosofía de la ciencia y de la termodinámica de no-equilibrio. El recorrido analítico se organiza en ocho movimientos: la formulación del dilema de Epicuro y la genealogía histórica del ideal de certeza; la paradoja del tiempo y la lectura antropocéntrica de la irreversibilidad heredada de la derrota de Boltzmann; el papel constructivo de los procesos irreversibles, evidenciado por las estructuras disipativas y las bifurcaciones; la ruptura de la equivalencia entre la descripción individual y la estadística en los sistemas dinámicos inestables; la extensión de la dinámica clásica y cuántica a partir de las resonancias de Poincaré; el despliegue cosmológico de la tesis de que el tiempo precede a la existencia; las implicaciones éticas y epistemológicas de la ciencia concebida como diálogo con la naturaleza; y, por último, la transposición del argumento al examen de la inteligencia artificial como bifurcación de la sociedad del siglo XXI. Se argumenta que la contribución decisiva de Prigogine no reside en añadir una cláusula de incertidumbre a un edificio determinista preservado, sino en inscribir la inestabilidad en la estructura misma de las leyes fundamentales, de modo que la flecha del tiempo deje de ser apariencia subjetiva y se convierta en propiedad de la naturaleza. Se concluye que el programa prigoginiano ofrece a la ciencia contemporánea una tercera vía — el "camino estrecho" entre el determinismo y el azar puro — cuya fecundidad excede la física y alcanza el modo en que las ciencias, incluidas las humanas y sociales, conciben la previsión, la explicación y la responsabilidad — y, de modo particularmente agudo, el modo en que la sociedad del siglo XXI se posiciona ante la inteligencia artificial.

PALABRAS CLAVE: Ilya Prigogine. Paradoja del tiempo. Irreversibilidad. Estructuras disipativas. Inteligencia artificial. Epistemología de la complejidad.

1 INTRODUCTION

Few works of scientific popularisation from the late twentieth century formulated so ample a claim with such economy as *The End of Certainty: Time, Chaos and the New Laws of Nature*, published by Ilya Prigogine in 1996 in collaboration with Isabelle Stengers. The title announces a closure; the subtitle, a programme. What is brought to a close is the three-centuries-old identification between scientific knowledge and certainty — the conviction that a law of nature deserves that name only when it permits one to deduce, from sufficiently precise initial conditions, the totality of a system's future and of its past. What is proposed in its place is neither the

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abandonment of lawfulness nor a surrender to chance, but a reformulation of the fundamental laws of physics in terms of possibilities. The thesis, stated in the prologue itself, is of a disarming clarity: “in both classical dynamics and quantum physics, the fundamental laws now express possibilities and no longer certainties” (PRIGOGINE, 1996, p. 13).

The interest of this formulation for contemporary epistemological debate derives less from its rhetorical audacity than from the place from which it is enunciated. Prigogine does not speak as a philosopher interpellating physics from outside, nor as an external critic of scientific rationalism. He speaks as a physical chemist awarded the 1977 Nobel Prize in Chemistry precisely for his work on non-equilibrium thermodynamics and dissipative structures, and what he lays before the reader is the technical extension of a formalism — classical dynamics and quantum mechanics reformulated at the statistical level — whose philosophical consequences he then proceeds to draw out. This is the difference that separates his argument from the more general pronouncements on uncertainty and complexity that have proliferated in recent decades: here, instability is not an imported metaphor but a mathematical property of well-defined classes of dynamical systems, and it is from that property that the theses concerning time, nature and the place of the human being within it follow.

The problem that organises the work is what the author calls the time paradox. It may be stated in a single sentence: how can the arrow of time, omnipresent in chemistry, geology, biology, cosmology and the human sciences, emerge from a world that physics describes by means of laws invariant under time reversal? The traditional answer — the one that became established after the failure of Ludwig Boltzmann's programme — ascribes the asymmetry to the observer: it would be we ourselves, with our necessarily approximate description, who are responsible for the difference between past and future. Prigogine rejects that way out entirely. For him, “it is not we who generate the arrow of time. On the contrary, we are its children” (PRIGOGINE, 1996, p. 12).

The general aim of this essay is to reconstruct and critically discuss the argument by which Prigogine shifts the laws of nature from the register of certainty to the register of possibility, examining the technical conditions he establishes for that displacement and the epistemological and ethical consequences he draws from it. Its specific aims are: (i) to situate historically the ideal of certainty that the work calls into question, beginning with Epicurus' dilemma and its consolidation in Newtonian mechanics; (ii) to examine the Prigoginian critique of the anthropocentric interpretation of irreversibility; (iii) to make explicit the constructive role of irreversible processes in systems far from equilibrium; (iv) to analyse the breakdown of the equivalence between individual description and statistical description, which constitutes the technical core of the proposal; (v) to present the extension of classical and quantum dynamics founded upon Poincaré resonances; and (vi) to discuss the cosmological unfolding and the ethical implications of the new rationality proposed.

From the methodological standpoint, this is a theoretical-bibliographical study, qualitative in approach and hermeneutic-interpretative in character. Prigogine's work is taken as a primary source and submitted to an integral analytical reading, with the identification of the central theses

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of each chapter, the mapping of its operative concepts and the recording of the passages in which the author makes his epistemological commitments explicit. In a second moment, the reconstructed argument is confronted with the pertinent secondary literature — above all the author's own works written with Isabelle Stengers (PRIGOGINE; STENGERS, 1990, 1997) and Grégoire Nicolis (NICOLIS; PRIGOGINE, 1977, 1989), together with the epistemological reflection developed by Stengers (2002) on the invention of the modern sciences, and the production of the philosophy of science on determinism, indeterminism and complexity. What is at issue, therefore, is neither a systematic review nor a reception study, but the internal examination of an argument, with attention to its consistency and to the reach of its claims. Direct quotations follow the Brazilian translation by Roberto Leal Ferreira, published by Editora da Universidade Estadual Paulista in 1996.

The justification for the study rests upon an observation: the expression “the end of certainty” has been absorbed into the current vocabulary of the Brazilian human and social sciences with an ease that has not always been accompanied by an examination of the argument sustaining it. Invoked to authorise everything from the critique of positivism to the defence of participatory methodologies, the formula frequently loses its link with the technical demonstration that gives it substance. Recovering that link is, here, the condition for assessing both the fruitfulness and the limits of transposing the Prigoginian argument beyond the field in which it was originally formulated.

2 EPICURUS' DILEMMA AND THE GENEALOGY OF THE IDEAL OF CERTAINTY

Prigogine opens the development of his work with the gesture of a historian of ideas: he reaches back to Antiquity in order to show that the problem he confronts is not an accident of modern physics but a constitutive tension of Western thought. “It was Epicurus who first established the terms of the dilemma to which modern physics has lent the weight of its authority” (PRIGOGINE, 1996, p. 17). The Epicurean dilemma arises from a difficulty internal to the atomism inherited from Democritus. If atoms fall through the void along parallel trajectories and at the same speed, how could they ever meet? And if they do not meet, how is one to explain the formation of bodies, the diversity of the world, novelty itself? The solution proposed — the *clinamen*, a minimal and unpredictable swerve that disturbs the parallel fall — has remained in the history of thought, Prigogine observes, “as the very example of an arbitrary hypothesis, one that saves a system by introducing an *ad hoc* element” (PRIGOGINE, 1996, p. 18).

What matters, however, is not the expedient itself but what it was intended to preserve. For Epicurus, the problem of the intelligibility of nature and that of human destiny were inseparable: a wholly determined world would be one in which human freedom would have nowhere to inscribe itself. The celebrated passage from the letter to Menoeceus, quoted by Prigogine, expresses the existential dimension of the question: “As for destiny, which some regard as the master of all things, the sage laughs at it. Indeed, it is still better to accept the myth about the gods than to submit to the destiny of the physicists” (PRIGOGINE, 1996, p. 18). Physics was already perceived, at that point, as a threat — not on account of its results, but on account of its form.

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Modernity did not dissolve the dilemma; it conferred authority upon it. The Newtonian law of gravitation unites two properties which, taken together, produce determinism in the strong sense: it is deterministic, inasmuch as given initial conditions univocally determine the evolution of the system; and it is invariant under time reversal, that is, it remains valid when *t* is replaced by −*t*. From these two properties follows the figure that Laplace made famous: an intelligence that knew the position and the velocity of every particle in the universe at a given instant could deduce the whole of its future history and the whole of its past history. Quantum mechanics, Prigogine observes, did not alter that picture in any essential respect: the Schrödinger equation is equally deterministic and equally symmetrical with respect to time.

The point that Prigogine underlines, and that is of particular interest to epistemology, is that this conception of law is not neutral from a theological and cultural standpoint. The subjection of nature to deterministic laws brought human knowledge closer to a divine and atemporal point of view — the legislating God of the seventeenth century —, and Leibniz's formulation in the *New Essays*, quoted in the work, expresses it without circumlocution: in the least of substances, eyes sufficiently penetrating could read immediately the whole sequence of the things of the universe. Prigogine adds, with support from Joseph Needham, that the conception of a passive nature, subjected to external laws, is a specificity of the Western tradition and not a universal self-evidence of thought.

Against this ideal, the work summons a lineage of resistances. Kant, Hegel, Husserl, William James, Bergson, Whitehead and Heidegger are mentioned as thinkers who sought to preserve the temporal dimension of existence against an objective representation of the world that suppressed it — without, however, succeeding in reconciling intelligibility and freedom. The quotation from Popper (1988), taken up by Prigogine, gives the measure of what is at stake: “I regard Laplacean determinism — confirmed as it seems to be by the determinism of physical theories and by their brilliant success — as the most solid and most serious obstacle in the way of an explanation and an apology for human freedom, creativity and responsibility” (PRIGOGINE, 1996, p. 21). And that of Bergson (2006), on the same page, formulates the decisive objection in the form of a question: what is time for, if everything is already given?

It is essential to note the distance Prigogine establishes between his own position and two others that might appear close to it. The first is Cartesian dualism, which resolves the problem by separating the *res cogitans* from the *res extensa* and leaving nature entirely to determinism. The second is postmodern scepticism, which he associates with Richard Rorty and with “deconstruction”, and which would convert the problems of the tradition into themes of civilised conversation, renouncing the claim to truth. Prigogine rejects both: the first, for dividing the world into two incommunicable halves; the second, for abdicating the task that seems to him properly scientific. His response is of another order: “to root indeterminism and the asymmetry of time in the laws of physics is the answer we can give today to Epicurus' dilemma” (PRIGOGINE, 1996, p. 23).

This formulation deserves attention because it contains the key to the whole programme. What is at issue is not the addition to physics of a clause of epistemic humility, acknowledging

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that our knowledge is limited; it is a matter of modifying the laws themselves, so that indetermination and the orientation of time belong to them and not to us. It is the difference between saying that we cannot predict and saying that there is not, in nature, what would have to be there for complete prediction to be possible. The whole technical difficulty of the work consists in showing that the second assertion can be sustained with the rigour of the first.

In the final chapter, Prigogine takes up this genealogy again in an explicitly historical key, drawing upon Stephen Toulmin (1990). The Cartesian ideal of certainty is there recontextualised: in a seventeenth century devastated by wars of religion in which men killed in the name of dogmas, Descartes sought a kind of certainty that all human beings might share independently of their faith — hence the *cogito* and the requirement that science be founded upon mathematics. Leibniz would take up the same programme in his search for a language capable of restoring peace among men. The quest for certainty was therefore not merely an epistemological choice: it was a response to a tragic historical situation. And Prigogine extends the analysis to Einstein, for whom science represented, in his own words, an escape from the tumult of existence towards the “quiet regions of the high mountains”. The conclusion he draws is a sober one: “the scientist can no more escape the polluted cities by going to the high mountains than can the city dweller” (PRIGOGINE, 1996, p. 196). The sciences take part in the construction of tomorrow's society, with all its contradictions and uncertainties.

3 THE TIME PARADOX AND THE CRITIQUE OF THE ANTHROPOCENTRIC INTERPRETATION OF IRREVERSIBILITY

The nineteenth century bequeathed to physics a double and incompatible inheritance. On the one hand, Newton's laws, which describe a static universe in which past and future play symmetrical roles. On the other, the second law of thermodynamics, formulated by Rudolf Clausius in 1865 in the formula that Prigogine quotes: “The energy of the universe is constant. The entropy of the universe increases towards a maximum” (PRIGOGINE, 1996, p. 25). Here, for the first time, a fundamental law of physics distinguishes the future from the past: irreversible processes produce entropy, and that production has a sign.

It was Ludwig Boltzmann who attempted to reconcile the two inheritances, and his attempt is presented by Prigogine as the decisive episode of the history he examines. The path he chose was Darwin's: to reason about populations rather than about individuals. The H-theorem of 1872 shows that collisions between molecules cause a certain function H to decrease towards a minimum, which corresponds to the Maxwell-Boltzmann equilibrium distribution. Collisions thus appeared as the microscopic mechanism of irreversibility — and the arrow of time acquired a dynamical foundation.

The objections were not long in coming. Loschmidt's paradox observed that, if the laws of dynamics are symmetrical, the reversal of all the velocities ought to produce the contrary evolution, which contradicts the theorem. Zermelo's paradox invoked Poincaré's recurrence theorem: a bounded dynamical system returns, after a sufficient time, arbitrarily close to its initial state — hence no process can be strictly unidirectional. Boltzmann ended by yielding. He renounced the link between collisions and irreversibility and reinterpreted equilibrium as the

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macroscopic state that is simply *the most probable*; irreversibility became a consequence of the approximate character of our description. Prigogine is explicit as to the cost of that retreat: “This was his tragedy: he sought to achieve in physics what Darwin had achieved in biology — and he failed” (PRIGOGINE, 1996, p. 26).

The point that matters to the argument of the work is not historical but systematic: that defeated interpretation became the orthodoxy, and it is this orthodoxy that Prigogine sets out to dismantle. In its current formulation — exemplified in the work by the reading of Murray Gell-Mann (1996) —, macrostates group together microstates regarded as equivalent, and entropy measures our ignorance as to which microstate is in fact realised. The arrow of time would therefore be an effect of our coarse description (*coarse grained*), not a property of the world.

Against this reading Prigogine advances an articulated set of objections. The first is that of Maxwell's demon: if irreversibility follows from the imprecision of our description, then an observer capable of discriminating between microstates would see a world perfectly symmetrical in time — which amounts to saying that irreversibility would vanish with the perfecting of knowledge. The second is empirical and, to my mind, the most telling: diffusion coefficients, thermal conductivities and relaxation times are well-defined, measurable and reproducible magnitudes, independent of the precision of the instruments with which we measure them. If irreversibility were an artefact of our ignorance, such magnitudes ought to vary with the degree of refinement of the observation — and they do not vary.

The third objection shifts the axis of the problem. The identification of irreversibility with the growth of disorder, consecrated by the vulgate of the second law, is insufficient. Prigogine has recourse to the example of thermal diffusion: on applying a temperature gradient to a homogeneous mixture of two gases, entropy is produced — and, simultaneously, homogeneity is destroyed, one of the components becoming concentrated preferentially in the hot region and the other in the cold one. The irreversible process, here, *generates order*. On the basis of this observation, and taking up again the theses already presented in *Order Out of Chaos*, the author formulates three propositions that sustain the whole of the work: irreversible processes are as real as reversible ones; they play a constructive role in nature; and they require, if they are to be understood, an extension of dynamics (PRIGOGINE; STENGERS, 1997).

There is a further argument, of a reflexive nature, that deserves to be recorded. If the arrow of time were an illusion produced by our condition as limited observers, it would be necessary to explain how limited observers came to exist in a universe without an arrow of time. Now, the emergence of life, and therefore of observers, presupposes irreversible processes far from equilibrium. The anthropocentric explanation is, in this sense, circular: it presupposes that which it ought to explain. Such is the burden of the sentence from the prologue already quoted — we are children of the arrow of time, not its authors.

A critical observation is in order. The rejection of the anthropocentric reading is, at the level of argument, solid; but it is worth noting that Prigogine writes within a debate in which his position was a minority one, and remains a matter of controversy among physicists. Authors working within traditional statistical mechanics continue to maintain that macroscopic

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irreversibility is compatible with microscopic temporal symmetry, by way of hypotheses concerning low-entropy initial conditions in the early universe. The force of the Prigoginian argument lies not in having closed that discussion — it did not close it —, but in having shown that the anthropocentric alternative carries high philosophical costs and empirical consequences that merit scrutiny.

4 THE CONSTRUCTIVE ROLE OF IRREVERSIBILITY: DISSIPATIVE STRUCTURES AND BIFURCATIONS

Prigogine's positive answer to the time paradox begins in the domain in which his scientific contribution is least contested: the thermodynamics of systems far from equilibrium. Starting from the school of Théophile De Donder in Brussels, he takes up the decomposition of the variation of entropy into two terms, $dS = d_eS + d_iS$, in which d_eS designates the flow of entropy across the boundaries of the system — which may be positive or negative — and d_iS the internal entropy production, always positive or zero. This apparently technical distinction has a consequence of principle: the second law ceases to be a statement restricted to isolated systems and comes to apply to open systems, that is, to practically all the systems of interest in chemistry, in biology and in the Earth sciences.

The case of the living illustrates the reach of the reformulation. Schrödinger (1997), in *What is Life?*, had described metabolism in terms of a negative flow of entropy: the organism in a stationary state maintains $dS = 0$, which implies $d_eS = -d_iS < 0$. Prigogine accepts the description, but shifts the emphasis: what characterises the living is not merely that it absorbs negative entropy from the environment, but that it *produces* entropy intensely. Life is not an exception to the second law; it is one of its most elaborate manifestations.

In the vicinity of equilibrium, in the so-called linear regime, the behaviour of systems is still governed by an extremal principle: the theorem of minimum entropy production, demonstrated by Prigogine in 1945 with the support of the Onsager reciprocity relations, establishes that the stationary state minimises entropy production, which guarantees the regression of fluctuations and therefore stability. Even here, however, an unexpected feature appears: the non-equilibrium stationary state may be *more organised* than the equilibrium one, as the example of thermal diffusion shows.

The picture changes radically far from equilibrium. Together with Paul Glansdorff, Prigogine demonstrated that, in that region, there no longer exists any extremal function whatsoever — neither free energy nor entropy production — whose minimisation would determine the state of the system. It is possible to formulate only sufficient conditions of stability, gathered together in the so-called general evolution criterion. The epistemological consequence is remarkable and frequently underestimated: near equilibrium, the laws are universal, in the sense that they are independent of the details of the system; far from equilibrium, they become *specific*, dependent upon the type of irreversible process involved. “Far from equilibrium, matter acquires new properties in which fluctuations and instabilities play an essential role: matter becomes more active” (PRIGOGINE, 1996, p. 68).

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The mechanism of this activity is the bifurcation. Consider an open chemical reactor in which the distance from equilibrium may be varied. So long as that distance is small, the system follows what Prigogine calls the thermodynamic branch — the prolongation, into the non-equilibrium domain, of the solution corresponding to equilibrium. Beyond a critical value, however, this branch becomes unstable, and new stable solutions arise: chemical oscillations, periodic spatial structures of the type predicted by Alan Turing (1952) in the context of morphogenesis, propagating chemical waves. These are the dissipative structures — coherent spatio-temporal organisations that maintain themselves only through the continuous dissipation of energy and that, unlike the thermodynamic branch, *increase* entropy production.

Two conditions are necessary for their emergence: a sufficient distance from equilibrium and the existence of catalytic or autocatalytic steps, in which a product intervenes in its own formation — a condition universally satisfied by living organisms by means of enzymes. Experimental confirmation came with the Belousov-Zhabotinsky reaction, in which billions of molecules change state collectively, rendering visible, in the alternation of the colour of the solution, a long-range coherence that does not exist at equilibrium. It is to this coherence that the formula Prigogine liked to repeat, and which runs through the whole of the work, refers: “In a metaphorical vein, it may be said that at equilibrium matter is blind, whereas far from equilibrium it begins to see” (PRIGOGINE, 1996, p. 71).

The bifurcation point introduces, moreover, an irreducibly probabilistic element into the description. When the system reaches the critical value, the laws determine which branches are available, but not which of them will actually be chosen: it is the fluctuations — irrelevant near equilibrium, decisive there — that decide. From this follows a characteristic of enormous conceptual reach: a system subjected to a succession of bifurcations acquires a *history*. To observe the system in a given state makes it possible to infer through which earlier bifurcations it has passed; the trajectory travelled is inscribed in the present state. Physical nature, here, becomes narratable — not because we ascribe a narrative to it, but because the succession of choices actually made constitutes an irreversible sequence of events.

From this picture Prigogine draws an inversion of the narrative of the “narcissistic wounds” that Freud had attributed to the history of the sciences. If Copernicus displaced the Earth from the centre, Darwin removed man from his position of exception and psychoanalysis divested consciousness of its sovereignty, non-equilibrium physics would operate in the contrary direction: it would show that human creativity is not alien to nature, but an amplification of features already present in the physical world. The formulation that synthesises this reconciliation is at once Bergsonian and Whiteheadian: “The possible is richer than the real. Nature does indeed present us with the image of creation, of unforeseeable novelty. Our universe has followed a path of successive bifurcations: it might have followed others. Perhaps we may say the same of the life of each one of us” (PRIGOGINE, 1996, p. 75).

It is necessary, however, to mark the limit of this result. Dissipative structures establish the constructive role of irreversibility at the macroscopic level, but they do not answer the question that constitutes the time paradox. They show *that* irreversibility produces order; they do not show

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where irreversibility comes from. And Prigogine is unequivocal as to the impossibility of circumventing this question by way of simple emergence: “Is time not an emergent property? But then its roots must be discovered. The arrow of time will never emerge from a world governed by time-symmetrical laws” (PRIGOGINE, 1996, p. 62). This sentence is the axis of the work: it is what obliges the author to descend to the microscopic level and to propose an extension of the fundamental laws.

5 THE BREAKDOWN OF THE EQUIVALENCE BETWEEN THE INDIVIDUAL DESCRIPTION AND THE STATISTICAL DESCRIPTION

Before setting out the technical core of the work, it is worth recording a piece of self-criticism that Prigogine himself formulates and that illuminates the sense of his proposal. In *From Being to Becoming*, published in 1980, he had presented the relation between the dynamical description and the thermodynamic description as a complementarity, after the manner of Bohr (PRIGOGINE, 2011). In 1996 he regrets that statement: if there were more than one equally legitimate description, who would decide which of them is the correct one? “The existence of an arrow of time is not a matter of convenience. It is a fact imposed by observation” (PRIGOGINE, 1996, p. 78). The solution, therefore, cannot be the peaceful coexistence of two points of view, but an extension of dynamics itself — a thesis that he would also develop in *The Laws of Chaos* (PRIGOGINE, 2002).

The technical core of the work is a thesis of modest appearance and considerable consequences. It may be stated thus: for a well-defined class of dynamical systems — unstable systems —, the description in terms of individual trajectories and the description in terms of probability distributions cease to be equivalent, and only the second allows the laws of evolution to be formulated.

It is worth making explicit what this equivalence means in classical physics. An individual state of a mechanical system is represented by a point in phase space, whose coordinates are the positions and the momenta of all the particles. A statistical collection — the Gibbs and Einstein *ensemble* — is represented by a probability distribution $\rho(q,p,t)$ over that same space. For Gibbs and Einstein, recourse to ensembles was an expedient of calculation, justified by our ignorance of the exact initial conditions; in principle, everything the distribution says could be reconstituted from the individual trajectories it covers, and the individual trajectory would be recovered as a limiting case, represented by a Dirac delta function concentrated at a point.

Prigogine shows that this reconstitution is possible for stable systems and impossible for chaotic ones. The argument is conducted, with notable economy, upon models possessing very few degrees of freedom — which constitutes, to my mind, the most effective rhetorical move in the book. In Boltzmann's gas, with its 10^{23} constituents, one could always invoke the practical impossibility of following the particles; in the examples Prigogine chooses there are only one or two variables, and even so irreversibility appears. As he observes, “in this case it is not conceivable to appeal to our ignorance or to approximations and yet the essential property that lies at the origin of irreversibility already appears” (PRIGOGINE, 1996, p. 96-97).

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The first model is the Bernoulli map, $x_{n+1} = 2x_n$ (modulo 1). Written in the binary representation, it amounts to a shift: at each iteration, every digit takes the value of the one that preceded it. Since the digits of an irrational number are independent of one another, the sequence generated is as random as a succession of coin tosses — in a rigorously deterministic system. The sensitivity to initial conditions is immediately legible: two numbers that differ only in the fortieth binary digit — that is, by less than 2^{-39} — will come to differ by half a unit after forty iterations. The Lyapunov exponent, which measures the rate of exponential divergence of neighbouring trajectories, is here equal to log 2.

The contrast between the two levels of description is then dramatic. Whereas the individual trajectory remains erratic and unpredictable, the probability distribution $\rho_n(x)$ converges rapidly and regularly towards a constant — the uniform distribution, which is the equilibrium of the system. Prigogine formulates the result in a sentence that inverts current intuition: “Instability at the level of the trajectory leads to stable behaviour at the level of the statistical description” (PRIGOGINE, 1996, p. 89). The statistical level is not, therefore, a degraded version of the individual one: it is the level at which the system exhibits lawfulness.

The technical reason for this asymmetry lies in the spectral structure of the operator that governs the evolution of distributions, the Perron–Frobenius operator. Besides the set of solutions that reproduces the description by trajectories, this operator admits a second set of eigenfunctions — the Bernoulli polynomials, with eigenvalues $1/2^m$ — which describe the exponential damping of the contributions and therefore well-defined relaxation times. It happens that these new solutions have meaning only when applied to regular distributions; applied to the delta functions that represent individual trajectories, they would produce products of singular functions, mathematically devoid of significance. As the author summarises, “the statistical formulation of the Bernoulli map concerns only the normal distribution functions ρ, and not the individual trajectories which, as we have seen, correspond to singular δ functions” (PRIGOGINE, 1996, p. 99). In order to accommodate the two types of function simultaneously, it is necessary to abandon the usual Hilbert space and to work in generalised Hilbert spaces, or Gelfand spaces.

The second model, the baker transformation, removes an objection that might be directed at the first. The Bernoulli map is not invertible, so that its temporal asymmetry could be attributed to the equation itself. The baker transformation — which flattens a unit square into a rectangle and cuts it so as to reconstitute the square, with one dilating and one contracting coordinate, and Lyapunov exponents +log 2 and −log 2 — is, on the contrary, “invertible, reversible with respect to time, deterministic, recurrent and chaotic” (PRIGOGINE, 1996, p. 106). It therefore gathers together all the properties in the name of which irreversibility is customarily denied, and it is precisely in it that Prigogine exhibits the emergence of two irreducible spectral representations: one applicable to the future, with damping; the other applicable to the past, with amplification.

The choice between them constitutes what the author terms the selection principle. Formally, in Hilbert space the evolution constitutes a group, in which the two directions of time remain undissociated; in generalised spaces, this group splits into two semigroups, and it is necessary to select the one in which equilibrium is reached in our future. The ground of this

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selection is not mathematical but physical, and rests upon a fact of observation of maximal generality: “All irreversible processes in nature are characterised by one and the same direction of their arrow of time. All produce entropy in the same direction of time” (PRIGOGINE, 1996, p. 108).

A predictable objection is confronted directly. It might be argued that, with infinite precision in the preparation of the initial conditions, the description by trajectories would remain valid. Prigogine compares this objection with one that would maintain that, since infinite velocities are “imaginable”, relativity would be dispensable. In both cases what is at issue is an idealisation that the structure of the theory excludes: as Pierre Duhem had already observed in 1906 (DUHEM, 2014), “the notion of trajectory is an adequate mode of representation only if the trajectory remains approximately the same when we slightly modify the initial conditions” (PRIGOGINE, 1996, p. 95). In a chaotic system this robustness does not exist — and a concept that is not robust is not a good physical concept.

The conclusion of the movement is formulated without mitigation: “when we are faced with unstable systems, we must formulate the laws of dynamics at the statistical level. This certainly changes our description of nature in a radical way, since the fundamental objects of physics are no longer trajectories or wave functions, but probabilities” (PRIGOGINE, 1996, p. 77-78). This is the precise sense in which the certainties come to an end: not because nothing can be known, but because the object of knowledge has ceased to be what the tradition supposed it to be.

6 POINCARÉ RESONANCES AND THE EXTENSION OF CLASSICAL AND QUANTUM DYNAMICS

The discrete-time models examined in the previous section fulfil a demonstrative function, but do not in themselves constitute a reformulation of physics. The next step of the work consists in showing that the same rupture occurs in real dynamical systems, and the technical instrument that makes this possible is Poincaré's non-integrability theorem.

A dynamical system is said to be integrable when its variables can be redefined in such a way as to eliminate the potential energy, rendering it isomorphic to a set of free particles — which amounts to saying that its equations can be solved exactly. Poincaré (1995) demonstrated that the overwhelming majority of dynamical systems are not integrable, and identified the cause: resonances between degrees of freedom, that is, simple numerical relations between their frequencies, of the type $n_1\omega_1 + n_2\omega_2 = 0$. Such relations cause denominators that vanish to appear in perturbative expansions — the “small divisors” already noted by Le Verrier in celestial mechanics —, and the series diverge. The three-body problem is already non-integrable.

The tradition read this result as an obstacle. Max Born, quoted by Prigogine, expressed the prevailing sentiment when he observed that it would be remarkable if nature had found a means of resisting the progress of knowledge by hiding behind the wall of the analytical difficulties of the *n*-body problem. Prigogine proposes the inversion: resonances are not an obstacle, but the source of a new lawfulness. Eliminated at the statistical level — where they produce not

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divergences but diffusive terms —, they break determinism and temporal symmetry simultaneously.

The decisive argument is conceptual in nature, and deserves emphasis because it is frequently omitted in summary presentations of the work. Resonances are conditions upon *frequencies*, not events localised at a point of space and at an instant of time. They therefore introduce an element foreign to the very notion of trajectory, which is by definition a local description. What is at issue here is not a limitation of our capacity for calculation, but an incompatibility between the kind of object that the resonance is and the kind of object that the trajectory is. This is the reason why the extension of dynamics cannot be carried out at the individual level.

Two physical conditions delimit the domain of validity of the reformulation. The first is the persistence of the interactions. In transient interactions — laboratory *scattering*, in which a beam approaches, interacts and moves away — the new effects do not appear. In persistent interactions — the molecules of a gas, which never cease to collide — they do. The second condition is the thermodynamic limit, with the number of particles and the volume tending to infinity and their ratio remaining finite, which characterises the so-called large Poincaré systems. Prigogine insists that this limit is not an artifice of calculation, but the condition of existence of real properties such as phase transitions. A finite system does not have well-defined solid, liquid and gaseous states; the distinction between them exists only in the limit.

Within this framework, the author constructs a spectral representation of the Liouville operator — the operator that governs the evolution of probability distributions — outside Hilbert space. The physical justification is the same as in the previous section, now applied to continuous systems: persistent interactions require non-localised probability distributions, whose Fourier transform is singular, whereas the trajectory is precisely the extreme case of localisation. The complex eigenvalues thus obtained produce contributions that decay in the future and diverge in the past, and it is from this structure that the breaking of temporal symmetry follows. The result is what Prigogine calls an irreducibly probabilistic description: “We thus obtain an irreducibly probabilistic description, characterised by a breaking of temporal symmetry. The conflict between the reversible time of dynamics and the oriented time of thermodynamics is thereby resolved within dynamics itself, without the interference of extrinsic elements” (PRIGOGINE, 1996, p. 114).

It is worth underlining the modesty with which the author delimits the scope of the thesis. The indeterminism defended here is not an absence of predictability: “Indeterminism, as defended by Whitehead, Bergson or Popper, henceforth imposes itself in physics. But it must not be confused with the absence of predictability, which would render all human action illusory. What is at issue is a limit to predictability” (PRIGOGINE, 1996, p. 115). The distinction is essential and is frequently lost in appropriations of the work: what is asserted is the existence of horizons of predictability, not the impossibility of predicting.

The transposition of the argument to quantum mechanics occupies the most technical chapter of the book and responds to what Prigogine calls the quantum paradox. Quantum theory, as codified by von Neumann, rests upon a dualist structure: on the one hand, the Schrödinger

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equation, deterministic and symmetrical in time, which governs the evolution of the wave function; on the other, the reduction of the wave function, an irreversible process associated with measurement, which converts a pure case into a mixture. There is in the theory no criterion that determines when the first process is to be abandoned for the second, nor any consensual realist interpretation of the second — which opened the way for the solutions that invoke the consciousness of the observer, multiple universes or environmental decoherence. Roger Penrose (1991), to whom Prigogine refers with esteem, had classified this duality among the “paradoxes” properly so called of the theory — those that do not allow themselves to be dissolved by interpretative refinement.

Prigogine's thesis is that the quantum paradox is a particular case of the time paradox, and that the same solution resolves both. Since Poincaré resonances appear also in quantum systems with a continuous spectrum, one obtains for them a statistical formulation outside Hilbert space, in which the fundamental quantity ceases to be the probability amplitude and becomes probability itself: “in this new formulation, the fundamental quantity is no longer the probability amplitude, but probability itself” (PRIGOGINE, 1996, p. 138). The reduction of the wave function ceases to require an external intervention and becomes a dynamical process produced by the resonances. There follows the result that the author considers decisive from an epistemological point of view: a measuring apparatus must be a large Poincaré system (LPS) with broken temporal symmetry, and “LPSs measure themselves, so to speak. The actualisation of the potentialities contained in the wave functions is accomplished thanks to LPSs” (PRIGOGINE, 1996, p. 155). The observer loses the status of demiurge responsible for the actualisation of the potentialities of nature.

It is important to record, in intellectual honesty, that this proposal has not obtained consensus within the physics community. The Brussels–Austin formulation remains a minority position over against the decoherence approaches that are dominant today, and the technical objections directed at spectral representations outside Hilbert space have never been entirely answered. This does not invalidate the epistemological interest of the programme, but it counsels caution to those who invoke it as a consolidated result of contemporary physics. What the work establishes with security is the formulation of a problem and the demonstration that the anthropocentric way out has costs; what it proposes as a solution is a research programme, and as such it must be presented.

7 THE COSMOLOGICAL EXTENSION: “TIME PRECEDES EXISTENCE”

The eighth chapter of the work opens with an anecdote that Prigogine visibly relishes. Invited by the physicist Ivanenko to write a sentence on the wall of Lomonosov University in Moscow, beside sentences left there by Dirac and Bohr, he hesitated and wrote: “Time precedes existence” (PRIGOGINE, 1996, p. 169). The sentence condenses the cosmological extension of the whole argument.

The question to which it responds is the following: if the arrow of time is a property of nature and not of the observer, and if it is universal — all irreversible processes pointing in the same direction —, then it must have a cosmological origin. Now, standard cosmology situates the

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origin of the universe in an initial singularity, in which the known laws cease to hold, and Stephen Hawking (1988) had proposed, by the expedient of “imaginary time”, a description in which the four dimensions become spatial and the universe appears as an eternal and purely geometrical structure. Prigogine refuses that path for the same reason that he refuses the anthropocentric reading of irreversibility: it eliminates time instead of explaining it.

His proposal is to replace the singularity with an instability: “The essential point is that the birth of our universe is no longer associated with a singularity, but rather with an instability, bearing a certain analogy to a phase transition or to a bifurcation” (PRIGOGINE, 1996, p. 187). The model, developed with Jules Géhéniau, Edgard Gunzig and Pasquale Nardone on the basis of the work of Brout, Englert and Gunzig, rests upon the observation that gravitational energy is negative and the energy of matter positive, so that the total energy of the universe may be null — the “free lunch” hypothesis formulated by Edward Tryon. The creation of matter out of the quantum vacuum then becomes possible without any violation of the conservation of energy, and the price is paid not in energy, but in entropy: “The birth of our universe is expressed by an explosion of entropy” (PRIGOGINE, 1996, p. 189).

The analogy with dissipative structures is explicit and worth recording, because it reveals the unity of Prigoginian thought. Just as a convection cell exists only for as long as it is traversed by a dissipative flux, the universe appears as a system far from equilibrium whose “dissipative structures” are matter itself and curved space-time. And, just as the second law breaks the equivalence between work and heat established by the first, it would break the equivalence between geometry and matter established by Einstein's equations, conferring a direction upon the process: the conversion of space-time into matter is dissipative, and the inverse process is excluded.

The consequence the author draws from this is the most speculative in the work, and he acknowledges as much. Since there is no stable ground state for the conformal field involved in the model, the process does not come to a halt with the birth of our universe: it would apply to a meta-universe in which an indefinite number of universes may be born, and in which the place and the moment of each birth have a merely statistical significance, bound to quantum fluctuations. Hence the formulation: “In this perspective, time is eternal. We have an age, our civilisation has an age, our universe has an age, but time, for its part, has neither beginning nor end” (PRIGOGINE, 1996, p. 173).

Two critical observations are in order. The first is that Prigogine is scrupulous in demarcating the status of these propositions. Already in the prologue he had warned that, at the frontiers of knowledge, physical reasoning and speculation are hardly to be demarcated from one another, and that it would be premature to speak of demonstration or of proof; what can be done is to analyse conceptual possibilities. This caution contrasts favourably with the tone of some later appropriations of his work.

The second observation concerns the argumentative function of the chapter. The cosmological model is not a necessary consequence of the thesis about irreversibility; it is rather a verification of consistency. If the arrow of time is universal, it cannot have arisen at some point

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in the history of the universe — it would have to be as old as the universe, or older. The chapter shows that there exists at least one cosmological model compatible with that requirement. Whether it is the correct model is another question, and Prigogine does not claim to have settled it.

8 THE NEW RATIONALITY: DIALOGUE WITH NATURE, ETHICS AND THE NARROW PATH

The seventh chapter of the work, situated between the technical developments and the cosmological extension, formulates in an epistemological key what the others establish in a physical one. Its thesis is that science is a dialogue with nature, and that this dialogue presupposes the reality of becoming: “Science is a dialogue with nature. [...] A world symmetrical with respect to time would be an unknowable world. [...] The reality of becoming is the *sine qua non* condition of our dialogue with nature” (PRIGOGINE, 1996, p. 157).

The argument is stronger than the formula suggests. Every measurement presupposes that the observed system can affect the observer, producing in him a record that persists. Now, a record that persists is, by definition, an asymmetry between the before and the after. If the world were temporally symmetrical at all of its levels, there would be no records, no memory and no knowledge. Irreversibility is not, therefore, one empirical datum among others: it is the condition of possibility of the very experience that grounds the physics which denies it. There is here a transcendental structure, in the Kantian sense of the term, although Prigogine does not employ that language.

From the same page comes a distinction that deserves to be retained by those who work in scientific education: “To understand nature was one of the great projects of Western thought. It must not be identified with that of controlling nature. Blind indeed would be the master who believed that he understood his slaves on the pretext that they obey his orders” (PRIGOGINE, 1996, p. 157). The image is harsh and its target precise: the reduction of intelligibility to the capacity to predict and to manipulate. A wholly controllable world would be a world from which there would be nothing to learn, and Prigogine associates that ideal — without time, without memory and without history — with the novelistic nightmares of Huxley, Orwell and Kundera.

The chapter further introduces the notion of entropic time, whose consequence is more radical than is commonly noticed. If the flow of time is rooted in the resonances, and if these depend upon the Hamiltonian of the system, then two systems subjected to different conditions age differently. Two chemically identical samples, one of them in the presence of a catalyst, produce distinct entropies and, in that precise sense, have distinct flows of time. Prigogine concludes: “The essential conclusion is that, even in a Newtonian universe, the flow of time is not unique” (PRIGOGINE, 1996, p. 164). Time ceases to be the universal container of events and becomes a property of processes.

The final chapter of the work gathers up the ethical consequences and is, from the point of view of a reader in the human sciences, the densest. Prigogine constructs there a remarkable argumentative symmetry. On the one hand, he examines Einstein's refusal in the face of Gödel's cosmological model, which admitted journeys into one's own past: Einstein, however great his attraction to eternity, could not accept that logical consequence of his own ideas, because to

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accept the return to the past amounts to denying the reality of the world. And he summons Borges (2007), who in “A New Refutation of Time” expounds the doctrines that make of time an illusion and concludes with the celebrated “And yet, and yet...”. The lesson drawn is unequivocal: “To deny time may seem a consolation, or may appear as the triumph of human reason; it is always a denial of reality” (PRIGOGINE, 1996, p. 197).

On the other hand, and it is here that the argument attains its equilibrium, Prigogine refuses with equal firmness the opposite solution: “Pure chance is as much a denial of reality and of our demand to understand the world as determinism is” (PRIGOGINE, 1996, p. 197). A world in which everything was decided in advance and a world in which nothing could be described in general terms are equally uninhabitable for thought, and both, by opposite routes, dispense with the labour of science.

Between these two denials lies that which gives the last chapter its title:

> What we are seeking to construct is a narrow path between these two conceptions, which lead equally to alienation: that of a world governed by laws that leave no place for novelty, and that of an absurd, acausal world, in which nothing can be predicted or described in general terms (PRIGOGINE, 1996, p. 198).

The formula that synthesises this third way is of a remarkable concision: “Laws do not govern the world, but neither is the world ruled by chance. Physical laws correspond to a new form of intelligibility which irreducibly probabilistic representations express” (PRIGOGINE, 1996, p. 199). It is not a matter of weakening the notion of law, but of redefining it: a law describes the field of possibles and the structure of their probabilities, without reducing events to consequences deducible from it.

Three implications deserve emphasis for the contemporary epistemological debate.

The first concerns creativity. Prigogine observes that scientific creativity is frequently underestimated in comparison with artistic creativity: had Shakespeare, Beethoven or Van Gogh died prematurely, no one would have produced their works, whereas it is supposed that science, being a collective enterprise subjected to rigorous criteria, would have arrived at the same results in any case. He acknowledges what is true in this contrast, but concludes that the constraints of scientific practice do not eliminate creativity — they are challenges to it. The very formulation of the time paradox is presented as an extraordinary example of human imagination.

The second concerns the situation of the human being within nature. He is not a demiurge, responsible for actualising the potentialities of the world through observation — that is the figure which the reformulation of quantum mechanics dissolves. But neither is he a spectator of a spectacle already written. He is a participant in a dialogue, and what characterises this dialogue is that difficulty is converted into resource: sensitivity to initial conditions and Poincaré resonances, which classical physics recorded as weaknesses of its edifice, become the point of departure of a new language.

The third is properly ethical and is articulated with the historical genealogy examined in section 2. If the search for absolute certainty was born, with Descartes, in a context of wars waged

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in the name of dogmas, then the critique of certainties is not an academic exercise: it touches upon the relation between knowledge and violence. And the conclusion that Prigogine draws is not sceptical, but affirmative: the sciences participate in the construction of tomorrow's society and cannot renounce hope. The work closes in openness, and not in answer: “We discern new horizons, new questions, new risks. We are living through a privileged moment in the history of the sciences” (PRIGOGINE, 1996, p. 199).

To conclude this section, a warning about the uses of the work is in order. The thesis that “laws do not govern the world” has been invoked in contexts very distant from the one in which it was formulated, at times in order to authorise the suspension of requirements of methodological rigour. There is nothing in Prigogine that sustains such a use. The indeterminism he defends is the result of demonstration, not of a renunciation of demonstration; the limits of predictability he establishes are determinate, calculable limits, associated with Lyapunov exponents and with well-defined relaxation times. The distinction he himself draws — indeterminism is not the absence of predictability, but a limit to predictability — is the barrier that separates his position from a relativism which he explicitly refused when criticising postmodern “deconstruction”. To transpose the work into the human sciences is legitimate and fruitful; to transpose it as a licence for imprecision is to betray it.

9 ARTIFICIAL INTELLIGENCE AS A BIFURCATION: THE END OF CERTAINTY IN TWENTY-FIRST-CENTURY SOCIETY

The previous section closed with a warning about the uses of the work, and the transposition now proposed runs precisely the risk denounced there. To speak of artificial intelligence on the basis of *The End of Certainty* may easily degenerate into that genre of commentary which lends the contemporary object a physical vocabulary it cannot sustain, producing the effect of depth without the cost of demonstration. There is, however, a reason for running the risk, and it is not one of opportunity. Artificial intelligence is not merely one object among those which might be examined with Prigoginian instruments: it is the technology in which the tension between law and possibility, between prediction and novelty, has ceased to be a question for epistemologists and has become a practical problem for entire societies. To examine it in the light of the work therefore requires four movements and one delimitation: the epistemic status of probabilistic machines; the production of scientific knowledge when prediction becomes dissociated from understanding; contemporary society as a system far from equilibrium; and the ethics of the narrow path applied to governance. The fifth movement, which closes the section, is that of the recognition of the limits of the analogy itself.

It is worth beginning with a historical irony that is rarely noticed. The computing machine was born as the last figure of Laplace's demon. Turing (1950), in formulating the imitation game, was reasoning about a device whose behaviour was, in principle, entirely determined by its table of states: given the initial state and the input, the rest followed of necessity. The cybernetics of Wiener (1961) was organised around the notion of control by feedback, that is, of the correction of deviation in the direction of a previously fixed target. And Shannon (1948), in constructing the mathematical theory of communication, borrowed from thermodynamics the very name of *entropy*

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to designate the uncertainty of a source — so that, in precisely the period in which physics was debating whether irreversibility was a property of nature or a limitation of the observer, information engineering was incorporating the concept as a measure of ignorance. The theme of this essay has traversed computation since its birth.

The rupture came from within the discipline itself. The systems today gathered under the name of artificial intelligence — statistical learning, deep networks, generative models — do not compute a function known in advance: they adjust parameters to a probability distribution estimated over data, and their output is the result of a sampling over that distribution. The same question does not produce the same answer. The machine which had been the emblem of determinism came to operate by expressing possibilities, and not certainties. The formula of the prologue of the work, transposed into this domain, describes the functioning of these systems with disconcerting fidelity — and it is precisely this fidelity that demands caution.

Caution, because the precept established in the previous sections obliges one to distinguish two probabilisms. Prigogine's entire argument rests upon the difference between probability as the expression of our ignorance, which leaves the deterministic edifice intact, and probability inscribed in the law itself, which modifies it. Now, the probabilism of a language model belongs, in principle, to the first kind: it is a modelling choice, not a property of the substrate. The network is executed upon a deterministic computational substrate, and fixing the seed of the pseudo-random generator reproduces the output. Whoever asserts that artificial intelligence “confirms” Prigogine commits exactly the confusion which the work devoted itself to undoing. What is sustained here is more modest and, for that very reason, defensible: it is a matter of structural analogy, possessing heuristic value, and not one of application or of corroboration.

The reservation once made, the heuristic is not trivial. Consider the argument, current among researchers in the field, that the opacity of these systems is provisional — that sufficient advances in interpretability would allow the reasons for each output to be reconstituted in full. Formally, this argument has the same structure as the anthropocentric reading of irreversibility examined in section 3: it attributes to the limitation of the observer that which may well belong to the object, and it projects an ideal observer — a Maxwell's demon of interpretability — capable of discriminating the microstates, here the weights of the network, and of reading in them the determination of macroscopic behaviour. The difference is decisive and must be recorded: in Prigogine's case, there exists a theorem of non-integrability which forbids the reconstitution; in the case of deep networks, there is no analogous result, and the question remains empirically open. There are reasons for distrusting the affirmative answer — the scale of the parameters, non-linearity, the sensitivity of the output to the formulation of the input —, but suspicion is not demonstration, and the difference between the one and the other is what separates this essay from the genre it refuses.

There is, however, a point at which the correspondence goes beyond loose analogy, and that point is historicity. A trained model is an object possessing a history in the precise sense established by section 4: its present state is not deducible from its architecture and its objective function, because it carries the memory of the path traversed — the data corpus, the order in

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which the examples were presented, the random seeds, the human choices made in the alignment phase. Two models of identical architecture, trained under slightly distinct conditions, diverge irrecoverably. The explanation of why such a system behaves as it behaves is, in the rigorous sense of the term, irreducibly narrative: it requires the trajectory to be reconstituted, and not merely the laws to be exhibited. Here one encounters again, realised in an artefact, the second of the three conceptual displacements which the fourth conclusion of this essay identifies as the transposable legacy of the work.

The second movement concerns the production of scientific knowledge. The exemplary case is that of the prediction of protein structures: Jumper and colleagues (2021) demonstrated that it is possible to predict, with an accuracy comparable to that of experimental techniques, the three-dimensional conformation of a polypeptide chain, without any intelligible theory of protein folding resulting from that prediction. The scientific gain is immense and is not in question. What is in question is what this form of success authorises one to conclude. Anderson (2008) formulated the maximal conclusion in the provocative form of the “end of theory”: with data in sufficient quantity, correlation would suffice, and the scientific method — hypothesis, model, test — would become obsolete. The thesis is weak and has been widely criticised, but its attenuated version operates silently in many research programmes: to predict well comes to count as to understand.

It is at this point that the epistemological chapter of the work, examined in section 8, ceases to be commentary and becomes criterion. The distinction which Prigogine establishes there between understanding and controlling nature, condensed in the image of the master who believes himself to know his slaves because he obtains their obedience, anticipates the situation with precision. A system that predicts without an intelligible model offers control without understanding; there is nothing illegitimate in this so long as the difference is maintained, and everything is lost when it is effaced. The stronger argument, however, is the other one: if science is a dialogue with nature, then it presupposes that the one who asks may be surprised and modified by the answer. An apparatus that returns answers of high accuracy and null explanatory content does not participate in this dialogue — it answers without teaching one to ask. The risk of the twenty-first century is not that machines should think; it is that cognitive difficulty, which is the place where scientific education effectively occurs, should become optional.

The consequence for scientific education and for the editorial system is direct and deserves to be recorded, for it touches the daily work of those who train researchers and evaluate manuscripts. To delegate the construction of the state of the art, the writing of the method or the interpretation of the results to a generative system does not produce merely text of variable quality: it produces researchers who have never passed through the difficulty of formulating a problem. Bender and colleagues (2021) drew attention to the fact that language models optimise the plausibility of form, not the truth of content — which, in the scientific domain, manifests itself in non-existent references, false attributions and syntheses that reproduce the apparent consensus of a corpus instead of examining it. Mitchell (2019) observes, in the same direction, that the competence of these systems is narrow and fragile outside the distribution on which they

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were trained. It would be one-sided, however, to close the matter here: the same instruments broaden access to the international literature, reduce the linguistic barrier which systematically penalises researchers from peripheral countries, and permit analyses of data that were previously unfeasible. What is required is not refusal, but the maintenance of the difference between what the tool does and what the researcher must continue to do.

The third movement shifts the examination from the laboratory to society, and it is here that the transposition becomes at once most fruitful and most hazardous. It is sustained here that the society of the beginning of the twenty-first century satisfies, in an analogical sense, the two conditions which Prigogine established as necessary to the emergence of dissipative structures. The first is sufficient distance from equilibrium: the climate crisis, the demographic transition, geopolitical rearrangement and the saturation of the informational environment together constitute a regime of intense flows and persistent disequilibria, and not a stationary state close to equilibrium. The second condition, the existence of autocatalytic steps, is satisfied in a literal and not merely metaphorical manner: artificial intelligence systems are today employed in the design of the circuits, in the writing of the code, in the curation of the data and in the training of the models that will produce the following generation of artificial intelligence systems. A product that intervenes in its own formation is the technical definition of autocatalysis.

The consequence of this configuration is known outside physics under another name. Positive feedback in the presence of increasing returns produces path dependence and lock-in in configurations which are not the most efficient ones, but those which stabilised first — the mechanism which Arthur (1994) formalised for economics and which Crawford (2021) documents, in the case of artificial intelligence, in the concentration of computational capacity, energy inputs and data in a reduced number of actors. This is the regime of bifurcation: small differences are amplified, and the choice between the available branches is not determined by the “laws” of the system — the market, technical rationality, the curve of costs —, but by fluctuations, that is, by decisions of small amplitude taken at the critical moment. Herein lies the properly political point of the transposition, and it is a precise one: it is exactly at the point of bifurcation that decisions of small amplitude have a disproportionate effect, and it is after the branch has been taken that the system re-enters a quasi-deterministic regime in which the alternatives, though still thinkable, have ceased to be available. Irreversibility is not, here, a figure of rhetoric: it is the technical name of that which makes a choice a choice.

From this picture there follows the simultaneous refusal of the two genres of discourse which today dominate the public debate on the subject. The first is technological determinism, which enunciates the future in the mode of inevitability: artificial intelligence will eliminate such and such a proportion of jobs, general intelligence is a matter of time, adaptation is the only policy available. In its form, this is Laplace's demon in contemporary dress, with the peculiarity that the deduction of the future from the present is effected by the extrapolation of curves rather than by the integration of equations — which renders it more fragile, not more robust. The second genre is its symmetrical counterpart: the discourse of radical unpredictability, according to which nothing can be said, everything is exaggeration or vertigo, and for that reason there is no sense in

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planning. The one and the other, as the final conclusion of this essay observes with respect to determinism and pure chance, dispense with the effort of knowing — the first because everything would already have been decided, the second because nothing would allow itself to be grasped. The Prigoginian position between them is the most demanding of all: to describe the field of possibles, to identify which branches are available, to estimate under what conditions each of them stabilises, and to recognise that the choice between them is not written.

The fourth movement is ethical, and it gathers what the final chapter of the work establishes. If responsibility has meaning only in a world that is neither entirely determined nor entirely random, then the two discourses refused in the preceding paragraph share a function that is rarely made explicit: both are alibis. Technological determinism absolves, because no one decides that which was inevitable; radical unpredictability absolves equally, because no one answers for that which could not be foreseen. It is worth noting — and the observation is empirical, not rhetorical — that the two discourses are frequently issued by the same actors, in alternation according to convenience: inevitability when it is a matter of justifying development, unpredictability when it is a matter of answering for its effects. To re-establish the narrow path between them is, before any normative prescription, the condition for there to be an addressee of the question of responsibility.

It is under this condition that the instruments of governance acquire meaning, and the work offers, for the purpose of thinking them, an unexpectedly exact image. In section 5 there was examined the selection principle by which, the evolution group having been split into two semigroups, one chooses that which is compatible with the preparation effectively realisable from our past. Regulatory frameworks operate as a selection principle inverted along the axis of time: they select, among the available branches, the one compatible with a future which the collectivity is able to endorse. The Recommendation on the Ethics of Artificial Intelligence (UNESCO, 2021), Regulation (EU) 2024/1689 (EUROPEAN UNION, 2024), Bill n. 2,338/2023 currently before the Brazilian National Congress (BRAZIL, 2023) and the technical protocols of standardisation examined by Alves Correia et al. (2026) are attempts to constitute such a principle. Their efficacy is uncertain and legitimately disputed; Russell (2019) argues that the problem of control must be inscribed in the design of the systems, and not only in the regulation of their use, whereas Floridi (2014) maintains that the transformation under way is of an environmental and not an instrumental order, which displaces the question from individual conduct to the design of the infosphere. The essential point, however, is not which instrument works: it is that no instrument whatsoever makes sense under the hypothesis that the trajectory is given.

There remains one conceptual instrument of the work which is rarely mobilised in this debate and which is perhaps the most precise of all. It is the notion of entropic time, examined in section 8: if the flow of time is rooted in the resonances, and if these depend on the conditions to which the system is subjected, then distinct systems age in distinct ways, and there is no single time within which all of them are inscribed. Transposed with due prudence, the notion clarifies the central problem of governance: technical development and institutional development possess incommensurable internal times. The interval between the moment at which a technology

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stabilises and the moment at which institutions produce an adequate response is not an administrative failing to be corrected by procedural efficiency; it is a structural property of the coupling between systems of different natures. A policy of governance that ignores this always arrives late, because it pursues a state already superseded; one that recognises it works by anticipation, that is, acts while the fluctuation is still amplifiable — before the bifurcation is resolved.

It is fitting to close this section by turning against it the warning formulated at the end of section 8. Society is not a chemical reactor; “bifurcation”, “autocatalysis” and “distance from equilibrium” possess here neither measure, nor equations, nor criterion of refutation; and nothing of what has been argued above has the status of a demonstration. It is therefore appropriate to distinguish three levels of legitimacy in the transposition. The first is that of the epistemological displacement — the passage from certainty to possibility as a form of intelligibility —, which is transposable with full legitimacy, because it concerns the form of knowledge and not a particular physical mechanism. The second is that of the structural concepts — historicity, path dependence, sensitivity to fluctuation, irreversibility of choice —, transposable as heuristics: they generate hypotheses which need to be tested by the methods proper to the social sciences, and not confirmed by analogy. The third is that of the technical apparatus — spectral representations, Poincaré resonances, semigroups —, which is not transposable, and whose use outside physics is metaphor when honest and imposture when it is not. Whoever keeps this hierarchy present will be able to read the twenty-first century with Prigogine without betraying him. And he will find, in the end, the same displacement that organises the whole of the work: the decisive question is not what artificial intelligence will bring about, a formulation that already contains the deterministic answer, but what we shall do with the field of possibles which it opens — a question that has meaning only in a world whose future is not given, and which is the reason why, a quarter of a century later, this book continues to be read.

10 FINAL CONSIDERATIONS

The itinerary here pursued permits a number of conclusions.

The first conclusion concerns the nature of the argument examined. *The End of Certainty* is not a book about the limits of human knowledge, although it is frequently read as such. It is a book about the structure of the laws of nature. The difference is decisive: the first reading preserves the deterministic edifice intact and merely registers our incapacity to traverse it in its entirety; the second maintains that the edifice is of another nature altogether. Prigogine defends the second, and it is from this choice that the radicality of his position follows. When he affirms that the laws express possibilities, he is not saying that possibilities are all we manage to attain; he is saying that possibilities are what there is.

The second conclusion refers to the architecture of the argument, whose economy deserves to be registered. The thesis concerning time is sustained by a chain that runs from non-equilibrium thermodynamics to chaotic models with few degrees of freedom, from these to Poincaré non-integrability, from this to the extension of classical dynamics, from this to quantum mechanics and, finally, to cosmology. Each link discharges a precise function: the dissipative

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structures establish that irreversibility produces order; the chaotic models establish that irreversibility does not derive from ignorance; the resonances establish where and why the equivalence between the individual description and the statistical description breaks down; cosmology verifies the consistency of the whole. It is a construction, and not a collection of intuitions — which is what distinguishes it from a good part of the literature on complexity that claims descent from it.

The third conclusion is of a critical order. The Brussels–Austin programme has not obtained, within the physics community, the consensus that its philosophical importance might suggest. The decoherence approaches have become dominant in the treatment of the problem of quantum measurement, and traditional statistical mechanics continues to sustain interpretations of irreversibility that Prigogine rejected. Whoever transposes his theses into other fields must do so in the knowledge of this, presenting them as a fruitful research programme and not as a consolidated result. This caution, moreover, honours the author himself, who was scrupulous in demarcating what he held to be demonstrated from what he held to be speculation.

The fourth conclusion concerns the fruitfulness of the work outside physics. It follows less from the specific theses about operators and spectral representations than from three conceptual displacements of general scope. The first is the understanding of instability as a source of organisation, and not merely of disorder — which reorients the manner of thinking about economic, ecological, social and institutional systems. The second is the notion that systems subjected to successive bifurcations acquire a history, so that their present state carries the memory of the path travelled and is not deducible from their laws alone: explanation, in such cases, is irreducibly narrative, which brings the sciences of nature close to a trait that was supposed to be exclusive to the human sciences — a convergence that Edgar Morin (2005) explored by another route in formulating complex thought, and that Whitehead (2010) had anticipated in making creativity a cosmological category. The third is the redefinition of the very notion of law as the description of a field of possibles. These three displacements may be appropriated with rigour by researchers who do not command the formalism of statistical mechanics, provided that the warning is kept present that what is at stake are structural analogies, and not direct applications.

The fifth conclusion concerns the contemporary pertinence of the argument. Section 9 sought to show that artificial intelligence constitutes, for the programme examined, more than an opportune field of application: it constitutes a test of its fruitfulness and of its limits. Fruitfulness, because the society that is organising itself around this technology exhibits the two conditions which the work associates with the emergence of dissipative structures — distance from equilibrium and autocatalytic steps —, and because the category of bifurcation makes it possible to formulate with precision what current discourses obscure: that the present is a critical point at which decisions of small amplitude have a disproportionate effect, and that this condition is transitory. Limits, because none of this amounts to a demonstration, and because the probabilism of generative systems is not the irreducible probabilism which the work establishes for unstable dynamical systems. The distinction between the three levels of legitimate transposition — the

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epistemological displacement, the structural concepts and the technical apparatus — is the safeguard that allows the work to be mobilised in the contemporary debate without converting it into ornament.

The sixth and final conclusion takes up once more the ethical axis. What Prigogine calls the narrow path is a requirement at once epistemological and political: to refuse both the world in which everything is decided and the world in which nothing can be said. The two alternatives dispense with the effort of knowing — the first because everything is already contained in the initial conditions, the second because nothing allows itself to be apprehended. Between them, the position which the work sustains is the most demanding: that there is lawfulness and there is novelty, and that to understand consists precisely in articulating the two. If there is one lesson that crosses the frontier between physics and the remainder of intellectual work, it is this one. The future is not given; it is constructed — and this construction, far from rendering science superfluous, is what confers meaning upon it.

DECLARATION OF THE USE OF ARTIFICIAL INTELLIGENCE

The authors declare that Artificial Intelligence tools were used exclusively to support grammatical and textual revision, as well as the verification and standardization of citations and references. All content was reviewed and validated by the authors, who assume full responsibility for the final version of the article.

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