Complexity in the Twenty-First Century: From the Limits of Growth to the Growth of Limits

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Ambiguous Terminology, Heuristic Fecundity

Complexity, a term that is both ambiguous and multifaceted, is used widely today. Various legitimate definitions can be proposed for it, as is the case with "ample" notions such as intelligence, consciousness or culture. The recurrent mention of this term can be attributed to the transformation of our societies and their artifacts, as well as the acceleration of time brought by the digital revolution—a technological upheaval comparable to the invention of writing and the printing press.

Some people rightly criticize the use and misuse of the word "complexity" to describe everything and its opposite. "It's complex" may naively mean "it's complicated," "the world is complex" or "everything is in everything." First, nuances: a Swiss watch and an Airbus plane are complicated, not complex, objects. The brain, the immune network and the internet are complex, not complicated, systems.

It is also important to note that complexity, as studied by scientists, is fundamentally problem-oriented. As such, it serves as a keyword for this century, allowing us to compress/comprehend/summarize the generic patterns and the signs of our times. Complexity represents a different way of viewing the world and understanding our actions, rather than magical thinking, that has the potential to overcome critical problems in the market, industry, government and society at large. Let us be clear about this: despite the ambivalent terminology, there is a genuine heuristic value in viewing things from different perspectives and linking them together to address problems that extend beyond the scientific specialities typically involved in tackling them.

Contemporary philosophers and thinkers, especially the more rigorous ones, are somewhat reluctant to use the term "complexity." Nevertheless, complexity represents an inclusive and multi-inter-trans-disciplinary scientific approach, rather than a specific discipline. For

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over 50 years, numerous researchers and scientists have adopted this approach to describe phenomena that cannot be adequately understood through the classical deterministic vision of science.

The scientific approaches to complexity are fascinating to explore and contribute to a perspectivist vision of the world and reality. These approaches have been enriched by rigorous studies in biology, physics, mathematics and computer science. Although this development began in the 1960s and 70s, it was built upon the early discoveries of the nineteenth century that revealed certain limits to reductionism, linearity and predictability. These scientific approaches represent the foundations of a renewed epistemology; that is, the knowledge of knowledge and its limits, which emphasizes the relationships between the observer and the observed, the subject and the object, as well as the dynamics of movement and its inherent uncertainties.

Physics of Immanence

Although complexity reveals a form of rationality that is no longer reduced and narrowed but extended, it is neither a contemporary myth nor a mystical or theological quest for understanding reality. It is rather an attempt to scientifically implement this extended/broader rationality by objectifying links, nodes and folds of reticular biochemical filaments and intertwined physical matter.

Reductionist science postulates the existence of a transcendental approach to knowledge: we start knowing from a certain height (which confers to the observer an extraterritoriality). From this vantage point, we gradually go down, digging more and more, sinking into reality until we reach the elementary parts using various techniques of control and manipulation.

In contrast, complexity approaches have typically progressed differently, following a reversed trajectory: they start from a geological bedrock, a biological background or a chemical soup and observe the empirical evolution of rudimentary entities that aggregate into phenomena characterized by pure immanence. These are formed through an ascending process, involving reticular projections, rhizomatic growth patterns and collective behaviors, each one richer than the last. At each level of a system, we observe an increase in collective power and the emergence of supplementary properties that become difficult to explain or completely vanish as soon as we attempt to analyze them at a lower level.

The main physical properties that enable the development of such levels of complexity are *nonlinearity* (when causes and effects are not proportional), *emergence* (when the whole is more than the sum of its parts) and *evolution* (when the irreversibility of time catalyzes novelty). To clarify, we can offer a minimal definition of complexity based on these three characteristics. Nonlinearity means that for specific systems and phenomena constituted by a significant number of agents, the same causes can lead to different effects. This happens when it is not possible to average a statistical behavior of the whole system and the law of large numbers does not apply. Emergence unveils the properties of a system or a phenomenon that cannot be reduced to and deduced from the properties of its components. Evolution relies on a creative medium, time, in which what matters most is not being but becoming.

With this minimal definition proposed—one that could be enriched with more descriptive features—we find that many systems, beyond their respective physical attributes, share the same dynamics and properties. This provides a strong argument in favor of multi-, inter- and transdisciplinarity. If we view the diverse scientific disciplines as specialized silos, where scientists dig endlessly to gain deeper and deeper knowledge on increasingly fewer things, then complexity represents the mesh that collects the coalescent knowledge generated from their perforation and percolation. The study of complexity inevitably leads us to explore many different objects and phenomena across life, material, computer and data sciences.

Non-Euclidean World

There has always been complexity surrounding us: in nature, among plants and animals, and within our bodies—our brains in particular. Ancient knowledge and spiritual approaches have tackled complexity, but on their terms without formal language or mathematical and physical equations. Instead, they have relied on natural languages, expressed in different idioms and through a variety of cultures, with no other tools than human memory and reasoning, relying on ink and paper.

We may even view the history of classical science, Newtonian science, as an evolutionary and contingent journey that is progressing with huge advances, discoveries and empirical applications. At the same time, this history has become increasingly complex, with an alternation of straight lines and bifurcations. For instance, for over 2000 years, it was believed that only one unique type of geometry existed: Euclidean geometry. However new geometries were discovered in the nineteenth century that led to remarkable scientific advancements. For example, the discovery of curved geometries revealed that concepts of space and distance cannot obey the axioms

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and principles of Euclidean geometry, which deals with flat surfaces and two-dimensional figures. Non-Euclidean geometries, such as elliptic and hyperbolic ones, were decisive in the elaboration of Einstein's groundbreaking proposition of the curvature of spacetime. This idea, introduced at the dawn of the twentieth century, marks the first step in his theory of general relativity, which is arguably one of the most important scientific theories ever conceived.

Other "strange" geometrical objects, initially regarded as mathematical monstrosities (such as the Peano and Koch space-filling curves), demonstrated at the same period, deploy unique properties related to their dimensions, continuity and iteration. These objects are the first examples of fractal geometry, which was later developed with the help of the computer and became closely associated with complexity and chaos theory.

The real world is not flat, and we are eminently non-Euclidean and nonlinear. Thinking in terms of complexity may help us to produce a geometrical expression [1] and a combinatory exploration of human existence within a disturbed biosphere. In this planetary context, contemporary, sophisticated societies are constrained by physical limits that define the possible and viable ways of life, shaped by specific forms and edges.

How can we pave the plane, without saturating or depleting it? How can we refill and inhabit our terrestrial space and time to avoid the worst of possible worlds? If we understand the notion of complexity not just in terms of interwoven and intertwined elements but also, as the etymology implicitly suggests, related to the notion of folding—a term derived from *complecti* ("to fold together," leading to words like *multi-pli-city*, *ex-pli-cation*, *du-pli-cation*, *re-pli-cation*, *im-pli-cation* and *com-pli-cati*on)—we might improve our situation regarding disharmonious deployment and unfolding in space and time. We should revisit the ideas of Leibniz, an influential mathematician and philosopher, a prophet of our digital era.

> "In the 18th century, the philosopher and mathematician developed a visionary approach to complexity in his *Theodicy*—particularly through his evaluation of evil in terms of combinatorial optimization—and his dazzling treatise, *Monadology*, which sets out 90 vitalist propositions on the simple: numerous points of view and perspectives on the complex. With Leibniz and his attention to detail, manner, and fold, whole-to-part relations are offered a genuinely alternative epistemology to that of the reductionist vision and classical analysis. Monadology enhances our understanding of how, the deeper we dig, the more matter reveals its multiplicity. Matter does not simply cut itself up; rather, it folds, fills, and unfolds its folds, which "extend to

> infinity." Leibniz's work clarifies the relationship between the (un)meaningful fragment and the (in)commensurable whole, whether in the sciences of life, matter, or computation." [2]

In his masterpiece philosophical treaty, *Monadology*, Leibniz illustrates that complexity revolves around this notion of folding:

> "But a soul can read in itself only what is distinctly represented there; it cannot unfold all at once all that is folded within it, for this (*ses replis*) proceeds to infinity (*vont à l'infini*)." [3, § 61]

Leibniz's conception of the fold has been explored by the French philosopher Gilles Deleuze [4]. On Leibniz's mathematical and philosophical system, a monumental work has been produced by the philosopher and historian of sciences Michel Serres [5].

What is needed is to rethink the human multi-pli-city and its plenitude through the constraints and potentialities of folding and filling, weaving and blending. If we adopt this new geometry for our troubled geopolitics and geography, we can offer humanity a soft therapeutic approach that addresses the challenges of human fragility and the planet's finite resources.

Tiling the Plane

In geometry, the question of filling or recovering a surface by repeating one or more shapes without overlaps or gaps is a difficult and profound problem. The physicist Roger Penrose proposed a technical solution for tiling the plane using only two lozenges. A study published in 2007 in *Science* [6] showed that medieval Islamic designers applied geometrical tiling patterns 500 years before Penrose. The Girih designs created by ordinary tilers from Herat and Ispahan applied the Penrose technique by using five basic geometric shapes to produce complex decorative patterns, without any overlaps or gaps. This serves as an example of a challenging mathematical problem that can be better understood through its deep simplicity, and where medieval tilers enlighten us on how to proceed.

From a geophysical perspective, the challenges humanity faces in this century reflect these geometrical difficulties related to tiling the plane. An increasing number of scientists, particularly those working on climate change and global warming, consider that our way of filling and inhabiting our Earth leads to a systematic form of consumption of space and time. We are running low on time, space, resources and energy. This poses an existential dilemma for humanity: what kinds of agency can deal with our multiplicities considering the shrinking of space and time, the finiteness of the biosphere? Can we inhabit

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the planet and occupy its space and time differently from the prevailing civilization of the last 500 years? Can we find or invent new geometrical agencies?

Civilizations as Tiling Patterns of Space and Time

We can already predict with certainty that, for the better but more probably for the worse, the next, post-Western, civilization will be planetary or will not exist at all [7]. This new civilization will need to adopt a radically new approach to filling space and time and should reflect various ways of living that are adapted to the constraints of our physical limits.

Ibn Khaldun, the fourteenth-century North African author of *An Introduction to Universal History*, created the concept of *‘umran* to define what civilization is. Arnold Toynbee, in his *Introduction to the Study of History*, considers this work as “a philosophy of history which is undoubtedly the greatest work of its kind that has ever yet been created by any mind in any time or place” [8]. The Arabic term *‘umran* has the etymological root *‘a-ma-ra* which suggests meanings of either “filling” or “duration.” This concept of *‘umran* defines civilization as a particular way of treating space and time, as a manner or pattern for filling these dimensions. According to Ibn Khaldun, a civilization exhibits a complexity with a distinct duration; it emerges, grows, flourishes, matures, declines and ultimately dies, paving the way for a new civilization to arise.

In his “new science” of world history [9], Ibn Khaldun inserts these cycles into a dialectics of civilizations, which oscillates between nomadic, rural ways of life (*‘umran badawi*) and sedentary, urban lifestyles (*‘umran hadari*). It seems that the notion of *‘umran* provides a historical insight for our times, except that we are witnessing a sudden and complete change in the dialectics of civilizations, where the cycles of rural-urban, nomad-sedentary, are all overlapping and amplifying an overflowing urbanization of the world, the proliferation of cities, the extension of mega- and meta-poles. This invasive way of filling space and time has culminated in a global issue of centration and concentration, of growth and outgrowth. The biosphere is impacted by our activities and artifacts, our way of filling space and time and our overuse of vulnerable and depleted resources (like air and water). Science indicates that the sixth biological mass extinction is manmade, and our plastic waste has created a “seventh continent,” covering millions of square kilometers in the North Pacific. Given the lack of resources, space and time, after having pursued exponential economic growth and treated nature as a commodity, we must confront a hard problem that I refer to as a *restrictive geometry*: how can we tile the plane and do much better with much less? We are navigating civilizational cycles and spatiotemporal limitations in search of a certain kind of complexity. This complexity has an info-techno-anthropological depth, the product of lengthy and slow calculation, cogitation and lived experience. This delicate form of complexity is to be found at the edge of possibilities enabling all beings, all individuals, all simple Leibnizian monads, to express locally and differentially the same and unique world.

> "The same town, when looked at from different places, appears quite different and is, as it were, multiplied in perspectives." [3, § 57]

This same and unique world, constrained by its limits, requires a combinatorial exploration of agencies that do not saturate and destroy the space and time they inhabit.

Limits to Growth

On this equation joining modern civilization and the planet as a limit to human *hubris*, the very first scientific report warning about the dangers of endless economic, industrial and demographic growth was undertaken under the mentorship of Aurelio Peccei, an Italian industrial manager and economist. In 1968, he anticipated the risks of what he viewed as "a predicament for humankind." Note that at that time, most thinkers and strategists were worried about the nuclear arms race. However, under the auspices of his nascent organization, The Club of Rome, also known as the "invisible college," Peccei wanted to assess [10]:

> "the complex of problems troubling men of all nations: poverty in the midst of plenty; degradation of the environment; loss of faith in institutions; uncontrolled urban spread; insecurity of employment; alienation of youth; rejection of traditional values; and inflation and other monetary and economic disruptions."

Have we since made significant progress in the treatment of any of these complex, interacting problems occurring in all societies, which involve intricate technical, social, economic and political dimensions?

Half a century ago, in 1972, the Club of Rome published a historical report under the univocal title *The Limits to Growth*. The report was produced by a team of researchers from MIT. These scientists developed the first significant formal model of the Earth's system, relying on MIT's established methodology to understand the dynamic behavior of complex systems, the so-called system dynamics. Through computer simulation and modeling, the MIT team studied the behavior of the planet system through five key interacting factors that are subject to exponential growth: population increase, agricultural production, nonrenewable resource depletion, industrial output and pollution generation.

The report had an unprecedented international echo with its conclusion that "the limits to growth on this planet will be reached sometime within the next one hundred years." The report was the first of its kind to show that economic growth does not equate to progress. It is the first significant modern alert on the necessity to change our way of life, our perspectives and our understanding of the world. The report aimed to prepare people for "the transition from growth to global equilibrium."

What happened and is still unfolding in this century was not anticipated by the Club of Rome's report. We have given up any hope of reaching a global equilibrium. We found out that we have disturbed the climate, with human-caused carbon dioxide emissions and other greenhouse gases (fossil fuel combustion and industrial activities accounting for nearly 90% and deforestation 10% of these emissions). Furthermore, if we add to these emissions the footprint of human and ruminant livestock populations, we have a concrete view of what is meant by the saturation of space and time. While human actions can disrupt the climate, they cannot regulate it. In the meantime, the timeline originally estimated for reaching the limits to growth has been surpassed by another unexpected form of nonlinear growth, that of the biosphere limits. Beyond these limits, life will no longer be viable for humans and many other species.

Planetary Boundaries and Vital Signs

Fifty-five years after the Club of Rome's warning and the publication of the MIT research report on the limits to growth, the time has come to confront an alarming truth: the growth of geological, biological and chemical limits. Regarding the impact and responsibility of humanity in this growth, its coefficient of certainty is correlated to the multiplication and the transgression of a certain number of fundamental limits.

We have an idea of what the limits to growth may mean. It is related to the hard problem of a restrictive geometry stemming from human *hubris* on one side, and the constraints of space, time and the finiteness of Earth on the other. Pursuing the economic growth and level of consumerism of Western societies would require resources from many other planets. However, the situation is getting worse, as we are now caught in a "growth of limits" that is gaining more acuity with every new scientific report on the Earth system. The only uncertainty now lies in whether we have already reached, or have yet to reach, the ultra-critical turning point of climate change and how we can mitigate its devastating consequences. When we next say that the sky is the limit, it will otherwise mean that we have reached our ceiling.

According to a report published in September 2024 by the Potsdam Institute for Climate Impact Research [11], the "great acceleration," which began in the 1950s due to the exponential growth of human industrial and agricultural activities, has now surpassed six out of nine planetary fundamental boundaries. These planetary boundaries are scientifically defined and correspond to nine "established limits within which humanity can safely operate, maintaining the Earth's environmental stability, resilience and life-support functions." The planetary boundaries, which include climate change, and freshwater and stratospheric ozone depletion, are highly interconnected and interdependent. A seventh boundary, ocean acidification, is close to being crossed. Even the World Economic Forum, the most influential organization when it comes to promoting economic growth and neoliberalism, has published an article relaying the red alert that the transgression of these planetary boundaries represents [12, 13].

Another scientific report published in October 2024 has been abundantly commented on by international institutions, such as the World Meteorological Organization. This report identifies several indicators, referred to as planetary vital signs, which include ocean heat levels, glacier thickness, meat production per capita and fossil fuel subsidies. According to the latest measurements, 25 out of 35 of these vital signs have already reached "extreme records" (both highs and lows) and some 28 feedback loops are reinforcing global warming, while fossil fuel consumption remains 14 times greater than that of solar and wind energy [14]:

> "We are on the brink of an irreversible climate disaster. This is a global emergency beyond any doubt. Much of the very fabric of life on Earth is imperilled."

Just as the Club of Rome's warning was relying on MIT's work done on complex systems in the 1960s, what is happening 60 years later requires us to better understand new forms of complexity. What is occurring is a planetary, topological transformation, where the limits of economic, industrial and demographic growth are being replaced by the multiplication of geological, biological and climatic ones.

Nevertheless, the scientific approaches to complexity have not changed the mindset of rulers, decision-makers, economists and industrialists. After six assessment reports from the United Nations

Intergovernmental Panel on Climate Change, 28 COP meetings, hundreds of reports and thousands of scientific articles, nothing has changed [14]:

> "In a world with finite resources, unlimited growth is a perilous illusion. We need bold, transformative change: drastically reducing overconsumption and waste, especially by the affluent, stabilizing and gradually reducing the human population through empowering education and rights for girls and women, reforming food production systems to support more plant-based eating, and adopting an ecological and post-growth economics framework that ensures social justice. Climate change instruction should be integrated into secondary and higher education core curriculums worldwide to raise awareness, improve climate literacy, and empower learners to take action. We also need more immediate efforts to protect, restore, or rewild ecosystems."

The Catastrophe Landscape: The New Normality

Changing radically our way of life and our global civilization is now a matter of survival. The problem is not that citizens, ordinary people, are unaware of this state of emergency; rather, individuals know, see and physically feel the manifestations of climate deregulation. Flash floods, wildfires, droughts, heatwaves… everyone feels the climate disorder; nevertheless, nobody believes it. A quasi-religious belief in market fundamentalism, economic growth, mass consumerism and laissez-faire principles prevails in modern materialist societies.

The pervasive impact of humanity on Earth, often referred to as the Anthropocene, does not have a technological solution. Still, too many believe—again, in the religious sense of the term—that sometime, somewhere, somehow a technological breakthrough will save humanity from its hypermodern demons. This bias, known as technological solutionism, is particularly strong among the technocratic elite and operates among managers, strategists and economists as a form of magical thinking.

Contemporary societies, whether in the North, South, East or West, will evolve, for better or worse, in an adaptative landscape that is extremely volatile, uncertain, ambiguous and complex. Today, technological, economic, political, humanitarian, ecological and climatic catastrophes have become our new normality. These crises have been multiplied by the interdependent properties of the global system. We will have to learn how to survive and cope with them as ordinary events, each bringing countless cascading effects. Extraordinary events have become ordinary, and the highly improbable scenario would be the planet reaching a new global equilibrium. Humanity needs to adapt and do its best to mitigate the consequences of these serial catastrophic bifurcations. Catastrophes may not have an apocalyptic significance; they are elements of a contingent history of frequent extreme events. How can we live within this new landscape, this new normal?

As a side note, it is worth remembering that a catastrophe theory was elaborated in the early 1970s by French mathematician René Thom, a former Fields medallist, known for his work in geometry. This theory focuses on the "edges of forms," examining discontinuous phenomena considered as topological events through continuous mathematical models, and derives from the theory of bifurcations related to the study of dynamical systems. Ivar Ekeland, a French mathematician specializing in deterministic chaos, described Thom's catastrophe theory as a "theory of action" [15] where a system is studied not for its own sake, with its internal multiple variables and their potential, but in its reaction due to external stimuli. More than ever, a theory of action is needed to tackle the growth of limits.

From this perspective, what is urgently awaited is to reinvent the economy in the context of a disrupted biosphere and seek prosperity and progress independently from the classical, talismanic pursuit of growth for its own sake, achieved by any means necessary. Economics is not an exact science, and its theories of scarcity and abundance, the concepts of sobriety and prosperity, must be rethought entirely, as they are nowadays constrained by the limits of growth and the growth of limits. The axioms of the twenty-first-century economy must be completely redesigned, not so much to try to meet the United Nations Sustainable Development Goals, but as an urgent program for survival under global warming. The world poly-crisis is systemic, with an increasing risk of collective collapse due to geopolitical tensions, military spending, autocratic, populist—or even extreme-right—governance, along with social protests and unrest. Consequently, the changes needed to limit the consequences of climate disasters must also be systemic. Until now, the elites have focused on certain parameters, but, once again, the issue is fundamentally systemic. The COVID-19 pandemic, despite proving to be very limited in terms of danger and lethality, has demonstrated that world governance is capable of adopting systemic measures to slow down the world economy in response to a global threat.

Fusion of Sciences and Cultures: No Limits to Learning

We often associate the notion of complexity with the phrase "more is different" which is the title of an article published by physicist Philip

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Anderson in 1972 [16]. What is meant by this statement? Through scientific inquiry, we have gained insights into how natural systems operate at different scales, revealing the interplay between wholes and parts by transforming mere quantities into subtle qualities. This is precisely what is at stake with the set of geophysical limits that are today the only data that counts and on which our future depends. Consequently, adopting complexity approaches and nonlinear thinking based on data science and empirical observations, but also on various cultural understandings and contexts, may help us renew our worldview from a multidimensional perspective. Additionally, the hierarchical structure of science, as highlighted in Anderson's article, has contributed to our current crisis in perception and description.

We are at the end of a civilizational cycle, where a particular understanding of matter and life, along with its associated standards and values, has paved the plane of every square meter of the planet's surface. We desperately need to adopt new ways of filling space and time, and the fusion of sciences and cultures proposed by Moroccan economist and futurologist Mahdi Elmandjra may help us invent or discover them. In a post-Western, multipolar world, establishing a new and productive relationship with knowledge should include different worldviews. The sciences that focus on patterns, qualities and singularities may contribute to enhancing creative modes of becoming, encouraging people to engage in anticipating and participating in alternative futures. We need less to project than reflect possible dissolutions of the twenty-first-century problem of Earth's limits. Elmandjra, a member of the Club of Rome and a former president of the World Futures Studies Federation and Futuribles International, believed that "modernization" should not have meant "Westernization," using Japan as an inspiring example of this distinction. For Elmandjra, cultural pluralism is essential for the future of humanity, and he was anticipating [17]:

> "a geopolitical rupture with the past and the role of cultural diversity in a pluralistic world where survival calls for the elimination of all forms of hegemony."

Rather than being once more subjected to a hegemonic civilizational narrative and a transcendental perspective of knowledge, like the one identified in the "More Is Different" article, the fusion of sciences and cultures could provide us with a truly cosmopolitan outlook on our destiny. This cosmopolitan perspective may protect us from the empirical blindness caused by the perception of light coming from a single horizon, that of a dead star. Unsurprisingly, Elmandjra was the co-author of another landmark report by the Club of Rome, titled "No Limits to Learning" [18], published eight years after the report "The Limits to Growth." In this book, Elmandjra addresses the "mounting challenge of complexity" by focusing on how to bridge the human gap and unveil potentialities rather than merely highlighting the physical constraints to economic growth. The notion of lifelong learners has its origin in this seminal report that emphasized the importance of a comprehensive educational project, one that would engage individuals and society through anticipation and participation in innovative learning processes. Learning is a source of endless exploration and discovery: the challenge lies in involving lifelong learners, not only from elite circles but from society at large, in anticipation that the futurologist considers as "solidarity in time" and participation as "solidarity in space."

Let us build on these arcs of solidarity and learn how to inhabit the world and create *planetary citizenship*.

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