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A paradigm shift for decision-making in an era of deep and extended changes

Mauro Lombardi[1] Simone Vannuccini[2]

Abstract

The complex interaction of contemporary techno- and socio-economic processes has set the stage for the emergence of a cyber-physical universe – the novel environment in which agents behave and interact. In this paper, we collect the different threads that lead to and characterize the cyber-physical world in a single analysis and outline a map of the complex dynamics at work in the new context. The resulting description is used to assess how decision-making should evolve in order to be able to address in a systemic manner the opportunities and challenges of the current era of deep and extended changes.

Keywords: ubiquitous computing; cyber-physical universe; artificial intelligence; decision-making

JEL Classification: O30; L21

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Introduction

We live in a time of great change. The 2020 pandemic adds to and amplifies three socio-technical and techno-economic processes, which are at the basis of three joint crises: biological-environmental (climate change), techno-productive, and economic-financial. It seems that the whole world is approaching what scholars of many disciplines define situations in which there are high risks of "unwanted collapse" (Scheffer et al. 2012: 344). An unwanted collapse takes the form of a tipping point, that is, a catastrophic bifurcation point, "where a minor trigger can invoke a self-propagating shift to a contrasting state" (ibidem: 344). The three joint crises behind the potential global tipping point occur after decades of evolutionary acceleration induced by an array of factors and forces leading towards a "hyper-connected" world; this, in turn, is characterized by the emergence of a multiplex of self-organized local and global interaction structures and processes within and between different domains.

The claim that the socio-technical and economic system is on the verge of a catastrophe is recurring, and often appear at particularly relevant historical nodes – for example in phases of transition between established and upcoming techno-economic paradigms. To put it with Gramsci: "the crisis consists precisely in the fact that the old is dying and the new cannot be born; in this interregnum a great variety of morbid symptoms appear" (Gramsci and Hoare, 1971). This explains the cyclicality (and, thus, the recurring fads) of the theories of cycles, such as that of Regulation, of World-Systems, or of Long Waves (Silverberg, 2003). However, not all catastrophes – in the sense of catastrophe theory – are alike. In this paper, we make the case for the uniqueness of the current unwanted collapse to come, and discuss how a view taking into account the transformations now in the making should inform decision-making.

In order to do that, we present a map of the deep and extended changes that are currently unfolding and shaping the hyper-connected world we live in. This map is described by a collection of fundamental coordinates: building blocks, concepts, and principles that we single out in details while we also highlight their interconnections. The core notion is that of the unprecedented cyber-physical universe taking shape – an informational and physical landscape drawing the boundaries for actions and transformations to unfold. Our contribution lies in the unique combination of several literature strands, which we use to stress the convergence of different and often non-proximate scientific domains around similar perspectives and problems. The snapshot analysis we propose is necessarily systemic, complex, non-linear and recursive, as it mirrors the manner in which the landscape on which actors operate is characterized. We use our map to derive implications for decision-making; in particular, we suggest that a shift to "adaptive strategic thinking" is required for actors to survive and succeed in the novel landscape.

1. Coordinates for the current era: the "Earth-System" and a cyber-physical universe

We ground our analysis on a set of (improperly speaking) axioms regarding the nature of socio-techno-economic systems. These basic statements define the paradigm of analysis from which our insights descend. They are: 1) the wave like properties of the evolution of complex adaptive systems. 2) The adoption of a general definition of technology as "any intentional extension of a natural process, that is, of processing of matter, energy, and information that characterize all living systems" (Beniger, 1986: 9). 3) The proposition that "A society cannot develop unless an adequate infrastructure for the movement and processing of matter, energy, and information already exists" (Beniger, 1986: 184). 4) Material and immaterial infrastructures are evolving multilayered networks of structured knowledge. 5) Sequences of socio-technical landscapes are complex and interrelated processes evolving towards asymptotic stationary equilibria, while are every now and then interrupted by distributed discontinuities. 6) Deep and extended changes occur when founding rules are changed and their effects propagate even after a long time.

In the introduction, we mentioned the three distributed discontinuities (crises) that are impacting and transforming – potentially in an abrupt, unwanted-collapse-manner – the socio-technical landscape, as indicated in point 5) above. In this Section, we outline the contours of the new landscape in the making and the dynamic forces shaping it. Our idea is that complex developments, approximated in 1) and 4) are producing 6); we outline these complex developments below.

The exponential increase of computational power and storage capacity, the pervasiveness of information processing devices (*Ubiquitous computing*), the creation of software systems able to process an increasing amount of information flows from all over the world (*Ubiquitous connectivity*), and advances in digital technologies and Artificial Intelligence (AI) have been key drivers of a generative process of intermingling networks at multiple scale and across traditionally different socio-economic activities. This generative process has definitively decoupled the locus of value generation and that of information production and processing, which now is ubiquitously distributed. Thanks to the consequent triggering of cross-scale positive feedback among these dynamics, thereby feeding systemic complexity both at the local and global level, a new global landscape has emerged. In this scenario of multiple complex systems and nested sub-systems, which interact and evolve within the "Earth-System" (Lenton et al., 2008), the outcome of the transformation is a widespread uncertainty and a looming instability. However, a set of emergent patterns is also taking shape. These are: 1) the development of self-organizing processes, able to manage hyper-scale infrastructures, which have been essential drivers of the formation of hyper-structures (Baas, 2013; 2016). 2) The techno-scientific advancements allowed representing (codifying) real processes and outputs from the nanoscale to the ordinary and global scale – especially as every phenomenon can be read through the lenses of information (O'Connor et al., 2019). Each codified "object" in the natural world becomes a source of fine-grained, real time digital data and can be paired with its own "digital twin", a full description of the object embedded in software systems, which can be used to simulate real-time changes and interventions. This kind of theoretically complete 1:1 map from the subatomic world to whatever level deemed appropriate for designing processes and outputs leads, in essence, to perpetual self-production. Indeed, interaction, feedback and exchange of information created what Zittrain (2006) has called "generative space" of ideas and knowledge. 3) The closed world of Newtonian theory, to paraphrase Koyré (1957), is over. Human beings live now in an open-ended universe (Kauffman, 1996; 2009), which is continuously expanding and evolving. 4) As a result, we experience a sort of accelerated expansion of the digital universe, parallel and tightly linked to real processes and their dynamics. We can define this complex and dynamic intermingling the *cyber-physical universe*, within which real and digital processes interact and influence each other to the point that sometimes it becomes impossible to distinguish real from virtual. 5) The openness of this cyber-physical universe implies that the Newtonian mechanistic clockwise "in which big problems can be broken down into smaller ones, analyzed, and solved by rational deduction" (Plsek and Greenhalgh, 2001: 625) is no longer working. The "machine" metaphor is out of date, and completely not appropriate to understand what is happening within the Earth-System (Steffen et al., 2007), where the standard model based on linear cause-effect relations does not work. Indeed, globalization of processes, within which goal-oriented interactors (individuals, collective entities) pursue their goal(s), give rise to interlocking relationships, with relational topologies emerging from exploratory activities performed in different techno-scientific search spaces. The cyber-physical universe becomes the world of non-linearities, because agents populating it evolve on the basis of exchanging information, constructing and modifying systems of beliefs, cognitive procedures, mental models and system of rules – all endogenously shaped by the topology and nature of multi-level and multi-domains interactions. These non-linear and systemic dynamics of cross-influences has triggered an exponential acceleration of change of the Earth-System on many levels.

Taking stock, profound techno-economic transformations and their co-evolution extended to the whole Earth-System are producing a novel, unprecedented landscape on which actors operate – the cyber-physical universe. This landscape is characterized by multi-level complexity, non-linearites, and is made coherent by the pervasiveness of its informational nature. Given that, and paraphrasing David Deutsch (1998), we advance the following statement: *The entire Planet has become a techno-social system, where Information Technologies constitute the "Fabric of Reality"*.[3]

Such an unprecedented configuration of reality necessarily shapes the set of opportunities and challenges actors face. At this point in the discussion, three issues deserve to be addressed: 1) What made these advances in techno-science possible? 2) Given the fundamental transformations we outlined, how has changed the decision-making landscape around us? 3) On which mental models (paradigms) should decision-making processes be based, now that we are immersed into the cyber-physical universe?

2. The trajectory over centuries towards a cyber-physical universe. What made these advances in techno-science possible?

In this Section, we outline three fundamental steps in the evolution of human attempts to represent the world around us. Cumulatively, these steps have set the stage for the cyber-physical universe to take shape.

1st step: the discovery that the written language of the world can be binary

Philosophers have always questioned the nature of mathematics and geometry, as well as their relationship. A watershed event certainly was the publication of Galileo's The Assayer, where the scientist states that the universe is an all-encompassing book written in mathematical language. For centuries before Galileo's claims, humans have attempted to represent the world through a numeral system. The diffusion of the decimal number system (also called Indo-Arabic), which had numerous advantages compared with the Roman numeral-based system, has not stopped the search for different non-decimal numeration, such as binary and duodecimal, as documented by Glaser (1971), as these were a potential source of utilitarian benefits. A big leap took place in the 17th century thanks to Leibniz, who for the first time in history elaborated the set of number from 0 to 15 in binary terms.[4]

[3] "The fabric of reality does not consist only of reductionist ingredients like space, time and subatomic particles, but also of life, thought, computation and the other things to which those explanations refer" (Deutsch, 1998: 28)

[4] Leibniz G.W, 1697, Letter to the Duke of Brunswick, reprinted in Glaser (1971: 31).

The importance of the binary representation by Leibniz should not be underestimated: the possibility to represent everything through 0s and 1s, even if conceived for theological reasons, has opened an enormous space for the development of human knowledge.

2nd step: insurmountable limits of human reasoning open up an unthinkable space of potentialities

About two and half centuries after Leibniz, Kurt Gödel (1931) wrote an article in which he demonstrated the undecidability of propositions belonging to a logical-formal system such as that of the Principia Mathematica by Whitehead and Russell. The achievement, known also as the First Incompleteness theorem, is above all remarkable from the point of view of the philosophy of Logic, but at the same time it displays a crucial feature: it has strong similarities with a modern computer program (Davis, 2000: 119-120). Many years before the invention of calculator, Kurt Gödel was designing a logical procedure through which formalize the "same issues that those designing programming languages and those writing programs in those languages would be facing" (Davis, 2000: 120). In brief, Gödel introduced an algorithmic approach as a method of proof. The possibility to formalize the reasoning process in such a way that it is possible to demonstrate in a definitive manner even the impossibility of axiomatizing within logical-formal systems, can be likened to the "invention of a method of inventing" (Griliches, 1957): new knowledge is generated by the parsing of existing knowledge through operations that describe a set of rules of transformation.

3rd step: Final leap to "abstractization" of human reasoning, subsequently embedding it into a real machine

This step was accomplished thanks to the contributions of two of the most important personalities in the field of the theory of computation. The first is Alan Turing, who in 1931 analyzed the computation process based on a further mathematical abstraction represented by an a-Machine, commonly known as a Turing-Machine; his result: anything computable by an algorithm can be computed by a Turing Machine (Davis, 2000: 188). The completion of the third step took place thanks to John von Neumann, who already in 1930 had perfectly understood the revolutionary content of Alan Turing's speech in front of the most eminent scholars of the twentieth century, gathered in Könisberg, where he anticipated the ideas expressed in the 1931 article. In fact, von Neumann had already autonomously reached Gödel's conclusions regarding the problem of the undecidability of propositions in the context of logical-formal systems. However, once the results obtained by Gödel were known, von Neumann no longer dealt with logic and devoted himself to the development of powerful computation machinery. In fact, von Neumann elaborated the famous Draft Report on the EDVAC computer (1945), in which essentially he proposed a device modeled on the "Universal Turing Machine". Thus was born the von Neumann architecture, which is the embedding into hardware of the sequential (Turing) model of computation (Prytkova and Vannuccini, 2020), still the prevalent architecture on which today's computers are based.

At the end of these three major steps, Leibniz's dream of creating a "*characteristica universalis*", that is, a symbolic system capable of representing with the binary system, beyond the syntactic differences existing between the various languages, human thought and all the fundamental concepts and real processes, seems to have come true. In reality, the developments we described set us on a path leading well beyond Leibniz's dream. The binary system and the von Neumann architecture led the way to information technologies, which have been enhanced in the last few decades to the point of becoming what we have called the fabric of reality, a fundamental infrastructure, which in turn interacts and is in a superposition with physical processes to form a global whole – the cyber-physical universe. In the cyber-physical universe, countless sources of information and novelties are continuously generating unexpected impulses: individual and societal needs widespread at the international level; need for strategic resources, such as food, energy, water, or Rare Earth Elements (Balaran, 2019); techno-scientific advances; competitive pressures between companies and countries. Given the nature of the new fabric of reality, it is necessary to rethink the modalities and mechanisms of decision-making processes, as they intervene in (and impact) a unique and unprecedented environment.

3. How has changed the decision-making landscape around us? Human decision-making processes facing a new complex landscape

The previous analysis brings us to frame a new global and extremely variable landscape, in which human decision processes must unfold. In this new context, the ontology of agents inevitably changes and evolves due to the underlined interaction structure among multi-level and multi-scale processes. In this Section, we describe the "ingredients" of the new landscape; more precisely, we describe: an ontological space populated by cyber-physical systems (CPS); the evolution of humans' external memory field (EXMF) and the implication for information processes; the emergence of new tools for modelling the world; new properties of processes and products; and the move beyond the traditional concept of firm towards innovation eco-systems.

3.1. Ontological space

By ontology of agents, we mean a conceptual space that they themselves construct and define according to their ability to frame processes and events, representing the real world and the entities that populate it. In the present era, the ontological space must be defined in relation to new components, which we introduce in the next sections, in the light of the unfolding interlocking relationships among nested networks and processes at the global level.

3.2. Cyber-physical systems within a cyber-physical universe

Given the continuous and enormous expansion of the *info-sphere* (Floridi, 2014; Handy, 2015) and of what Brian Arthur calls *The Second Econo*my (Arthur, 2011)[5], real activities unceasingly generate signals and information, thus giving rise in human minds to an ontological space teeming with multidirectional interconnections between cyber-physical systems, which "integrate". We consider CPS the *crucial agents* (the relevant unit of analysis) populating the new ontological space, as they are "composed of physical subsystems together with computing and networking." (Lee and Seshia, 2017: 12) and "integrate physical dynamics and computational systems" (ivi: 77).[6]

3.3. Humans and their External Memory Field

While CPS are the fundamental agents of the new ontological space, another fundamental component is worth examining: what Merlin Donald calls the External Memory Field (or EXMF). In Donald's words, "the EXMF usually consists of a temporary array of visual symbols immediately available to the user. The symbols are durable and may be arranged and modified in various ways, to enable reflection and further visual processing" (Donald, 1991). In analyzing the evolution of the human mind and cognition, Donald distinguishes three transitions in the representational systems created by the brain during evolution. The adaptive emergence of the third one is the extension of "visuocognitive operations into, and becoming a part of, an *external symbolic system*" (italics added; Donald, 1991: 274). Starting from the invention of written language, a lot of graphic and visual tools have been created through interactions among people and more in general with the operation environment. This evolution has been the result of the attempt to bridge an ever-renewed gap between acquired knowledge and at the same time the need for new knowledge to solve problems. Indeed, the "symbolic use of graphic devices" has been enriched over the centuries through different forms of expression (artistic, technical, scientific, and so on). This unfolding has come about until the turning

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[5] "All digital processes are conversing, executing, interacting, updating, transforming, triggering changes… It is vast, silent, unseen, autonomous, parallel, self-configuring, self-organizing, self-architecting, self-healing…. [like] an aspen root system" (Arthur, 2011).

[6] "Cyber-Physical Systems (CPS) are integrations of computation with physical processes. Embedded computers and networks monitor and control the physical processes, usually with feedback loops where physical processes affect computations and vice versa". (Lee, 2008: 363).

point (we add) of the binary system proposed by Leibniz, who provided an extremely powerful impetus for the development of an essential cognitive workspace, thanks to a symbolic system inherently tending to represent the world in its entirety (universality), starting from basic principles and building on them rules and systems of rules.[7]

Since CPS combine computation, communication, and physical dynamics, while the EXMF has become an expanding universe of both organized information flows and chaotic information particles, it is not surprising that human mental frames have been striving to pursuing ever-greater computational power and ever more sophisticated representational systems. Indeed, cumulative feedback loops between the application of information-processing devices to the production of new information have powered a sort of arms race between knowledge-accelerated growth and the tools to master it. The binary system was therefore a key driver in feeding the continuous expansion of the info-sphere and consequently of making information technologies the fabric of generativity, as defined by Zittrain (2008: 70): "*Generativity is a system's capacity to produce unanticipated change through unfiltered contributions from broad and varied audiences*". Generative systems occur when information flows, possibly coming from countless sources, self-organize based on the congruence between shared interests, values, paradigms and worldviews, or "simply" since the agents share compatible research guidelines and objectives. The novelty of our age is that, thanks to information technologies, generative systems *are drivers and result* of global interconnections, so that they show particular features: 1) *scalabilit*y, due to ubiquitous computing and connectivity. 2) *Adaptability*, as physical architecture and software systems unceasingly evolve, in this way allowing more and more information be created and/or processed. 3) *Progressive blurring of boundaries* between material and immaterial processes, thanks to their integration realized by the globally spreading of CPS.

3.4. New tools for modelling the world from the nanoscale to the ordinary scale and global level

A further and fundamental aspect on which to focus attention is the following: the development of computational power opened a completely new world (scale) for experimentation and discovery.[8] Indeed, it is now possible to computationally design one-dimensional and two-dimensional materials, which can be used in the production of products such as, for example, microprocessors and for many

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[7] Here we are broadening and extending Donald's original view by taking up what we have previously covered in Section 1.

[8] Something similar happened in 1959. We cannot help but remember Feynman's famous lecture "There's Plenty of Room at the Bottom", transcript of the talk given by Feynman on December 29, 1959, at the annual meeting of the American Physical Society at Caltech, printed in *Engineering and Science ,* 1960, February. An incredible boost was given on that occasion to the birth of nano-sciences.

other outputs, which are yet unknown when they are invented. Those materials do not exist in nature – as far as we know – and are created by engineering them at the atomic and sub-atomic level, or at the nano-scale, and then built-up to the scale of everyday life, in what is labelled multilevel materials design (McDowell and Olson, 2008; Olson, 1997; Gibney, 2015; Castelvecchi et al., 2017).

Basically, the computational and integrated modeling of the entire production process at every scale is currently underway, ranging from inputs, considered to be infinitesimal in size, to the final output, through what is called "integrated computational engineering" (ICME, 2020). It is therefore a reality with which to measure the computational modeling of both economic-productive sequences and the final products, which, for the previously indicated elements, take on completely new properties.

3.5. New properties of processes and outputs

From the previous point, we can also deduce that each process or output (e.g. a product) tends to be the result of a diverse set of technologies, i.e. knowledge domains that are dynamically combined through intersections, overlaps and convergences between different disciplinary fields. Consequently, as in the present era the identification of techno-productive problems and the search for their solution occur within the new global landscape, outputs assume a variable configuration, that is, a multi-technology and multi-disciplinary composition, *as a mix of traditionally separate knowledge bases*. The degree of complexity therefore increases, as processes and outputs take on a systemic nature. More knowledge-intensive components are connected in such a way as to perform some functions, which can vary depending on the context in which they are inserted and on the degree of embedded intelligence in the algorithms that are involved in the process, which can in turn be transformed and added depending on evolving human needs. Thus, products become smart, connected and complex (Porter and Heppelman, 2014). Our analysis lead to highlight that they acquire a new property: they can be rationally (purposefully) imagined and designed as sets of variable functionalities. As they derive from integrated physical and virtual-digital activities, their interacting with the cyber-physical universe, where multiple and repeated feedback between producers, consumers, technical-scientific domains and socio-economic dynamics take place, feed the emergence of new requirements, which can be matched through changing physical architecture (materials, components, logic structure), embedded knowledge (software) and interaction mechanisms (protocols, interface rules).

3.6. Beyond traditional view of firms: Innovative eco-systems

Ubiquitous computing and digital ubiquity allow the unfolding of positive feedback loops between many techno-scientific and techno-productive innovations, such as: digital technologies (3D printing, advanced robotics, Internet of Things), new materials (Bio- and nanomaterials, supermaterials), new techno-scientific processes (data-driven production cycles, synthetic biology, post-genomics, data-driven scientific discovery, and applications of artificial intelligence systems). The outcome of these feedback loops is the dissemination of knowledge-intensive processes and outputs, where interdependencies, complementarities, cognitive and operational conflicts, systemic integration become essential dynamic properties. In this scenario, it is not surprising that the boundaries between firms are no more crisp, but rather "fuzzy and blurred", and they tend to be conceived in terms of innovative eco-systems (Paulus-Rohmer et al., 2016). In fact, we can claim that the study of companies' decision-making in the new landscape will miss the mark if it will continue to focus on the firm as unit of analysis. The correct unit of analysis is rather *the bundle of organized process that harness distributed information flows from the concert of sources we singled out* in this paper. This means that the mechanism of formation of firms' boundaries cannot be fully proxied by the classic "make or buy" trade-off or by simple transaction costs arguments. Firms, as micro-organisms in symbiotic (though not always healthy) relation with the Earth-System and immersed in the cyber-physical universe, are subject to continuous structural re-modulations, given the complex, ever-changing pressures and opportunities at multiple levels.

At the level of the economic and productive sequences, the variable sets of phases and operational tasks (Baldwin, 2012; Yonatamy, 2017) can be modeled with computational tools on the basis of a systemic, multi-scale and integrated perspective. This frequently includes the design of the structural properties of processes, the characteristics of outputs and performances, up to control along the entire life cycle of the products, whereas it is always possible to add functionalities, as we have previously pointed out. All this takes place through top-down and bottom-up information processing activities, in the context of deductive, inductive and abductive processes. In short, what we witness is the emergence of a new techno-economic paradigm, which results from the combination of Engineering, Physical Sciences based on computational modeling, and strategic management, strengthened by new and powerful information processing technologies. These in turn rely on multiple sources of data: structured (databases, spreadsheets), non-structured (written texts, photos, videos, images and sound documents) and semi-structured (tags, markers useful for identifying certain elements, but for which it is not possible to develop models capable of giving them a structure).

The importance of computational power and the ability to capture and store information from different sources cannot be underestimated; to that we add an additional essential factor: *processing systems must have adaptive capacity*, in the sense of not being limited to a static representation of the collected data and information. It is necessary that they perform dynamic functions, in order to support the management of material and immaterial flows, as well as the creative interpretation of increasing information flows. However, the ever-expanding cyber-physical universe on a global scale incessantly generates sets of problems that scientists, experts and researchers from various disciplines strive to solve. A fundamental problem is that of making intelligible the growing mass of data and information, transforming them into useful knowledge to face perennially emerging economic needs. A logical implication of all this is that there is always the need to overcome the gap between the computational capacity of agents (individual and collective) and the information generated by a constantly evolving environment.[9] In situations characterized by limitations in computational power, in the amount of time and memory, the decision maker "is confronted with the problem of behaving approximately rationally, or *adaptively*, in a particular environment" (Simon, 1956: 120-130, *italics added*).

Currently, the main trajectory pursued by agents to achieve adaptive capacity is to increasingly augment decision making processes with information processing systems embedding AI; this is the dynamics we discuss next.

4. A paradigm shift for decision-makers to address the challenges posed by the new landscape

4.1. Rational decision-making with Artificial Intelligence

In the previous Section, we suggested that processing systems, in general and in particular within the cyber-physical universe, need to be dynamic and display adaptive capacity. This requirement brings us directly to the growing importance of the field of AI for decision-making. In fact, an increasing strand of literature focuses on the possibility of strengthening human decision-making processes through the development of powerful software systems and their use in all activities at any level. Such software systems are in essence information processing algorithms falling under the category of AI.

Two fundamental approaches have been used in AI studies. The first is the "classic" paradigm (Newell and Simon, 1972) of symbolic processing, or good-old-fashioned-AI (GOFAI), centered on the hypothesis of "physical symbol systems", that is, physical information processing systems that

[9] Precisely in relation to this gap, intrinsic to the decision-making processes of living beings, the Nobel Prize for Economics Herbert Simon has developed the concept of bounded rationality (Simon, 1991: 175).

process information based on “declarative knowledge bases”. In this case, the knowledge relating to the domain of a problem is represented through “declarative sentences” and it is processed through first-order logic. While classic AI analyzes well-defined problems using deductive logic rules, the second approach is the sub-symbolic paradigm, explicitly inspired by the biological neural systems of the brain. Starting with the seminal book by Rumelhart and McLelland (1986), neural computing, also known as connectionist approach, models processor-node networks without explicitly representing knowledge trough symbols. All (artificial) neural networks are directed graphs processing input into output having defined a certain activation functions for the nodes of the graph (Prytkova and Vannuccini, 2020); modern neural networks extend such topology to encompass multi-layered directed graphs and more modular and hierarchical structures (e.g. “capsules” as in Sabour et al., 2017). The approach (from the initial experiments with perceptrons to current bio-inspired AI) tries to simulate the individual and collective dynamics (rules of activation and propagation of information) of the neural networks that are activated in the brain.

After the first successes, the 90s saw the latest among the cyclical “winters” of AI, because even the connectionist models (initially with only three layers of neurons) seemed to show limits in emulating cognitive functions such as language processing, perception, memory. The consequence was loss of interest, reduction of investments in the research trajectory, and stasis in the creation of new, more sophisticated computational models. The connectionist approach gained new life in the early 2000s, when a group of researchers from the University of Toronto, led by Geoffrey Hinton, introduced the Deep Learning technique. In short, Deep Learning applies the backpropagation algorithm based on gradient descent to update nodes weighting to a new organizational model of the artificial neural networks, made up of many layers (and thus “deep”), with groups of modules in each of them and transversal connections in an impressive numbers (billions). Deep Neural Networks (DNN) models are showing remarkable performances in the recognition of spoken and written texts, images, simple phonemes, reconstructing complex representations from simple and scattered typological details or categories. For example, a type of DNN, convolutional neural networks, uses the operation of convolution to extract feature from complex data input (e.g. images as grids of pixels), layering up these features from the most essential (corners, contours) to more articulated ones (full objects).

The success of Deep Learning in combination with artificial neural networks and the universe of new techniques and refinements developed in the last decade (for example parallel advances in the technique of reinforcement learning) could not have been achieved without impressive advancements in computing power and in the data availability (see Prytkova and Vannuccini, 2020). Increasing computational power and data availability are the byproduct of the unfolding dynamics that lead to ubiquitous computing and connectivity – the generalized digitization of physical objects and processes that is at the core of the cyber-physical universe.

The last twenty years have witnessed an impetuous development of computerized systems and artificial agents capable of performing tasks and functions that normally require human intelligence. New methods and procedures with genetic algorithms turned out in the planning and control of optimization processes¸ while models based on neural networks have gradually assumed an increasingly important role in the recognition and processing of natural language and in artificial vision. Several scholars have developed Bayesian models of computational processing, which combine structured knowledge representations with statistical inferential machines. Hierarchical Bayesian models have made it possible to discover "correct structural forms of many real-world domains" (Tenenbaum et al., 2011), as well as causal relationships and analogical transfers of knowledge in different domains. At the origin of these approaches are the contributions of Pearl (1988), Muggleton and De Raedt (1994), and Richardson and Domingos (2006): Pearl has developed Bayesian probabilistic models of causal relationships; Muggleton and De Raedt have contributed significantly to the inductive logic programming trend, which aims to create artificial systems capable of learning autonomously, through what is called statistical relational learning (De Raedt and Kersting, 2017); Richardson and Domingos introduced Markov Logic Networks, which consist of sets of formulas written in the logic of first-order predicates, with an assigned and variable weight based on experience and inductive processes. In an attempt to answer questions about how rich representations can emerge from partial, fuzzy, incomplete data, Lake et al. (2015) proposed the Bayesian Program Learning framework, based on three fundamental principles: compositionality, causality and learning to learn. These are the founding elements of a process of construction based on cognitive blocks of an inductive nature, which uses and reuses fragments of knowledge broken down and grouped according to probabilistic methods in new forms.

The evolution of the field of AI seems to follow a (tortuous) path towards models hybridization and to the definition of a unifying style that combines the properties of symbolic and sub-symbolic approaches (Domingos and Lowd, 2020; Marcus, 2020). With these advances at hand, AI technologies become a key tool to operate within the cyber-physical universe, given the exponential growth of global information flows and the need to incessantly process them.

4.2. A paradigm shift for decision-making: toward an "adaptive strategic thinking" approach

The changes analyzed in the previous pages imply the need for a paradigm shift for decision making, in terms of general principles and operational criteria. Regarding the principles, the emerging problems around the world require designing systems capable of withstanding temporary and structural shocks through the acquisition of resilience and robustness. Following Folke et al. (2004: 558), we define resilience as “The capacity of a system to absorb disturbance and reorganize while undergoing change so as to retain essentially the same function, structure, identity, and feedbacks”. Instead, robustness of a system indicates the decisional and structural flexibility suitable for absorbing in the long-term changes induced by fluctuating environments (NRC, 2007: 33-34). Studies on this subject show two general principles favor both properties: redundancy and modularity. Redundancy (“the property of one component to perform another’s function”, NRC, 2007: 49) can avoid catastrophic effects resulting from the loss of specific components, such as to generate cascading effects in the event of systemic interdependencies. Modularity means “compartmentalization, or the decomposition of a system into discrete units, into subsets of entities with high-frequency interactions between them and low-frequency interactions between subsets” (Simon, 1962). Modularity confers strength, because it reduces the possibility of spreading negative impulses, similarly to the “social distancing” the world is experiencing in the present era.

From these strategic principles derive no less important operational criteria to be followed in a scenario characterized by acceleration, uncertainty and unpredictability. First, the fragility of the so-called “command and control” paradigm – the pursuit of maximum efficiency according to mental and organizational schemes planned in conditions of complete knowledge of the operating environment – emerges clearly. As a complete insulation from the complexity of the cyber-physical universe is impossible, over-capacity and redundancy, considered inefficient in a controlled environment, become essential to guarantee operating conditions when more or less sudden shocks arise, together with safety problems and blockages of supply flows, for example, in global production sequences, as it is currently happening (Schneier, 2020).

Connected to the previous one is a second criterion: the time horizon of each operator must extend beyond short-term expectations; it must be rather long-term oriented and with a focus on interdependencies, on multi-dimensional feedback loops within social-ecological complex systems. In a hyper-connected world, actors must be “patient”, as the complexity of interrelationships makes contexts highly variable and less predictable in their outcomes; learning processes become crucial and the application of “mechanical management” models based on bounded sets of choices to maximize lose value, because the variability of the parameters useful for decisions must be taken into account. Thus, adaptive strategic thinking (M. Lombardi, 2020, A strategic frame for innovation policies, Creative Commons, June, Chapter 3) and adaptability become fundamental, as they are based on incessant research activity in three directions: 1) exploration of the technical-scientific potential. 2) Analysis of systemic interrelationships and multiple risks. 3) Transformation of operational models according to the identified trajectories.

From the perspective of managerial models, all this logically implies the overcoming of models anchored to a fixed set of tools and the adoption instead of models that are orthogonal to these, namely models grounded on the continuous search for new tools, bearing in mind that economic processes are interconnected with the social and natural environment. In the horizon just described, the indication of the transition from mechanical management, based on the search for permanent and definitive solutions to complex problems, to "biological thinking", centered on very different principles, is suggestive: experimentation, resilience instead of efficiency, systemic and holistic vision, plurality of choices, tools and skills to develop adaptive potentials (See also Reeves and Levin, 2017) become key vectors for strategy.

Ultimately, it seems to us that *adaptive strategic thinking* is the theoretical and operational perspective suitable for making the most of the potential that is opening up to humanity, even if unknowns and risks are looming. This managerial frame may be the key approach to allow humanity to be able to maintain control of the "fabric of reality". Otherwise, this can be subject to uncontrolled dynamics with devastating effects: it is difficult to hypothesize that a multidimensional, complex and systemic vision can emerge without a conscious processing, both individually and collectively. This paradigm shift is essential to gain awareness of the multiscale and global nature of the changes taking place, and therefore to be able to develop fit strategies for survival.

Conclusion

In this paper, we uncovered the core principles, dynamics and drivers behind the emergence of what we called the cyber-physical universe. The cyber-physical universe is the fundamentally novel landscape in which agents operate, molded by the ubiquitous nature of information and the generative dynamics its production and use entails. The information technologies that are the infrastructure of the cyber-physical universe become the fabric of reality that blends together physical and virtual (digital) processes.

Through continuous approximations, we focused first on the emergence of the Earth-System as the common playground or workspace in which processes of different nature take place. Then, we singled out the historical steps that drove humanity towards the cyber-physical universe, and described some identifiable patterns occurring in the current landscape. From there, we unbundled the complexity that characterizes the intertwined forces at work in this context in order to shed light on which opportunities and challenges actors face in the novel ontological space opened by the establishment of the cyber-physical universe. In particular, we described transformations in the mode of conducting production activities, in the boundaries of the firm, and in decision making-processes. The latter, in particular, is subject to a proper paradigm shift, due to advances in AI that can help and augment decision-making. The dynamic matching between progresses in autonomous decision making system and restless mutations in the search-problem-solution space – both byproducts of the rapid evolution of the cyber-physical universe – requires the adoption of principles and operational criteria that are less inspired by the command-and-control approach and more fit to capture the non-linearities of the novel landscape. We suggest that a frame based on adaptive strategic thinking would be the most appropriate for actors to continue thriving in the current era of deep and extended changes.

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