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Global systems dynamics and policy: Lessons from the distant past*

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1. Introduction

Many human societies on Earth have at times experienced what we would call a 'crisis'. In the case of simple societies, in a wide range of environments throughout history, such crises have manifested themselves as famines. In complex societies, they may have taken the form of economic depressions such we are currently experiencing, social conflicts or wars of some kind between groups, or even the collapse of complete empires such as the Roman and the Chinese Empires (cf. Tainter, 1988).

The recurrence of this phenomenon, at a wide range of scales from small bands to complete empires, and in virtually any environment or domain of human endeavor raises the question whether such crises are inherent in the socio-environmental dynamics of all human societies? And if that is the case, would comparative studies of a number of instances reveal to us what drives societies into such 'crises'?

The study of crises has led to many descriptive publications, case studies and doomsday hypotheses, from Gibbon (1776–1789) and Spengler (1918–1922) to Diamond (2005), but it is only in recent years that elements of a more general *scientific* theory of socio-environmental dynamics, including 'societal crises' or even 'societal collapse' are emerging, combining insights from four research domains. The natural sciences have contributed to the set of ideas that is sometimes called 'the science (or theory) of complex systems' (e.g. Prigogine, 1978; Kauffman, 1993; Bak, 1996; Levin, 1999; Mitchell, 2009). Social anthropology has contributed in the area of 'Cultural Theory' (Thompson, Ellis, & Wildavsky, 1990), and the sciences of organization and information have contributed to our understanding of the organization dynamics of social structures (e.g. Pattee, 1973; Simon, 1969; Huberman, 1988; White, 2001). Some of these ideas on the nature of organizations have been taken up and adapted by ecologists (e.g. Allen & Starr, 1982; O'Neill et al., 1986; Allen & Hoekstra, 1992). Finally, the first attempt at a synthesis of these different ideas comes from a collaborative effort of ecologists and social scientists (Gunderson & Holling, 2002; Holling, 2001; Walker & Salt, 2006).

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Without overloading this paper with jargon and scientific debate, I will try to first present the reader with an outline of a theory that in my opinion is able to explain many of the characteristics of such crises; I will then illustrate these ideas with a couple of case studies; finally, I will describe some of the characteristics of such crises. At that point, I will shift the perspective from scientific description, analysis and synthesis to the domain of policy and try to make some recommendations relevant to the current situation in which the global system finds itself.

2. A framework for the study of socio-environmental dynamics

Humans differ from most other species in that they can learn and learn how to learn,[1] that they can categorize, make abstractions and hierarchically organize them, and that they communicate between themselves by various kinds of symbolic means. Human learning involves the recognition of patterns of all kinds, whether temporal, spatial, semantic, syntactic or yet other. By identifying such patterns, we organize the world around us, infuse it with structure and meaning, make it possible for us to understand it and/or know things about it, intervene in it, etc. As part of that process, human beings have the capacity to transform their natural and material environment in many different ways, and at many spatial and temporal scales. Our relations with our environment are part of the uninterrupted process of human learning, which may be seen as a positive feedback loop that creates order out of our experiences of the world, by isolating patterns, defining them in terms of a limited number of dimensions, and storing the latter in the form of knowledge. The more cognitive dimensions exist, the more problems can be tackled, and the more quickly knowledge is accumulated, roughly speaking according to the following feedback loop (van der Leeuw, 2007):

> Problem-solving structures knowledge $\longrightarrow$ more knowledge increases the information processing capacity $\longrightarrow$ that in turn allows the cognition of new problems $\longrightarrow$ creates new knowledge $\longrightarrow$ knowledge creation involves more and more people in processing information $\longrightarrow$ increases the size of the group involved and its degree of aggregation $\longrightarrow$ creates more problems $\longrightarrow$ increases need for problem-solving $\longrightarrow$ problem-solving structures more knowledge... etc.

The result of this process is the continued accumulation of information-processing capacity, which enables a concomitant increase in matter, energy and information flows through the society, and thus enables the society to grow. That information-processing capacity includes the sum total of the understanding, know-how and skills of the people involved, including their technical and organizational means of solving problems, their means to maintain group cohesion, etc.

[1] I.e. their capacity to process information is genetically encoded, but the information they process, and the ways in which they do so, is not. It is socio-culturally and self-referentially developed and maintained.

In this light, human societies can be seen as 'flow structures' (Prigogine, 1980).[2] Their existence is dependent upon flows of matter, energy and information that allow the needs of the individual participants to be met by distributing resources throughout the society.[3] Material and energetic resources are identified in the natural environment, transformed by human knowledge in such a way that they are suitable for use in the society, and again transformed during use into forms with higher entropy. These can then be recycled, or they are excreted by the society. The first kind of transformation increases the information content of the resources, whereas the second one reduces their information content.

The flows of matter, energy and information do not follow the same pattern. Matter and energy are subject to the laws of conservation, and *cannot* be shared. They could therefore never have created durable human social institutions, let alone societies. Information, on the other hand, *can* be shared. Human societies are held together by shared information, shared expectations, shared institutions, shared world-views, in short by a shared culture!

The channels through which information is processed emerge through a recursive communication process that 'aligns' people's ideas, language and culture. It draws more and more individuals into a network in which they can communicate and obtain resources more easily and with less effort and/or less risk of error than they would experience outside the network. On the other hand, when the recursive communication remains below a certain threshold, it keeps people out of a network because they cannot sufficiently maintain their alignment.

The shared information also creates the channels through which energy and matter flow, whether these channels are material (e.g. roads, cables etc.) or remain virtual (e.g. exchange networks such as the *kula* (Malinowski, 1922) or similar trade patterns (Sahlins, 1974). Sometimes the channels for information, matter and/or energy are the same, but that is not necessarily so: electricity, petroleum and coal are transported, processed and delivered in different ways, as are virtually all goods in everyday life that we do not collect or process ourselves. The 'fabric of society' consists of flows through multiple networks, held together by different kinds of (information) relations (kin, business, friendship, exchange, client-patron, power, etc.), and transmitting different combinations of matter, energy and information.

Ultimately, as Luhmann (1992) reminds us, the information processing occurring in society is also determinant for the society's definition of its environment, its environmental challenges and the solutions it might propose for them, as the society does not

[2] Prigogine, a chemist, proposed (1978) to change our usual perspective on a flow in a liquid from one where the flow is seen as a disturbance of stability to one in which the flow is a dynamic structure in an entropic environment. He also called these 'flow structures' 'dissipative structures', dynamic structures that dissipate entropy.

[3] In certain domains of study, one thus analyses the 'metabolism' of social organizations such as the city as the interaction of the flows that run through the urban system (for example, Newman, 1999).

communicate with the environment, but communicates within itself, auto-referentially, about its environment.

Maintaining a society's growth requires a continuous increase in the quantity of energy and matter flowing through the society, implying the identification, appropriation and exploitation of more and more resources. The dynamic is driven by the information-processing feedback loop. If not enough information is processed the members of the society will not be able to acquire sufficient matter and energy to satisfy all of them; people will then act in their own immediate interests and the society loses coherence. Avoiding this requires a continual stream of innovations spreading from the center to the periphery.

Continued innovation is facilitated by the fact that the closer one is to the center, the higher the density of aligned individuals and thus the more rapid the information-processing. Hence the innovation density of a social system is always higher nearer the center. Innovations create value for those for whom they represent something desirable, but difficult to attain. The farther from the center of the society, the more unattainable the innovations are because of the distance from the know-how that created them. The value gradient is therefore inversely proportional to the information-processing gradient. The perceived value of innovations prompts export of raw materials and resources available in the periphery to the center. These raw materials and resources, in turn, are transformed into (objects of) value wherever the (innovative) know-how to do so has spread. The objects are then exchanged with whomever considers them of value, i.e. whomever cannot make them (or not make them as well, or as efficiently), thus closing the loop between the two flows.

3. The Roman republic and Empire

To illustrate how this long-term perspective works at its most global, we could look at the history of the Roman Empire (van der Leeuw & de Vries, 2002). The expansion of the Roman republic was enabled by the fact that, for centuries, Greco-Roman culture had spread northward from the Mediterranean. It had, in effect, structured the societies in (modern) Italy, France, Spain and elsewhere in a major way, leading to inventions (such as money, the use of new crops, the plough), the building of infrastructure (towns, roads, aqueducts), the creation of administrative institutions, and the collection of wealth. Profiting from this situation, the Romans instituted a flow structure that aligned the organization of the periphery of their sphere of influence with their own culture, creating the channels for an inward flow of matter and energy into the core of the Empire. To achieve this, they used an ingenious policy of stepwise assimilation and organization of indigenous political entities based in cities, making them subservient to their needs, i.e. to the uninterrupted growth of flows of wealth, raw materials, foodstuffs and slaves from the conquered territories to Rome. This flow structure functioned, linking cities across

the Empire, for as long as there were more pre-organized societies to be conquered and wealth to be gathered (Tainter, 1988). But once the armies came to the Rhine, the Danube and the Sahara, that was no longer the case and conquests stopped. Then began a phase of major internal investment in the conquered territories, expanding the infrastructure (highways, *villae*, industries) within the Empire in order to harness more resources for the Empire. As large territories were thus "Romanized", they became less and less dependent on Rome's innovations for their wealth, and thus expected less and less from the Empire.

Circa AD 250 the innovation/value-creation system at the core stalled. The "information gradient" between the center and the periphery leveled out, and so did the value gradient between the periphery and the center. This made it more and more difficult to ensure that the necessary flows of matter and energy reached the core of the Empire. As the relative cost of maintaining these flows grew (in terms of maintaining a military and an administrative establishment, for example: see Tainter, 2000; Tainter & Crumley, 2007), the Roman emperors first devalued their money in order to deal with the immediate needs, and then split the Empire into four parts to drastically reduce the administrative overhead. In the end the coherence of the western part of the Empire decreased to such an extent that it ceased, for all intents and purposes, to exist. People began to focus on their own and local environment rather than on maintaining the central system. Other, smaller, structures emerged at its edges and there, the same process of extension from a core began anew, at a much smaller scale, and based on different kinds of information processing. In other words, the alignment between different parts of the overall system broke down, and new alignments emerged that were only relevant locally.

4. The emergence of the European world system

In order to understand this process in much more detail, we will next apply the energy/information flow structure approach to the last thousand or so years of Western European history. During that millennium, we see a gradual strengthening of the urban (aggregated) mode of life, but this millennial tendency has its ups and downs, and manifests itself in different ways. A second long-term dynamic is that of European expansion and retraction. Both reflect different ways in which the European socio-economic system strengthened itself *vis-a-vis* the external dynamics that it confronted. To quantify these attributes, we will emphasize changes in the following proxies where available:

- The demography of the area concerned: relative population increases and decreases;
- The spatial extent of European territorial units, as a measure of the area that a system can coherently organize;
- The spatial extent and nature of trade flows as a measure of the information-processing potential between the center and the periphery, and thus of area from which raw resources are brought to the system – its 'footprint';

- The density and extent of transport (road, rail, water) and communication (telephone etc.) systems as a proxy for the density of information flows;
- The degree and gradient of wealth accumulation in the system, as an indicator of the innovation and value gradients;
- The innovativeness of particular towns, regions and periods.

Most of these cannot comparably be measured for each and every historical period and region. Moreover, they operate at different temporal rates of change. But these proxies are for the moment all we have.

4.1. The Dark Ages

After the end of the Roman Empire we observe across Europe a weakening of society's structure and coherence (e.g. Lopez, 1967). Between AD 600 and 1000, the fabric of society reached a high level of entropy in Western Europe, whereas in South-Eastern Europe the traditions of Greco-Roman urban culture were only conserved to a very limited extent. In this period, there is an enormous loss of knowledge, in crafts and trades, for example, as well as an abandonment of infrastructure. The flow structures exchanging organization for energy and matter were limited to the immediate environment. Trade and long-distance contact virtually disappeared, towns saw their population dwindle (the city of Arles was for some time reduced to the perimeter of its Roman arena), and most villages were abandoned. Society thus fell back on local survival strategies and much of Roman culture was lost. Only the Church maintained some of the information-processing skills it inherited, especially writing and bookkeeping, and a semblance of long-distance interaction.

4.2. 1000–1200: The first stirrings

This was a period of oscillation between different small systems, in which cohesion alternated with entropy even at the lowest levels. In Northern Europe, trade connections forged in the (Viking) period before AD 1000 led to the transformation of certain towns into commercial centers, later loosely federated into the Hanseatic League. But these towns remained essentially isolated islands in the rural countryside, linked by coastal maritime traffic.

Duby's classic study (1953) shows how, from about 1000 AD, society in Southern France began to rebuild itself from the bottom up. Although the urban backbone of the Roman Empire survived the darkest period, a completely new rural spatial structure emerged, even relatively close to the Mediterranean. In a couple of centuries of local competition over access to resources, various minor lords climbed the social ladder by conquering neighboring positions of potential power, leading to the emergence of a new (feudal) social/hierarchical structure. The local leaders with the best information-processing skills were able to attract followers by providing protection for peasants who

bought into the feudal system. They in turn provided surplus matter and energy used to support a small army and court. In the process, more wealth accrued to the favored, and we see the resurgence of a (very small and localized) upper class with a courtly culture in the so-called 'Renaissance of the 12th century' that included tournaments, troubadours, and other (mostly religious) artistic expressions. A similar process occurred in the Rhineland, where a separate cultural sphere developed on both banks of the river. Further East, in Germany, this period saw the decay of whatever central authority the Holy Roman Empire had, and the rural colonization of Eastern Europe. At this time also, parts of Europe began to look outward: it was the time of the crusades against Islam.

4.3. 1200–1400: The Renaissance

Three major phenomena characterized the next period, (1) the establishment of a durable link between the southern and the northern cultural and economic spheres, (2) the major demographic setback of the Black Death in the 14th century, and (3) the beginnings of the Italian Renaissance. The link between South and North was established in the 11th and 12th centuries, overland from Italy to the Low Countries via Champagne, and then connecting with the maritime British and Hanseatic trade systems. In the 13th century this connection became the main axis of a continent-wide trading and wealth creation network, enabling urban and rural population growth and eventually driving rural exploitation in many areas to the limits of its carrying capacity, pushing farming out towards more distant and less fertile or less convenient areas (Spufford, 2002).

The impact of the three waves of bubonic plague was very uneven. Where it hit badly, it profoundly affected both cities and the surrounding countryside, bringing people from the periphery into the traditionally more populous urban areas (where the plague had hit hardest), thus increasing both the degree of aggregation of the population and its average per capita wealth (cf. Abel, 1986). Other profound changes occurred in the cultural domain, including a re-evaluation of the role of religion, life and death, society and the individual, shaking society out of its traditional ideas and patterns of behavior (Evernden, 1992).

These phenomena contributed to a localized 'era of opportunity' in Northern Italian cities, where cultural, institutional, technical and economic inventions led to a uniquely rapid increase in the information-processing gradient between these centers and the rest of the continent.[4] Many of the ideas developed here were relatively quickly adopted in the trading centers in the Low Counties, which next became rich and powerful. The emergence of a bourgeoisie set the scene for systemic change: from this time onward,

[4] Padgett (1997) for example, describes brilliantly how financial and social innovations go hand in hand to transform the Florentine banking system, drawing in more and more resources and investing them in an ever-widening range of commercial and industrial undertakings that, in turn, transform the practices in these domains.

reaching the 'top of the heap' was limited to geographic areas where urbanization led to concentrations of more – and more diverse – resources, as well as more effective information processing because towns were linked in Europe-wide information flows.

4.4. 1400–1600: The birth of the modern world system

This period marks the central phase in the continent-wide transition from a rural, often autarchic barter economy to monetized economy driven by towns, in which craft specialization and trade set the trend (Wallerstein, 1976). This transition introduces fundamentally different system dynamics. These cities are market-based, heterarchical structures, as opposed to the hierarchical ones that dominate the rural landscape. Simon (1969) defines such structures as those that emerge, in the absence of hierarchy and overall control, from the interaction of individual and generally independent elements, each involved in the pursuit of separate goals, and with equal access to information; competition for resources characterizes such organizations. Contrary to hierarchical systems, heterarchical ones do not strive to optimize behavior; they can link much larger number of people, especially if they are organized as networks with nodes, and they are more flexible (cf. van der Leeuw & McGlade, 1997 for an explanation).

In this first phase of urban dominance, the world of commerce and banking expanded across different political entities, cultures and continents. Much of Southern and Northern Europe, including Britain, Scandinavia and the Baltic were now integrated the European world system. Rural areas saw their interaction with towns increase. Cities began to look attractive to farmers in an overpopulated countryside continually disturbed by armies fighting out others' political conflicts, and this led to a wave of rural emigration to towns, relieving the population pressure in the countryside and keeping the urban labor force cheap, which in turn enabled an industrial expansion.

This period is the heyday of city power. Cities were not controlled by political overlords; rather, they controlled these overlords' purse-strings. Urban elites put to work the enormous gains in information processing capacity made during the Renaissance. Through relatively unregulated commerce and industry, commercial houses (e.g. Fugger) amassed enormous wealth, used it to bankroll the political conflicts and wars that disrupted the continent, and thus extended their control over much of the continent. To this effect, they created extensive information-gathering networks linking every important commercial, financial and political center.[5]

This is also the period of the first voyages to other continents. By investing in these distant parts, European traders added new areas downstream along the information-processing gradient, in which the commonest European product (such as glass beads) had immense value. The huge, immediate, profits made up for the risks, and this long-distance trade initiated for the trading houses centuries of control over an increasingly

[5] Many houses now had their own spy and courier systems, the first and foremost among them run by the Vatican.

important and resource-rich part of the world. As a result, this period has the steepest information gradient from the center of the European World System to its periphery, and the steepest value gradient in the reverse direction. But towards the end, that gradient began to level off in the European core, as cities in the hinterland, and eventually territorial overlords, began to seriously play the same game.

4.5. 1600–1800: The territorial states and the trading empires

The rulers of Europe had inherited legitimacy, or something approaching it, from the Roman Empire, but that did not pay the bills. Their need to keep up a certain status was a financial handicap until they could leverage their legitimacy against financial support by exchanging loans for taxes as their principal source of income. But that required them to guarantee peace and security within their territories. A degree of territorial integration and unity was achieved in many areas by AD 1600,[6] transforming the heterarchical urban systems into hybrid heterarchical-hierarchical ones including both towns and their hinterlands. The regions that first achieved this (Holland, England and Spain) had the most extensive long-distance trade networks providing the steady income necessary to maintain rulers' armies and bureaucracies. As a result, the city-based economic system was transformed into one that involved the whole of the emerging states' territory.

Inevitably, the value gradient leveled out as the Europeans in the colonies assimilated indigenous knowledge and shared their own knowledge with the local populations, but this was for some time counterbalanced by the discovery of new territories, the introduction of new products in Europe, and the improvement of trade and transport, extending the reach of the trade empires. But ultimately the leveling of the information gradient led towards independence, as in the case of the US, or, as in the East Indies or Africa, to the transformation of the trading networks into colonies under military control. These saw the local production of a wide range of necessities for the colony as well as western-controlled production systems for products needed in Europe, and a degree of immigration from Europe. As a result, the European core and the colonies became economically more dependent upon one another.

The same leveling off occurred in Europe as more people began to share in the production of wealth and its benefits. The profits from long-distance trade enabled an increase in the industrial base of the main European nations, achieved by involving more and more people in production and transformation of goods. The tentacles of commerce and industry spread into the rural hinterlands, aided by the improvement of the road systems. As a result of both these systemic changes, the 'flow structure' that has riven European expansion became vulnerable to oscillations.

[6] In Germany, Russia and Italy, the process took much longer, and did not come to completion by the end of the period we are discussing.

4.6. 1800–2000: The industrial revolution

But as the overall structure of the European system had begun to fray at the edges, the massive introduction of fossil energy as a resource and the concomitant 'industrial revolution' re-established the information gradient across the European empires, and the value gradient between the colonies and the heartland. The resulting shift was profound. It gave European dominance a new lease of life, but at the expense of major changes. From a zone in which internal consumption of high-value goods imported from elsewhere did generate most of the wealth, Europe became the mass-producer of a wide range of goods for export to the rest of the world. To maintain that system, it had to create wealth in the periphery that would allow the local populations to acquire European goods. It did so by creating large-scale production systems in the colonies for raw materials that were transformed in Europe into products sold to the same colonies. Thus, the status of these colonies changed – from producers of goods that had relatively little value locally, but high value in Europe, to areas mass-producing low value goods for export to Europe and markets for the low-value European products. Maintaining this system required improved political control over the colonies concerned, as it brought large numbers of local people into the system as low-paid labor.

In Europe itself, the invention of new technologies in both the core and the periphery created much wealth, but ultimately undermined the flow structure by disenfranchising large groups of people. Now, industrialization tied a large working class into (mechanized) production in low-paid, often dangerous, jobs that gave little satisfaction.[7] Social movements were quick to emerge in the core (from 1848), and up to the Second World War. Countries that had not been part of the flow structure aspired to create similar dynamics. The French thus occupied areas of Africa and Southeast Asia. Italy and Germany – unified in the late 19th century – had to satisfy themselves with the leftovers of the colonial banquet. That contributed to the causes of the two World Wars – both countries sought expansion in Europe because it was denied them elsewhere.

And finally, the control over large parts of the world that Europe had thus far enjoyed spread to North America, Australia, Japan, South Africa, and more recently to Southeast Asia, China and India. Europe and the United States are no longer in sole control of the information gradient responsible for the continued wealth creation, innovation and aggregation of the World System, but have to compete with these other regions.

4.7. Summary

We argue that the European system has undergone two major transformations to date, dividing its history in three phases. In the first phase, after a predominantly 'flat',

[7] It created major opportunities for those who mastered one of the newly emerging technologies. For many, education became the way out of misery, reflecting the need for improved information processing to maintain innovation and social cohesion. This led to the education revolution occurring in many countries around the turn of the 20th century.

entropic, period (AD 800–AD 1000), in which whatever flow structures there were, occurred essentially at the scale of individuals', families' or villages' subsistence strategies, we see (roughly between AD 1000 and AD 1200) structures which involve information processing by larger (though still small) local units; most of these are small rural principalities, but in Northern Europe a few urban ones emerge (the Hanseatic towns). Later in the period, several such rural flow structures are often subsumed under a larger one, leading to feudal hierarchies. But the hierarchical structure of the information networks structurally limited their opportunities of expansion (cf. van der Leeuw & McGlade, 1997).

The second phase (AD 1200–1800) was driven by the aggregation of the population in both old and new towns as a result of the Black Death, which caused innovation to take off. It drove a rapid expansion of the urban interactive sphere through long-distance trade and communication. The resulting urban networks that emerged from c. AD 1400 were independent of the rural lords, and had a novel, heterarchical information-processing structure (cf. van der Leeuw & McGlade, 1997), facilitating the growth of interactive groups and the systems' adaptability. In the next two centuries, these cities drove the establishment of colonial trading networks. But between AD 1600 and AD 1800, urban and rural systems were forced to merge by rural rulers who needed to acquire in the towns the funds to increase control over their territories. This led to the formation of (systemically hybrid) nation-states and the transformation of the urban trading networks into colonial exploitation systems. Towards the end of this period (c. AD 1800), these flow structures seem to reach their limits: innovation stalled in the cities and the energy and matter flows from the colonies were limited by the structure of their exploitation systems. Europe had reached a second tipping point.

At that point (1800–2000) a new technology kicked in – the use of fossil fuel to drive steam engines, lifting the energy constraint that had limited the potential of all western societies thus far. The innumerable innovations that followed enabled transformation of the European production system at all levels, rapidly increasing the information-processing and value gradients across the European Empires again. Girard (1990) outlines how in that process, the term 'innovation' changed its value, from something to be ignored or even despised, to the ultimate goal of our societies. As part of this process, notably in the second half of the 20th century, innovation became supply-driven rather than demand-driven as it had been up to then, and ultimately our society became so dependent on innovation that one may currently speak of an addiction that resembles a Ponzi scheme in that innovation has to happen faster and faster to keep the flow structure intact.

5. The current crises are manifestations of a single crisis

In the last decade we have seen that maintaining the flow structure may no longer be possible, and much of the current deliberation is about a perceived 'crisis' in many

different domains. According to most, what we are experiencing are a number of quasi-simultaneous crises, in domains as different as natural resources, ecosystem services, our economy, our financial system and the security of our societies. That is, of course, true if one looks at each of these through disciplinary or sectorial eyes. But from the holistic perspective that we are developing here, we could see all these, together, as manifestations of *one underlying crisis*, notably *a temporary incapacity of our society to process all the information needed to deal with the dynamics in which it finds itself*. After all, the fact that we do not have the answers to deal with all these issues, whether individually or all together, is in effect a lack of knowledge and understanding that we would subsume under 'information processing', as well as a lack of sufficient communication and alignment within our societies to actually take comprehensive action together. One has just to look at the current political squabbles in Europe and the US to understand that.

How did we come to that point? The history of Rome and that of Western Europe, as well as innumerable examples at other times and places seem to indicate that such 'crises' occur in any society at one time or another. There should thus be a systemic explanation for such crises, beyond the proximate ones that are proffered by historians.

I would argue that such an explanation is to be found in the fact that human cognition, at best, grasps only a very small number of the many dimensions of the real world (Read & van der Leeuw, 2008; van der Leeuw, 2010). Hence, any human intervention is based on a very limited understanding of the processes in which one intervenes, while that intervention itself actually affects all the dimensions of the processes concerned. Moreover, while the intervention responds to relatively frequently observed phenomena, it affects also the very long-term temporalities of the system. Over time, one thus sees a shift in the risk pattern, in which known short-term risks (frequent ones) are removed only to engender unknown longer-term risks. In the domain of sustainability studies one calls these the 'unanticipated' or 'unintended' consequences of human action. Because of the enormous difference in dimensionality between the very limited number of cognized dimensions and the very large (infinite?) number of un-cognized ones, even if we assume that our knowledge and understanding grow geometrically (an unrealistic assumption I think), the domain of unintended consequences at the same time grows at least exponentially. Hence, in the evolution of any system of social-environmental dynamics, there comes a point where the society is overwhelmed by unintended and un-understood consequences of its own actions – a phase in which knowledge is overwhelmed by the unknown, and which is experienced by the society concerned as a crisis.

6. The resilience perspective

Whereas there is very little literature aiming to explain the kinds of very long-term trends we have observed holistically and in systemic terms, there is considerable literature doing that for different case studies in the recent period (Anderies, Walker, & Kinzig, 2006). In my opinion the most promising direction that discussion has taken is

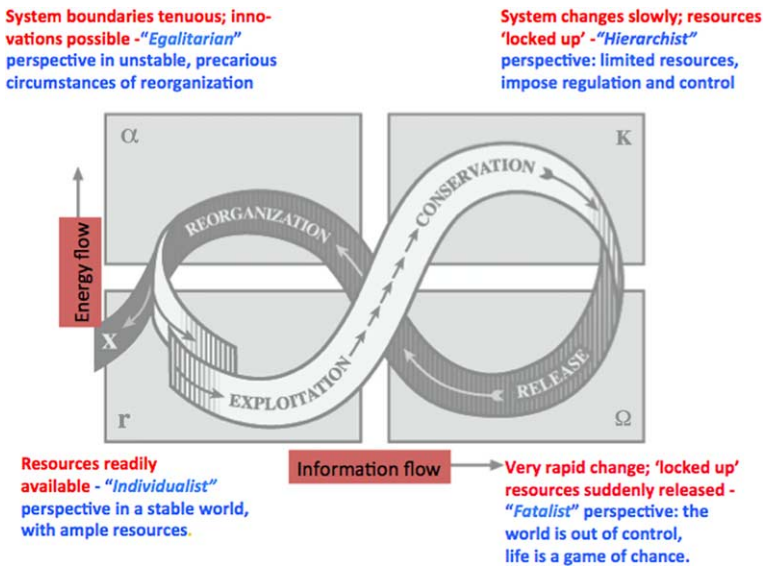

Figure 1.

that of the 'resilience studies' community. In their book '*Panarchy*' (2002) Gunderson & Holling, two of the founders of this community, view any social-environmental system as a nested set of dynamic institutions that resemble the 'flow structures' concept we have used here. They see the dynamics that each of these institutions undergoes as constrained by '*potential*' and '*connectedness*'. In this discussion, '*potential*' is the extent to which a system can expand further while maintaining its structure, by increasing the scope of its organization and its energy flow. '*Connectedness*' represents, in the framework proposed here, the degree of alignment of the people, external processes and resources that constitute the information flow.[8]

Much of the focus of this community has been on studying the transitions that dynamic systems go through in their relationship with their environment. While not in the least arguing that history repeats itself, at the most abstract level they do conceive of four major stages that the interaction between energy and information can drive any such 'flow structure' through. By way of metaphor, they represent these phases as a horizontal figure 8 combining the 4 phases through which systems cycle according to them. Because this metaphor is in my mind indeed a handy 'tool for thought' (see Figure 1), I'd like to discuss it briefly here even though I am fully aware such metaphors are oversimplifications.

[8] To explain briefly the occurrence of the environment and resources in this context, think of the latter – materials in the environment are not really resources until they have been identified as such and the society has been structured so as to use them as such. It follows that any society aligns part of its environment with its social structure and its needs for energy/matter.

The first of these phases, *exploitation*, is the one in which the society and its environment grow based on a particular form of organization that permits an increase in energy flow in exchange for an increasingly coherent institutional organization that increases its impact on the environment over time. As resources are overabundant, every individual has a chance to make something of his or her situation, and according to Thompson, Ellis, & Wildavsky (1990), the culture is one of *individualism*. The phase of growth of the Roman Empire (until c. AD 200) and that of Europe between AD 1400 – and AD 1800 are – to an extent – examples of this dynamic. A crucial aspect of this phase is that the system suppresses structural innovation and institutional change because the dominant structure is (and later appears to be) so effective that there seems no reason to innovate. Because any institution is based on the exploitation of a limited set of resources, ultimately the growth curve involved levels off and the system's effectiveness and growth decrease.

The next phase is that of *conservation*, in which the limits of expansion are appearing on the horizon and the society 'defends itself' by becoming more reglemented and *hierarchical* as a consequence of the need to deal with increasing levels of conflict over resources (Thompson, Ellis, & Wildavsky, 1990). 'Bottom-up' power to achieve things is slowly but surely replaced by 'top down' power over people (cf. Foucault, 1973). We see this in Rome after c. AD 200, and beginning in the political history of modern Europe after AD 1600[9] and coming to a head around AD 1800. As the limits of the particular mode of organization become clearer, elements in the system may contemplate change. But generally, fundamental change is not implemented because the system as a whole is still aligned on the pre-existing dynamics.

In the next phase, '*release*', innovation is suddenly freed up once the system reaches a tipping point in which the potential for further growth of the existing structure collapses. The immediate result of that is a complete lack of institutional structure, a true 'chaos' in which the system can transform in many different ways, but none of these profiles itself clearly enough to give a sense of direction. It is this phase that we have characterized above as a 'crisis': the collapse of the existing structure results in the disaffection of people with that structure, and their inability to understand. This in turn leads, in Thompson et al.'s "Cultural theory of risk" perspective (1990), to a '*fatalist*' attitude. In effect this is collapse that we see in Europe at the end of the Roman Empire, between AD 600 and AD 1000, and which we may encounter in our own future if we are not careful.

The fourth phase distinguished by the resilience community is that of *reorganization* – a phase of experiments with different forms of organization on a very local scale (Thompson, Ellis, & Wildavsky, 1990). Once some of these succeed, one sees the slow but unstoppable growth of new forms of institutional organization 'bottom up', aligning

[9] With this difference, that in the modern European case a new mode of resource exploitation (the use of fossil energy) delayed the most immediate institutional consequences of resource stress until after the turn of the 21st century.

more and more people. As the contours of the organization that will ultimately dominate profile themselves, the institution itself will increase its potential, strengthen and stabilize. Particularly in the initial part of this trajectory, people will seek support locally, forming small *egalitarian* groups. With time, these will align others, so that the structure can grow and form the basis for a new phase of exploitation – rooted in a different worldview, and extracting a different set of resources from the environment.

7. The Epirus crisis

Next, I will try to show how one might generalize from a description of a crisis to a systemic interpretation of the dynamics leading up to an (environmental) crisis. For that purpose, I will present in some detail the recent history of Epirus (Greece), and attempt to describe that history in terms of the resilience perspective presented above.[10] For reasons of limitations of space, however, the reader will have to accept that this evolution is presented in the form of a simplified historical account.[11]

Until WW II, the inhabitants of any Epirote village formed an isolated and closed, small group, in a very isolated rural area where people lived off the land and the herds it sustained. The technical, social and economic differences between the inhabitants were relatively small, and the information pool was very homogeneous (everyone knew everything about everyone else); most decisions were made on a consensus basis. That socio-environmental system had been functioning for a long time, so that the people knew the area intimately, and their way of dealing with the environment was closely matched with local circumstance. In effect, over the centuries, a long-term sustainable strategy had evolved.

After the world war, the area was the focus of a civil war that in many ways was more destructive of society than WWII itself. It triggered widespread emigration among a population that had always been very mobile, often spending many years away from home only to come back to retire among relatives and friends. At about the same time, the imposition of a boundary between Greece and Albania by the superpowers led to the construction of paved roads in the area. These two processes triggered a series of complex transformations in the society, its relationship to the landscape, the spatial structuring of the latter and the means of existence of the population. The paving of the roads triggered increasing contact between many of the isolated villages. As people started moving along the roads, information from the outside began to influence village life: stories and observations on how things could also be done. Because not everyone shared

[10] The in-depth study on which this section is based was carried out under the direction of S.F. Green (University of Manchester, UK) by herself, V. Papapetrou and V. Nitsiakos (University of Ioannina, Greece) with the help of G.P.C. King (Institut du Physique du Globe, Paris, France).

[11] For a more encompassing description of these events, see van der Leeuw (1998, 2004). This part of the present paper presents a general perspective that is complementary to the one offered in van der Leeuw (2000). The latter paper describes the Epirus events in terms of self-organizing information flows.

the urge to visit, the information pool began to differentiate. At the same time, the roads brought increased contact between the countryside and the provincial capital, Ioannina. That linked the villages to a whole range of different administrative hierarchies, and facilitated the meddling of regional and supra-regional institutions into village affairs. The appointment of village headmen, for example, gave the authorities in Ioannina some influence over village activities, and simultaneously gave the headman a status of his own and a communication channel to the outside. Ultimately, that process transformed the spatial macro-structure from one based on tribal territories to one based on the road and promoted, along the roads, the 'seeding' of nodes linked to the urban system, further and further into the countryside.

The emigration contributed to the reduction and aging of the rural population, and to fundamental changes in lifestyle and in perspective on society and its future. Notably, it accelerated the social and economic differentiation of the population, so that not everybody knew everything any longer about everybody else, leading to occasional conflicts of interest between people and/or groups.

Changes in perspective on the landscape also occurred. Seasonally trans-humant people who used to consider their hilltop village as their 'real' home and the valley as a temporary (winter) abode, now generally considered themselves as living in the valley and their hilltop houses as temporary (summer) places of residence. As a result, residence in the valley became longer, and grazing more localized. The prohibition to regularly burn the hillsides to provide grass for the animals would in itself not have had any particular spatial effects if the herds would have continued to graze the same grounds every year, as they would have kept all non-grass vegetation short or out. But under the changed circumstances, thorny bushes in the uplands saw their chance, and an important part of the uplands became inaccessible almost overnight, even to goats. This forced the herdsmen to bring the animals ever closer together in other areas, which were thus overgrazed – leading to erosion on the very vulnerable (because tectonically highly active) slopes. Thus, outside authority and local changes in perception colluded to allow '*garrigue*' growth and increased gulley erosion (because brushwood barriers were no longer maintained). Ultimately, the abandoned uplands were colonized by various species of trees.[12]

The increased dependency of the population on valley cultivation has also wrought changes in the economy. Cash became more and more important as 'urban' ways, norms and ideals penetrate the countryside and stimulated people to acquire other material goods. The (trans-humant) herding economy of the hills and mountains was thus transformed into a (sedentary) agricultural economy based on fodder production and – consumption in the valleys. This in turn created increased dependency on the commercial aspects of the regional (national, supranational) economic system, and the vulnerabil-

[12] One of the interesting consequences is that the upland villages in Epirus nowadays frequently have a shortage of drinking water, as the increase in vegetation cover reduced the amount of water that ends up in the karstic aquifers.

ity that such dependency entails. The local traditions were rapidly transformed. Young people deserted the rural lifestyle. The increasing symbiosis between the region and the outside world multiplied the risks for the farmers. It became easier to protect oneself against natural calamities, but more difficult to escape the consequences of imported economic crises, or of the European Union's system of agricultural subsidies. The emigration had important consequences for the local economy and lifestyle, as the lack of competent laborers led the Epirotes to reduce their dependence on goats and sheep, and increase the number of pigs, which did not require close supervision. To increase their income, certain villages tried to promote tourism by building the necessary infrastructure with European money. With or without European subsidies, the region pursued the development it was now locked into. A tertiary sector developed itself in Ioannina and along the paved roads. And the region became increasingly dependent on money coming from the outside, notably the contributions of the émigrés who amassed a degree of wealth elsewhere. And that, in turn, changed the equilibrium between the different powers in the villages, and in the region as a whole. Altogether, the Epirotes lost most of their autonomy.

8. Generalizing the Epirus crisis in terms of resilience theory

In the case of Epirus, our post-war observations begin at the end of an "*exploitation*" phase that lasted several centuries, first under the Ottomans and after 1917 as part of Greece. That phase allowed a local agro-pastoral economy to develop, centered on the individual villages and, at a higher level, on the tribes that occupied the territory of present-day Epirus. That economy had two characteristics that connected it to other regions: long-distance transhumance and temporary emigration of the male population. Both originated during the Ottoman occupation. During the last centuries of that occupation, the socio-environmental system of the Epirotes had exchanged much of its initial resilience for a high level of interconnectedness between all aspects of daily life. It had thus become more efficient and profitable, but it had lost much of its diversity and flexibility. In one word, it had become "hyper-coherent". Thus, the Epirus socio-environmental system had for some time survived by virtue of its robustness. It had become an example of "an accident waiting to happen".

The double shock of WW II and the civil war affected the dynamic structure of the socio-environmental system at all levels simultaneously. Too many processes were interrupted at the same time. The societal dynamics were no longer able to adequately respond to the environmental ones, and the socio-environmental system found itself in a "window of vulnerability". In other words, the perturbation was so important that the society could not absorb it and keep its fundamental, historical structure intact. It was not resilient enough to absorb a perturbation of this size.

Emigration at the end of the civil war temporarily increased the total quantity of resources (the "capital") at the disposal of the each of the Epirotes. But it also reduced the

control of the traditional structure over these resources still further. These two tendencies, together, forced the society to innovate, while at the same time reducing the social and economic cost of such innovations. The ensuing reconstruction occurred under the external pressure of the very rapid urbanization of the last fifty years, and was facilitated by the creation of the transport infrastructure that broke the tribal geography of the region. By introducing new lines of communication, the new road network changed the traditional flows of information that maintained the coherence of Epirote society. We observe this, for example, in the information exchange patterns in each and every one of the villages. Traditionally, the villagers did not give much credibility to news brought to them by strangers, believing only what they heard from the inhabitants of their own village. But from the 1960's, and beginning in the villages closest to Ioannina or along the roads, the rural Epirotes forged privileged links with certain "townsfolk". They learned to believe what such contacts told them and, relatively quickly, preferred such information over the "gossip" they were told by their fellow-villagers.

As a result, new networks became the foundation on which the society reconstructed itself. But these new networks were not woven sufficiently quickly to avoid that, during a whole generation, the Epirotes experienced this transformation as a "crisis". The demographic downturn may in part explain this, because it reduced the potential connectivity in the region. But the feeling of "crisis" experienced by the population was also due to the need to negotiate new connections around new concepts and ways of life, even a radically different world-view. This phase of "creative destruction" lasted around forty years. In that period a wide range of solutions were pursued in order to try and end the crisis. The natural environment was profoundly transformed, calling into question the perspective of the villagers on their own place in the landscape and in society. The herdsmen of the heights transformed themselves into farmers in the valleys. Their means of subsistence, as well as the nature of their crops and their herds, changed; "*garrigue*" and forest replaced the deserted meadows, leading to shortages of drinking water for some villages. But new connections developed everywhere, albeit initially very slowly, and in the end the socio-environmental system reconstructed itself on a different basis, consisting of subsidies, eco-tourism, the export of milk products and craft objects, and a certain degree of industrialization (mainly in Ioannina). In the 1980's and 1990's the socio-environmental system thus entered into a phase of "reorganization".

9. Crisis dynamics

Let us now turn to the present. From the long-term perspective that is mine, I would argue that we are in the last stages of the run-up to the 'tipping point' that the transition from 'conservation' to 'release' represents. Of course this is a very contentious statement that would require at least a monograph to justify it for the skeptics among us. In a nutshell, however, from the *environmental* perspective, I stand by the argument made in Rockström et al. (2009) that we are nearing a point where we exceed more than one of the

boundaries within which we can with some degree of confidence predict that the Earth System will not tip into chaotic behavior. As far as the exploitation of *ecosystem services* and *resources* are concerned, the looming shortages of water and oil, or at least the huge increase in the cost of providing them, are signs on the horizon, but so is the state of our fisheries, the loss of biodiversity, etc. A very different kind of signal is the use nuclear energy. There again, our society has exchanged known short-term risks for unknown (and unpredictable) long-term ones. From a *security* point of view, the global decentralization of conflict that occurred after the cold war seems in itself a sign of the breakdown of structure, as is the increase in terrorism and insecurity within our western societies. In the *financial* sector, the huge debt load that our societies have to live with is testimony to our tendency to '*eat the future*' (cf. the title of Flannery, 1994) – to accumulate short-term interventions that put a burden on the future to solve. These interventions are none other than the shifts in risk spectrum that we have discussed earlier, removing immediate short-term risks while creating long-term future risks. In the *political* domain, short-term political considerations seem to have overwhelmed concern with the longer-term future of our nations, at least in Japan, the US and Europe. And in the *economic* domain, business leaders speak of the 'tyranny of Wall Street', which, again, favors short-term profit over longer-term investment.

Without in any way intending to assert that we approach a 'tipping point' with certainty, I do believe that these are enough signs to warrant spending some time of a simple archaeologist looking at what is happening from the long-term perspective that is mine, to better understand what may have caused our present conundrum and to suggest ways in which we might meet at least some of the challenges involved or mitigate their consequences.

First, let us therefore look at some proximate causes (rather than the ultimate one – that our information-processing tools are overpowered by 'unintended consequences') that highlight 'changes of change' that have happened in the last couple of centuries without being very much remarked.

9.1. Path-dependency

Our ideas (theories, etc.) are under-determined by our observations. This is most easily understood by referring to the example Atlan gives (1992): Take five traffic lights, each with three states (red, orange, green). The 'system' of these traffic lights can assume 3^5 ($= 243$) states. But the number of possible configurations of the connections between these states that could explain them is much higher, 3^{25}, which amounts to about a thousand billion. That is also the number of random observations we would need to have in order to decide between these configurations, but evidently we never have anywhere near that number of observations.[13] Hence, we must assume that our theories

[13] The number of sequential observations would be considerably smaller, as one could extrapolate from them towards 'trends', but it would still have to be much larger than is in effect practicable with traditional scientific means.

and ideas are indeed under-determined by our observations, and (an important corollary) over-determined by pre-existing ideas, patterns of thinking that we apply to each new data-set and that shape our interpretation of it. That over-determination is the principal factor that causes intellectual traditions to be difficult to change, especially after they have existed sufficiently long to have been applied in many different domains, so that changing them would demand a very large restructuring effort, and therefore a long period of uncertainty.

9.2. The fragmentation of our world-view[14]

The fragmentation of our world-view, which we see as one of the main handicaps in our attempts to understand the full complexity of the processes going on around us, has been institutionalized in the way academia is structured in disciplines that have co-evolved with separate communities that use their own concepts and language to express themselves on the phenomena they study. But that scientific/academic fragmentation is part of a more general process, driven by the need for communication to become more precise in order to avoid misunderstandings and errors. If we take as point of departure the feedback loop between population aggregation and information-processing capacity we have presented at the beginning of this paper, it will be evident that as the number of people involved and the complexity of the information processed grow, the chances for errors in communication increase substantively because more needs to be communicated among more people (and therefore in shorter time). This process has driven the development of more and more precise ways of expressing oneself in an ever-shorter lapse of time. On the one hand, that led to a proliferation of ever 'narrower', concepts (categories, terms) at any particular level of abstraction – making finer and finer and more context-linked distinctions, reducing the number of dimensions in which these concepts could be interpreted and increasing the number of unknown dimensions that they related to. Simultaneously, an increase in the number of levels of abstraction itself compensated for this fragmentation, so that one could still find ways to 'lump' over these increasingly narrow concepts along crosscutting dimensions. And in parallel, the syntax evolved in order to accommodate the transmission of more complex meanings.

9.3. The scientific method

In western society, science has played a particularly important role in this process. Ever since the fourteenth century, science has emphasized the need to solidify as much as possible the relationship between observations and interpretations. Thus, these interpretations linked the phenomena investigated to what was already in existence at the

[14] The term 'Fragmentation of our world view' was first introduced to me by the Dutch historian Jan Romein in an essay that was to my knowledge never translated (Romein, 1946).

time these phenomena were observed, rather than to what was still to come (and could not be observed). We will call this here the 'ex-post' approach, with reference to the fact that phenomena are studied from the perspective of what came after. This kind of (Natural) History seems to have been the predominant explanatory paradigm, at least until the 18th century (cf. Girard, 1990), and is still very important in many disciplines.

Whereas we see and conceive the past by reducing the number of dimensions we observe in the present into a more or less coherent narrative in terms of causalities and certainties, we conceive of the future by amplification of the number of dimensions experienced in the present, describing it in terms of alternatives, possibilities and probabilities. The long-standing emphasis in science on linking present to past has therefore resulted in a kind of science that is essentially reductionist, achieving a sense of 'reality' or 'truth' by simplification. It necessarily emphasizes the explanation of extant phenomena in terms of chains of cause-and-effect. In particular, it has emphasized thinking about "origins" rather than "emergence", about "feedback" rather than "feed-forward", about "learning from the past" rather than "anticipating the future".

9.4. Proliferation of material culture

In our material world, as well as in the organization of our society, this fragmentation has a corollary: the explosion of material artifacts, services, organizations and institutions. Behind this explosion is, of course, the invention/innovation dynamic that we have referred to before, which is responsible for the exaptation of more and more specialized artifacts and functions out of the ones existing at any point in time. It is an inherent function of the innovation-processing-population feedback loop we have mentioned earlier, and has led to the millions of products and services now available worldwide. But it is one that has undergone a particular acceleration since the constraint of energy was temporarily removed by the use of fossil fuels, leading to the kind of supply-driven innovation that we see nowadays (rather than the demand-driven innovation of earlier days). The need is no longer for innovation to meet existing challenges, but simply to create 'value' to maintain the growth of the world economy. Once inventions have been recognized, they are mass-produced and marketed, rather than relying, as they did in earlier centuries, on word of mouth and need to find a market. This in itself has created a new feedback loop, in which the economy is now dependent on innovation, rather than innovation on the economy (cf. Arthur, 2009).

9.5. Dis-embedding

If we concede for the moment the hypothesis that in nature, most processes and phenomena are part of very highly multidimensional networks, what strikes one is that the modern human system has dis-embedded large parts of society and its immediate environment from that wider ecology. The narrowing of categories and the multiplication of exapted artifacts and functions has created a world that seems controllable to us be-

cause we effectively ignore the dimensions of it that we do not control. It is an artificial, constructed world, rather than a real one. Science has contributed to this process in a major way.

This development shows very clearly when one compares the way science deals with everyday challenges, with the way people in everyday life (and politics) do. Scientists investigate challenges and unknown phenomena by raising questions, trying to find 'rational' answers by simplifying the objects of study until they can be handled 'objectively', building cause-and-effect arguments to explain them, and calculating the uncertainties involved without dealing with them. In many ways, people in everyday life do the reverse: they do not pretend to 'objectivity', mediating non-rational but emotionally satisfying operational solutions to the challenges encountered. In doing so, they look forward, bring out hidden dimensions rather than hiding perceived ones, and accept that they have to deal with uncertainty.

As science has become more and more dominant in society during the 20th century, the rational, constructivist approach has permeated larger and larger parts of our lives, and removed us more and more from the 'natural' multi-dimensional approach.

9.6. New feedback loops

The essence of the growing complexity of our societies is the emergence, throughout history, of new feedback loops in the dynamics of the system. These are of course infinite in number and range in scale from the here-and-now to the very long-term affecting huge domains. Probably the most salient one during our lifetime is that between medicine and population growth, affecting birth and infant mortality rates as well as life expectancy, etc. Because of the increase in population numbers, this also had a major impact on communication and information processing resource use and so many other aspects of our lives, including climate change. Other feedback loops that have emerged have transformed the traditional link between economy and finance, in which finance serves the economy, into the reverse: the economy serves the financial industry. From a consumer perspective, the traditional approach in which the client is king, has been transformed in such a way that the client now serves the company instead of vice versa. Another important reversal is that between innovation and economic growth – from a situation in which innovation stimulated growth, to one in which the need for economic growth forces more and more rapid innovation.

Many more such new feedback loops and reversals of feedback loops have of course occurred in the last century or so, and many more are currently occurring as a result of the aging of western populations. I am mentioning them here merely to signal that our current system is no longer adequately represented by the knowledge we have of it – which in itself adds to the mass of unanticipated consequences of our actions. This insufficiency is particularly important in the domain of the social sciences, which still have difficulty to think in dynamic complex systems terms.

9.7. Education has not kept pace

The western world system's main means of rational communication is the language of the sciences, or in US parlance, STEM (science, technology, engineering and mathematics). It has enabled the information processing on which our current flow structure depends, both by opening wide new domains to innovation and by facilitating communication among the world's elites. But we notice over the last couple of decennia an increasing disenchantment of society with science. I interpret this as a result of the creation of unrealistic expectations for science as a result of its success as well as the aspirations of scientists, and due to the increase in unintended consequences of scientific actions. But for parts of society, especially in the US, this is amplified by insufficient education in science at an early age, so that other ways to explain the world around them have taken root among these individuals, and scientific explanation takes a backseat. Other contributing factors are a deficiency in science communication and the inability of most scientists and scholars to express their ideas in readily understandable ways. Last but not least, both the scientific community and civil society have become defensive vis-à-vis each other: scientists are perceived as 'arrogant' and 'self-centered' by society, whereas scientists consider many in society as 'scientifically illiterate'. As a result of these tendencies, the core means of communication and alignment of western societies is losing its efficacy, as does our information-processing system.

9.8. Globalization

This tendency is accelerated by globalization – the alignment of elites in fundamentally different cultures into our (STEM-based) information-processing approach. The speed with which that has happened has tilted the signal-noise ratio in our communications channels towards noise (non-STEM communication), and it has also increased the error-rate in STEM communication itself because of the greater diversity of cultural backgrounds involved. Finally, it has drastically reduced the bandwidth of communication among many participants in globalization – limiting them to basic communication on material aspects of life, without an in-depth understanding of the fundamentals of the different cultures.

10. Challenges and potential solutions

10.1. Overcoming the limitations of human STWM

Although I am not an expert in the field at all, it seems to me that the ICT revolution has indeed created the conditions for us to overcome the fundamental limitations to our brain's calculating capacities that are imposed by our short-term working memory. Present-day computers do have the capacity to deal with an almost unlimited number of

dimensions and information sources in real time, and thus to overcome what appeared at first sight to be the most fundamental of the barriers mentioned above.

But that capacity has not fully been exploited because of our long-standing and ubiquitous scientific and intellectual tradition, which has emphasized the use of such equipment as part of the process of dimension-reduction that provides acceptable explanations, rather than as a tool to increase the number of dimensions taken into account in our understanding of complex phenomena. Under the impact of complex systems science this is clearly changing (as seen, for example, in the increased use of high-dimensional Agent Based Models), but much more needs to be done, mainly in developing conceptual and mathematical tools as well as appropriate software.

10.2. Overcoming the under-determination of our theories by observations

Similarly, and with the same caveat that I am not a professional in this field, I am under the impression that the very recent revolution in IT capacity to continuously monitor processes on-line, and to treat and store the exponentially increased data streams that are generated by such monitoring, points to the fact that we may indeed be on the brink of (at least partly) overcoming the under-determination of our theories by our observations. The reduction in the size and cost of the monitoring equipment is quickly bringing such massive data collection within reach. Simultaneously, the development of novel data-mining techniques is helping us to make sense of the data thus collected, or at least in selecting the appropriate data to be scrutinized in order to better inform our theories.

10.3. Generalizing ICT

In order to be optimally effective, and thus to massively increase not only the data at our disposal, but also our information-processing capacity itself, we need to integrate ICT better with information-processing in society at large. Currently, societal and electronic information-processing are still far too often considered as two different domains, whereas societies have always been information-processing networks, and the only thing that has changed is that we now have electronic means to enhance that function. Not only will such integration require substantive adaptations in our way of thinking as well as in the interfaces between ICT and people, but it will also fundamentally change the structure of many social and political dynamics, such as is becoming evident among the FaceBook generation.

10.4. Transforming our scientific and intellectual tradition

One way to think about solving some of our current problems is to improve the way we think about the future and in doing so make an effort to enhance the number of dimensions we take into account scientifically rather than reduce them. Although I am not among those who fall easily for panaceas, I do believe that the complex (adap-

tive) systems approach is a useful first step on the way to fundamentally transform our scientific and intellectual tradition from studying stasis, choosing simple over complex explanations, and focusing on origins, to studying dynamics, with an emphasis on emergence and inversion of Occam's razor (increasing the number of dimensions taken into account). As a result, I would hope that we would in future accord in our scientific work as much importance to an '*ex ante*' perspective as we currently do to the '*ex-post*' approach. Clearly, we have a long way to go in this domain, but the rapid and substantive advances in certain fields, including physics, biology and economics, coupled with the rapid recent spread of this approach in Universities in many parts of the world and the growing awareness of the need for more holistic approaches in such domains as sustainability and health, cause me to be moderately optimistic about our chances of transforming our scientific and intellectual tradition.

10.5. Improving our understanding of innovation and unintended consequences

It is commonplace in the current literature to argue that innovation will ultimately allow us to develop a sustainable society, but much less so to remind the readers that unbridled innovation in every domain is actually what got us into the current unsustainable situation. Innovation has generally been considered 'out of the bounds' of scientific study, as innovation can of course not be studied from a reductionist perspective. Hence, while our society's coherence pushes us towards more and more rapid innovation, we still cannot in any way plan that process or even understand it completely. To use innovation more efficiently, gaining such understanding (and eventually control) would be an important step forward. As part of that, we would need to better align innovation with the needs of society – which can be achieved by crowd-sourcing of needs and potential solutions, creating a feedback loop that one could call "emergence by design".

We have seen that all innovation has unintended consequences. To effectively and efficiently use innovation to change our trajectory, it is thus of essential importance to begin thinking systematically about the unintended consequences of our innovations and actions, and to evaluate choices we make against options that are open to us, but which we do not choose. Developing systematic use of dynamic models and scenario-building exercises seems an important opportunity. Other tools to be developed are systematic post-innovation monitoring of the unintended (as well as intended) consequences of the implementation of such innovations.

10.6. Transforming education

All these domains above do, of course, need major investment and development, and this will not come easy or be rapid. But by far the greatest challenge from the perspective of human and financial capital and effort appears to me to be in the domain of education, from the earliest childhood throughout university and into adult life. Yet that is essential if we want to maintain the basis of our information-processing as a

society: STEM. Our current education system is, overall, no longer adapted to the challenges of the 21st century. We have to move away from knowledge acquisition aimed at question-driven research towards challenge-focused education that aims to help deal with substantive challenges, from 'linear explanation' in terms of cause-and-effect to 'multi-dimensional projection' in terms of alternatives, from one-to-many teaching (in which an instructor tells students what to do, what is right and what is wrong), to many-to-many teaching in which instructors and students all interact, learn and teach. At the same time, we must develop education systems that stimulate the acquisition of creativity, risk-taking and diversity rather than conformity and risk-adverseness. In doing so we must harness the tools referred to above, but more than anything we must 'bend' minds around to thinking in new, uncharted, ways.[15] The underlying challenge is how to communicate other than linearly and in writing or speech with an increasingly large number of partners at very variable distances, in order to overcome the reliance on narrower and narrower concepts, and the consequent fragmentation of our perspective on the world. Contrary to some, I do not think language is subject to deliberate change – it adapts itself to human needs and ideas in a 'bottom-up' process. But even if it were possible to transform the ways in which we speak and write, we would still have an essentially linear communication tool. We need to develop completely new tools.

11. A note of cautious optimism

For those among the readers of this paper to whom these changes seem so complex, and requiring such huge investment that they seem unachievable, I would like to repeat that my archaeological perspective teaches me that humanity, in the nick of time, has thus far always found creative solutions to its central challenges. But I should add a cautionary note: in many instances there has been very considerable 'collateral damage' – and one could argue that the longer we wait, the greater that damage will be.

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