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Things are different today: the challenge of global systemic risks

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ABSTRACT

While most OECD countries have been rather successful in reducing risks to human lives, health, and the quality of the environment, the record for new global risks such as climate change, pandemics, financial breakdowns, and social inequality is much less convincing. This is the challenge of systemic risks. Since the global financial crisis, it has received rapidly growing attention. However, considerable conceptual confusion mars research on and practical responses to this challenge. We undertake an effort of conceptual clarification, starting with the paradigmatic example of the financial crisis. This leads to a view of global systems as involving an interplay between micro- and macrodynamics internal to the system, with the system simultaneously interacting with its environment. Such dynamics typically show periods of stability, punctuated by situations opening up several possible futures. Alternative global futures, like other prospects, constitute risks for an agent if she considers some of these futures as less desirable than others. Agents may have lexicographic preferences over futures they would like to avoid, so as to consider some futures as just undesirable, but others as catastrophic. If an agent expects some of the relevant futures at a bifurcation point of a global system to be catastrophic in this sense, they are faced with a systemic risk.

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1. Introduction

Since the global financial crisis of 2008 the concept of systemic risks has risen to prominence in a broad literature, as well as in risk management and governance. By now, the concept is used to discuss not only the risks of financial crises, but also those of climate change, pandemics, terrorism, war, cybersecurity, and more (Goldin and Mariathasan 2014).

However, the

> first issue in addressing systemic risk is to define the system. Despite the large volume of recent articles on the topic of systemic risk, there has been little attention paid to what is endogenous to the system and events that are external. (Fouque and Langsam 2013, XX)

In fact, talk about systemic risks more often than not comes with a fair amount of confusion about the system under consideration, and about what it means for an action or event to be risky in a systemic way.

The conceptual confusion is hard to overcome because the concept of systemic risks emerged as an attempt to find orientation in uncharted territory, to gain understanding of phenomena that are

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historically new. They are new because they have emerged against the backdrop of modern risk management as it has developed over generations with increasing success. More precisely, modern risk management has become a success story in terms of conventional risks, i.e. risks for which enterprises, governments and academia can reasonably define damages and probabilities, and that they can deal with by designing and implementing specific measures for each risk.

Based on the combination of insurance and safety-enhancing regulation, modern risk management has been a key factor of economic growth and increasing welfare since the beginnings of industrial societies. This success is documented in many statistical data. Referring to Germany (Renn 2014a, 102ff.): the number of fatal accidents at work decreased from almost 5000 in 1960 to less than 500 in 2014; the number of traffic accidents from 22.000 in 1972 to 3700 in 2014; the number of fatal heart attacks and strokes decreased from 109 cases per 100,000 to 62 in the time period between 1992 and 2002. In addition, the number of chronic illnesses as well as fatal diseases from environmental pollution or accidents has steadily declined over the past three decades in most Organization for Economic Co-operation and Development (OECD) countries.

The picture becomes, however, less favorable if we look at globally interconnected, non-linear risks such as those posed by climate change (IPCC 2014), the present global financial system (Lo 2012), geopolitics in the nuclear age (Mearsheimer 2010), pandemics (Lee 2003), or the growing inequality between rich and poor (WEF 2017). It is this kind of risks that made Beck (1992, 24) claim that 'risk society is a *catastrophic* society'. There is no reasonable doubt that risk management has made modern society safer with regard to a wide range of risks: floods, droughts, and thunderstorms due to natural climate variability, loss of lives and property through fire, accidents at work, in transport and elsewhere, many kinds of illnesses, and more. But there is growing awareness that modern society itself has generated a new kind of risks, in the face of which existing institutions and methods of risk management and governance look if not helpless, at least insufficient.

In order to take account of the difficulties in addressing such non-conventional risks, the OECD produced the report on 'Emerging Systemic Risks' (OECD, 2003; Renn et al. 2002). It took the concept of systemic risks that had been developed by specialists of financial markets, and placed it in a much wider context. The subsequent global financial crisis then led to worldwide awareness of the need to somehow rein in the systemic risks that have developed with globalization.

Distinguishing between conventional and systemic risks is warranted by the need to understand risks like those of global financial crises or of climate change (Renn 2014b, 2016). But for this purpose, a definition like the one of OECD (2003, 30) offers little more than a preliminary hint: 'A systemic risk, in the terminology of this report, is one that affects the systems on which society depends – health, transport, environment, telecommunications, etc.' This might be useful if the following questions could be answered. How large must the potential impact of some risk be for it to count as systemic? How large must a human collectivity be for it to count as society in the sense of this definition? To what extent must a society depend on some system for it to matter in the same sense? But neither does OECD (2003) address, let alone answer any of these questions, nor is there a plausible way to do so.

A widely quoted definition takes a completely different approach: 'Systemic risk refers to the risk or probability of breakdowns in an entire system, as opposed to breakdowns in individual parts or components, and is evidenced by co-movements (correlation) among most or all parts' (Kaufman and Scott 2003, 372). The definition was formulated in view of financial crises, where there is 'high correlation and clustering of bank failures' (Kaufman and Scott 2003, 372) in one or several countries. But the death of a living being, the bankruptcy of a single firm, even lighting a match, all fit this description: an entire system breaks down amid correlated breakdowns of most of its parts. Therefore, despite the intuitive appeal it has as long as one thinks about the intended examples, the definition is hardly useful for the purposes of theoretical research or practical risk governance.

With the present paper, we want to reduce the existing conceptual confusion about systemic risks. For this purpose, we offer a conceptual analysis that we consider both necessary and fruitful – including the controversies that it may provoke. The concept of concepts, however, is less obvious than it might seem at first sight (Margolis and Laurence 2014; offer a state-of-the-art review). The Aristotelian legacy of defining a concept by subsuming it under a more general category and indicating what distinguishes it from other members of that category has found new relevance in the world of computer programming (Stepanov and McJones 2009). In some applications of formal languages, definitions work as substitution rules for some combination of relatively simple concepts through a single, but more complex one. However, in most settings – including the present one – it is mandatory to start by relating a concept to a family of paradigmatic examples for how to use (and not to use) it. From there, one can then look to other, perhaps more distant relatives of the initial family.

Paradigmatic examples establish a web of family resemblances. To grasp a concept then requires some understanding of properties and relations involved in this web, and why and where it is important. This typically involves developing insights about the realities the concept relates to. To the extent that such an effort is successful, it will lead to a better understanding of those realities and to new abilities in dealing with them, including the ability for further investigations. Hopefully, the present conceptual argument will contribute to a better understanding of the far-reaching shift that is transforming the role of risk in modern society.

As in other fields of inquiry, there is no need for a single standardized definition of systemic risks, but there is a need for some clear, distinct, and practically useful concepts to deal with the systemic risks that have begun to challenge the way modern society has handled risks so far. In the present paper, we develop such a concept. In a nutshell, the concept development can be summarized as follows.

(1) We start with paradigmatic examples like the risks that became visible in the financial crisis of 2007, those of global climate change, as well as those of international tensions that could lead to World War III. These examples show the catastrophic character, and thereby the relevance of systemic risks.
(2) We then emphasize four major properties (Jaeger, Renn, and Lucas, in preparation; Lucas, Renn, and Jaeger, submitted; Renn 2014b, 2016), according to which systemic risks are:
(2a) global in nature,
(2b) highly interconnected and intertwined, leading to complex causal structures,
(2c) non-linear in the cause–effect relationships, often involving unknown tipping points or tipping areas and
(2d) stochastic in their effect structure, so that more than one future is possible.
(3) To these descriptive properties, we add a crucial explanatory component: systemic risks are due to the interplay of individual micro- and global macro-processes within the system under consideration, combined with exogenous processes that modify the internal dynamics of the system.

It is essential to keep in mind that this concept of systemic risks is anchored in paradigmatic examples. Further research will hopefully lead to further improvements of the concept proposed here. Such improvements may come from better understanding of what is discussed in the literature under the headings of deep uncertainty (Walker, Lempert, and Kwakkel 2016) and ambiguity (Ferreira, Salgado, and Cunha 2006), from case studies of non-global risks that display important similarities with global ones (e.g. the industrial accidents discussed in Meyer and Reniers 2016), and from many other sources. Given its grounding in paradigmatic examples, our concept of systemic risks leads to opportunities for fruitful theoretical research as well as to issues of considerable practical relevance. It clearly highlights the complexity of systemic risks – if somebody prefers simpler concepts, they should perhaps not mingle with this kind of risk.

In this spirit, we next (Section 2) discuss the concept of systemic risk in view of the global financial crisis. We identify aspects of this paradigmatic example that in one way or the other matter for other instances, too. Particularly important is the role of complex dynamic structures for analyzing systemic risks. To analyze such structures, we discuss examples from physics and other fields; against that background we propose a qualitative investigation of dynamic structures involved in systemic risks (Section 3).

We also sketch possibilities for quantitative extensions. We conclude by relating the main insights developed so far to challenges for further research (Section 4).

2. A paradigmatic example: global financial risks

The concept of systemic risk has emerged out of discussions about the global financial system after the collapse of the Bretton Woods arrangement in the 1970s. The financial crisis of 2008 has then become a paradigmatic example for systemic risks, and has triggered a vast literature on systemic risks in the global financial system (Anand 2016; Cont et al. 2016; Fouque and Langsam 2013; Glasserman and Young 2016).

The concept of systemic risk used in that literature is connected to the distinction between micro-prudential and macro-prudential regulation. The former is classical bank regulation. It targets banks individually, e.g. requiring them to be part of a deposit insurance scheme, or requiring them to hold a minimum amount of capital per asset volume. The purpose is primarily to reduce the risk of an individual bank going bankrupt through a bank run. This is a conventional risk, similar to the risk of a house burning down due to a fire. In both cases, the basic toolbox of modern risk management – combining insurance and safety-enhancing regulation – offers the resources to successfully address the problem.

In the past decades, concern about another risk has grown: the risk that bankruptcy (or substantial losses) of an individual bank might have contagion effects that put the functioning of a national or even the global financial system at risk. A similar risk can arise if a big debtor, e.g. a national government, is unable to pay back its debt. This kind of risks has been labeled as systemic risk, and regulations aiming to reduce it are known as macro-prudential. An example is the counter-cyclical capital buffer in the Basel III accord, which modifies capital requirements for banks, based on the deviation of the credit-to-GDP ratio with respect to its trend (Repullo and Saurina 2011).

2.1. Two misleading conceptualizations

So far, the concept of systemic risk underlying these regulations is of the kind exemplified by the definition of Kaufman and Scott (2003) quoted in the introduction. It is a concept that considers the system at risk as some network of components without further specification. In a similar vein, three of the most important regulatory agencies in the global financial system – the International Monetary Fund, the Bank for International Settlements, and the Financial Stability Board (IMF–BIS–FSB) – defined systemic risk as the risk of a 'disruption to financial services that is: (i) caused by an impairment of all or parts of the financial system; and (ii) has the potential to have serious negative consequences for the real economy' (IMF–BIS–FSB, 2009, 5f).

There is little doubt that the IMF–BIS–FSB conceptualization covers the paradigmatic case of the global financial crisis, but it raises two serious objections. The first objection regards the operational usefulness of such a conceptualization in view of future decisions: What counts as 'serious negative consequences for the real economy'? How does one know whether some event 'has the potential' to have such consequences? How are the many open issues about causal attribution for events in financial markets to be settled? These are the kind of questions that have led renowned Stanford economist John Taylor to claim that 'there is no clear operational definition and measure of systemic risk at this time' (Taylor 2009). The problem is serious because, in the words of Christian Noyer, then governor of the French central bank: 'As the crisis has shown, systemic risk is THE risk that financial regulation has failed to capture' (Noyer 2009, II; emphasis in the original). Taylor tends to discredit talk about systemic risks and policy interventions to counter them, Noyer has the opposite stance. They differ in what they consider legitimate actions by regulatory authorities, e.g. in view of the rescuing or not a large bank in distress. Concepts are not true or false the way propositions can be. But they can facilitate or obstruct the understanding of a situation, and they can legitimate or delegitimate particular actions and the interests they may serve. There is a remarkable similarity here with the case study about GM crop provided by Desmond (2017). In both cases, efforts at defining specific risks involve major struggles of legitimation.

A second objection concerns the systems to be considered. The IMF-BIS-FSB (2009) version tries to refer to a single system, namely the financial one. This misses the opportunity (perhaps: the need) to see the connections between systemic risks in the financial domains with those in other domains. Moreover, it is by no means clear where the boundaries of 'the financial system' are. As Fouque and Langsam (2013) remark: 'The financial system is a system in which humans, their emotions, politics and responses to incentives play a critical role.' Under these circumstances, the IMF–BIS–FSB conceptualization leaves the question where to draw the system boundaries wide open.

The Kaufman and Scott (2003) version on the other hand, as mentioned in the introduction, can be applied to any system with a temporal dimension, which is obviously way too large a domain – is it helpful to speak of the systemic risk of a stone, a melody, a rainbow? In particular this conceptualization would include the bankruptcy of an individual bank, which is a system that can break down as a whole, too. But the concept of systemic risk was included specifically to distinguish individual bankruptcy risks from risks to the financial system as such.

These conceptual weaknesses may well be one reason for the fact that efforts at improving the global financial system are still far from making the risk of a next global crisis a minor worry:

> despite some decent progress in a few areas, the sad news is that the general approach to reforms is largely still been based on an outmoded and by now largely repudiated conceptual framework of regulations, which does not start from the 'system-wide' characteristics of risks and often misses key risks. (Claessens and Kodres 2014, 4)

These authors advocate 'a more "Bayesian" approach where reforms are implemented in areas where knowledge is greater, while in other areas both a more "experimental" approach is taken and more resources – data, analysis – are invested to clarify the best approach' (see also Haas, Onischka, and Fucik 2013).

Such an 'experimental' approach could profit from a better conceptualization of systemic risks. To move forward in this direction, we next discuss characteristics of the global financial crisis that seem relevant in other domains as well.

2.2. Complex internal dynamics

In the Handbook on Systemic Risks, Fouque and Langsam (2013, XX) list three important characteristics of the global financial system: 'The topology of the system is extremely complex, dynamic, and not well studied. The system does not recognize national boundaries. […] The financial system is not deterministic.'

The first characteristic has led several authors to emphasize similarities with complex engineering systems (Bookstaber 2007; Schwarcz 2009). This is especially relevant in view of the influential 'Perrow Hypothesis', according to which tightly coupled complex systems are risk prone (Perrow 1984). As Schwarcz (2009, 215) writes about the increasing sophistication of financial markets:

> This not only can produce cognitive complexity but also a 'tight coupling' within credit markets in which events tend to move rapidly into a crisis mode with little time or opportunity to intervene. […] The failures have characteristics similar to those that engineers have long faced when working with complex systems that have nonlinear feedback effects, and indeed many characteristics of complex engineering systems are similar to those of financial markets.

The very occurrence of financial crises, however, allows to identify a crucial additional feature of the global financial system: it displays periods of stability, punctuated by crisis situations opening up possible futures. The collapse of the Bretton Woods system in the 1970s is an instructive case in point. In the 'calm' periods, the system behavior can be characterized by a few 'macroscopic' variables like rates of interest and inflation as well as institutional arrangements like the use of the Dollar as reserve currency. In crisis situations, things are different, because the system as a whole is unstable, and random 'microscopic' events can drive it in very different directions.

These characteristics have led Saam (1999, 48) to argue that: 'In ferromagnetism, fluid dynamics, and laser theory, physicists deal with phenomena that are in some respect isomorphic to the micro–macro link in the social sciences: They deal with systems of many particles and certain characteristics: (1) they display an ordered state or sequence of states that is approached from some combinations of initial and boundary conditions; (2) the ordered state results from the interactions of the system's components, not from external influence; and (3) the ordered state is reached sponteaneously'. She uses this approach to implement a computer simulation of how a developing country (Thailand) experiences periods of stability punctuated by – successful or failing – military coups.

Tentatively, we are led to look at systemic risks as involving major transitions in the dynamics of global systems that are characterized by an interplay of a huge number of micro-agents with a small number of macro-variables. To get a better understanding of such transitions, we now consider the environment of the global financial system.

2.3. Critical external dynamics

In their acclaimed history of financial crises, Reinhart and Rogoff (2009) convincingly show that while financial crises happen again and again, it usually takes hardly more than a few decades for policy-makers and researchers to forget the past and ignore warning signals because they believe 'this time is different'. Of course, there are differences between the global financial crisis and previous ones, but they were and are no reason to stop worrying and ignoring warning signals. Quite the opposite, broad historical changes in the environment of the financial system have probably contributed to the systemic risk that became visible in the global financial crisis.

One such external change was the process of globalization, understood as both a technological and institutional dynamics (Centeno et al. 2015; Claessens and Kodres 2014; Fouque and Langsam 2013; Goldin and Mariathasan 2014). Globalization has affected systemic risks in the financial system in two different ways. On the one hand, it has greatly increased the complexity and tight couplings in that system. On the other hand, it has moved the financial system from a situation where banks, financial markets, etc. were strongly dependent on national regulators, to a situation where national regulators were to a considerable extent dependent on global financial dynamics. Mechanisms of global financial coordination exist, but they are clearly much weaker than coordination at the national level.

Another external change that has been strongly emphasized in some countries was the increase in public debt (Spiegel 2014). While this increase is an issue deserving scrutiny in its own right, it is not clear by what mechanism it could have increased systemic risk in the global financial system, nor does the empirical evidence support the existence of such a mechanism (Fontaine 2012). Things are different with non-governmental debt: here there is evidence suggesting that the increase in private debt in the decades before 2008 did indeed increase systemic financial risk (Jordà, Schularick, and Taylor 2013). Moreover, long before the crisis Minsky (1986) identified a plausible mechanism for this causal link by analyzing the role of credit in expectations-driven speculative bubbles.

The influence of private debt leads to one more external dynamics that should be taken into consideration when conceptualizing systemic financial risks: the rise of intranational inequality that happened in the decades before the global financial crisis (Bazillier and Héricourt 2014; see also Michell 2016). With regard to the link between inequality and financial crises, there is empirical evidence for a combination of three causal mehanisms, all involving credit booms. Increasing inequalities have increased credit demand; they have induced governments to support credit supply in order to avoid social tensions; financial deregulation simultaneously increased inequalities and credit volumes.

These kinds of external dynamics have driven the global financial system from a period of considerable stability (often labeled as 'the great moderation') to a bifurcation point. There, it depended on random events at the micro-level whether the previous trajectory would be continued, or a switch to some other trajectory – including the possibility of a breakdown of the whole system – would happen. At such a point it may be possible to roughly characterize a few possible futures for the system, but not a complete event space of possibilities relevant for decision-making (Jaeger 2016). In the case of the global financial crisis, a key random event was the fast sequence of social interactions that led to the bankruptcy of Lehman brothers.

2.4. A possible picture

Concepts often come with mental images. While the idea that such images somehow constitute the meaning of concepts has been debunked by Wittgenstein (1953), this doesn't mean they are useless. The global financial crisis, e.g., offers a useful picture for systemic risks. It looks as follows.

Humankind has developed a variety of global systems – an energy system based mainly on fossil fuels; a telecommunication system increasingly based on the Internet; a global financial system presently centered around the Dollar; and many more. Global systems cross national boundaries and involve myriads of components: human beings, technical artifacts, natural resources, words, symbols, etc. Somehow these components form large patterns that often can be characterized by a small set of variables and display periods of relatively stable development. However, there also is a relatively small number of external variables whose change can drive a particular global system to a bifurcation point.

People may have different views about the futures they expect at such a point. E.g. some people may prefer a future with coral reefs to one without, but be willing to live in a world without coral reefs if it comes with higher economic growth. Others, however, may not be willing to let coral reefs go for any amount of additional growth (Gustavson, Huber, and Ruitenbeek 1999). The latter are neither irrational nor ill-informed, they simply have so-called lexicographic preferences about this particular situation: due to esthetic, ethical, or other reasons they are not willing to trade a future of type A with a future of type B (Anderson 1995; Jaeger, Schellnhuber, and Brovkin 2008). Of course, people may distinguish more than two categories in this way, and be perfectly able to consider trade-offs within each category. For our present purposes, it is sufficient to distinguish catastrophic from non-catastrophic futures. The fact that different people may make that distinction in different ways does not diminish its importance for research and decision-making.

When faced with the financial meltdown after the Lehman bankruptcy in September 2008, e.g. key decision-makers considered a collapse of the global financial system as perfectly possible and definitely catastrophic, which is why they took dramatic action to stabilize that system. When meeting at the Paris climate change conference in November 2015, key decision-makers considered not a collapse, but a catastrophic future of the global climate system as perfectly possible in the longer term, which led them to initiate a coordinated process to avoid such a future. More generally, in the picture suggested by the global financial crisis, agents are faced with a systemic risk if they believe that the possible futures at a global bifurcation point include developments that they deem catastrophic.

3. Complex dynamics in systemic risks

Presently, the structures and dynamics involved in systemic risks are only poorly understood, and this leaves the concept of systemic risks open to considerable refinement. It is obvious that the complex structure of triggers and consequences involved in systemic risks demands new efforts for modeling and simulating risk careers. For this purpose, it is helpful to look into scientific fields that have accumulated experience in modeling-related dynamic structures (Lucas, Renn, and Jaeger, submitted). These fields include evolutionary biology, thermodynamics, inductive statistics, and in more general terms dynamic systems analysis. The idea is to delineate typical patterns of emerging structures that can be applied to improve our understanding and facilitate the modeling of situations involving systemic risks.

3.1. A starting point

A useful point of reference is given by Saam's (1999) simulation of a political development punctuated by military coups that we have already met in Section 2.2. Building on the approach of synergetics, presented e.g. by Weidlich (2000), Saam uses the master equation technique, originally developed in the study of physical and chemical systems, to represent a social dynamics. At the micro-level, individuals are represented as being in one of a finite number of states at any moment in time. Transition probabilities govern their state changes, and these probabilities depend on the average states of other agents and on evolving properties of their shared environment. The micro-states represent attitudes to democratic vs military regimes. The macro-states represent these two regimes, and the probability of regime switches depends on the configuration of micro-states. The result is a stochastic, non-linear system of differential equations that cannot be solved analytically. Numerical simulations, however, yield patterns of the kind observed in the data for the country studied (of course, with a stochastic process it would be pointless to simply try to reproduce a single given trajectory).

This model is a proof of concept for the chosen modeling approach. In the past years, similar approaches have been advocated and applied in multi-agent models representing financial markets (Thurner 2011), epidemics (Epstein 2009), city systems (Pumain 2011), and more. In view of the concept of systemic risks, this is a highly promising start. Avenues for further progress include the representation of global macro-states, in-depth analyses of bifurcation points and the influence of changes in external variables. There is little doubt that judicious study of techniques and findings from natural scientists, engineers, and mathematicians investigating similar complex dynamics will be of great help in this endeavor.

3.2. Dynamic structures in physico-chemical systems

The dynamics of systemic risks exhibit strong analogies with dynamic structures encountered in a wide range of systems in nature, technology, and sociology. For some model systems of physics and chemistry, these phenomena have been studied in detail since the second half of the twentieth century (Haken 1977; Prigogine 1981). In these investigations, it became clear and was formulated in mathematical–physical terms that in such systems entirely unexpected phenomena arise when they are driven far away from thermodynamic equilibrium by an in-and outflow of energy and material. Then, by increasing the influence of some external control parameter beyond a threshold value, the system may reach a region of instability with a dramatic sensitivity against random fluctuations, and turn to a new ordered state, characterized by a relatively small set of order parameters. This behavior resembles a phase transition, such as studied with freezing, condensation or magnetization in physical chemistry, and so this term is frequently used to denominate dynamic structure generation in open systems. Well-known examples are monochromatic light in a laser, hexagonal rolling cells in a liquid heated from below, vortices in fluid flow, chemical patterns and oscillations in reactors, and many others.

Frequently, it is a whole set of new states which becomes available to the system and it is in principle unpredictable which ones of the possible states the system will choose. Its path is determined by random choices at the various instability points, so-called bifurcations, which in turn are approached gradually and continuously and so the way the system takes over time develops its own complex history.

It has been shown that these new ordered states, as dynamic macroscopic structures, have their origin in the properties of and, crucially, in the interactions between the elementary agents, here the molecules, of the system. When a critical region of instability is reached by exogenous impact, the elementary interactions generate a collective field in a bottom-up effect, with properties of the field acting back top-down upon them. This circular causality between the micro-level and the macro-level gives rise to complex feedback loops (Portugali 2011, discusses similar patterns of circular causality in city systems).

Looking into the details on the micro-level, a competition between often chaotic interactions has been shown to generate a hierarchy of different microscopic time scales which eliminates most of the elementary effects from relevance for the macroscopic structure generation. As a consequence of this reduction of complexity, the stability of the system can then be characterized by simple macroscopic parameters like the Reynolds-number in flow systems or a critical combination of reaction and diffusion rates in chemical pattern formation. On the macro-level, too, different time scales become apparent: while the system slowly evolves macroscopically under the influence of some exogenous disturbance, it may change abruptly after surpassing a stability threshold.

3.3. A blueprint for qualitative analysis

The systems from which this detailed knowledge has been generated by physical–mathematical methods are special, physicochemical cases. However, a wealth of empirical evidence reveals strong analogies between the dynamic structures in these relatively simple systems and those in much more complex systems in nature, technology and society that are relevant for the study of systemic risks. In this perspective, qualitative and quantitative model analyses, separate and in mutual feedbacks, can be designed which may provide a widely applicable interdisciplinary toolbox for analyzing and modeling systemic risks.

Any systems analysis along the lines outlined above must start with a thorough qualitative empirical investigation. The interactions between the various levels of the system must be clarified. Also, the elementary agents of the system must be identified. Although the global situation and evolution of a system is the result of very many micro-actions on the part of the elementary constituents, these are not fully free in their actions but are guided and coordinated by the global field generated by them, of whatever nature this may be (Midgley 2012; Sheldrake 2012). This cyclical relation creates and sustains the macroscopic dynamic structure.

While in well-understood physicochemical systems the set of order parameters results from self-contained mathematical–physical analysis, it has to be elaborated empirically in the general case. So it is essential to elaborate, through qualitative analysis, those relatively few aspects of individual behavior, so-called order-parameters, which are activated and relevant as key variables in a critical situation, contrary to the many which are irrelevant. In this sense, the principles of dynamic structure analysis as developed in physics and chemistry provide a heuristic scheme to construct qualitative models for any system. Although no analytical approach based on natural laws is available in the general case, the conceptual approach may be analogous and should be taken seriously in any effort to model systemic risks.

Further on the qualitative level, one is advised to be alert to different macroscopic time scales: while the system may evolve slowly and hardly noticeably under the continuous influence of some exogenous impact, there may at some moment appear a sudden tipping, disastrous or not, of only partially predictable consequences. One is further motivated to look for characteristic parameters indicating instability regions, which may announce themselves empirically by irregularities, as discovered e.g. by a time series analysis. Finally, historical insight into a system should be valued, since the approach to instability points may be anticipated from comparison with earlier situations, although, at the phase transition itself, such knowledge is not sufficient to predict the future behavior of the system that will result from random fluctuations.

The procedure of setting up a qualitative model based on knowledge about dynamic structure generation represents a value of its own right. It provides a mental framework for ordering the analysis and helps to systematize empirical considerations.

3.4. Food for quants

More detailed knowledge may be obtained by progressing to a quantitative level. The lessons learned from physicochemical systems make it clear that for this purpose an explicit model of the micro-dynamics has to be designed and this has to be linked with the macrostructure of the system. This is the classical problem of molecular physics (Lucas 2007). As adapted from there, its solution can be found by deriving master equations for the evolution of the ordering macro-variables of the system, as in the study of Saam (1999) discussed above. The elementary dynamics are then introduced empirically via probabilistic transition rates. As it may be hard or even impossible to establish such rates, a direct simulation of the agents' behavior in terms of empirical interaction laws can be performed, as in molecular dynamics. In both approaches, which are not mutually exclusive, care must be taken to honor the empirical knowledge about dominating and induced properties and the generation of a collective field to ensure circular causality.

Many different versions of this kind of mathematical approaches have been proposed (Gilbert 2007; Helbing 2010; Weidlich 2000). When properly designed along these lines, models should be able to reproduce characteristic features of self-organizing dynamic structures, such as sudden tipping to new states under the influence of some exogenous disturbance, bifurcation phenomena and attractors as rhythmic limit cycles and the like, in any system. Stability investigations may indicate critical combinations of parameters.

What results can be expected from such stochastic mathematical tools? As shown in the physicochemical case, it turns out generally that many details of the agents and their interactions will lose their relevance when it comes to analyzing the generation of new structures at instability points. They cancel out due to the statistical effects of large numbers. So, in an effort of appraisal of the system under consideration, many fundamental dynamic properties may be studied quantitatively on the basis of rather crude models for the elementary dynamics. The mathematical model has the character of an addition to qualitative empirical analysis, not of an alternative.

Detailed quantitative predictions of the dynamics are not the goal. This is impossible in principle, even for the relatively simple systems of physics and chemistry, due to random effects at instability points. However, by varying the parameters of the model and thus studying different scenarios, a detailed understanding of the relative importance of influential parameters may be obtained. Information about cause–effect relationships in a system can be generated and may be used to categorize it in terms of simplicity, complexity, uncertainty, and ambiguity. A virtual laboratory is generated in which knowledge about fundamental social mechanisms can be collected. It is thus possible to carry out experiments on artificial systems that would be quite impossible to perform in the real world.

3.5. Challenges

Clearly, the architecture of the systems relevant in systemic risk analysis is much more complex than in the molecular systems of physics and chemistry. A fundamental challenge is the fact that in systemic risks human actions play a key role, and the actions of human beings depend on what they want and what they believe. A possible approach may combine an integration of biological and cultural evolution with ideas of rational action (Gintis and Helbing 2015; Laubichler and Renn 2015). By representing wishes and beliefs as properties of individuals one might be able to get a Markov chain format, and from there reproduce complex dynamic structures as suggested here.

Whatever way one may choose to represent the wishes and beliefs of human beings, decision-makers tackling systemic risks need to be self-reflective enough to take into account that they are human beings, too, and therefore must be able to apply their models of human action to themselves. This is important in view of the criteria by which decision-makers evaluate risks, and also in view of their beliefs about how other people may react to their decisions. Avoiding this self-reflection in the face of systemic risks would lead to dangerous control illusions (Fast et al. 2009), while reflective models would foster a more realistic co-evolutionary approach.

Last not least, human beings talk to each other, and words have consequences. It is far from clear how this can be integrated into formal models, and where models that neglect language become misleading. In any case, it is an important challenge to embed the use of models dealing with systemic risks in narrative and discursive practices (Chabay 2015; IRGC 2007).

These challenges are not objections to our conceptual argument, quite the opposite: they show that the concept of systemic risks elaborated here can help both to produce better models of relevant systems and to use such models in responsible ways.

4. Conclusion

The concept of systemic risks originated from the experience of international financial crises after the breakdown of the Bretton Woods system, and gained prominence with the global financial crisis that started in 2007. Looking at this paradigmatic example of systemic risks, we have seen how attempts to conceptualize such risks can be either too generic – including roughly any breakdown of some system – or too specific – targeting only international financial crises. Such misspecifications are not only problematic for research, they also hamper practical measures at risk governance because they don't offer ways to define operational criteria for action.

The work of OECD (2003) shows that there are more systemic risks than those of the global financial crisis. It also shows how hard it is to come up with a concept of systemic risk that is not overly arbitrary. Still, a closer look at the global financial crisis is helpful to develop a sound concept of systemic risk, as indicated in the introduction. This starts with the catastrophic dangers and global nature involved in today's financial markets (points 1 and 2a in the scheme proposed in the introduction). The role of myriads of often tightly coupled financial processes and agents highlights the importance of complex causal structures (point 2b) and non-linear feedback mechanisms (2c). Moreover, the financial crisis vividly demonstrates the stochastic nature of critical situations – not necessarily in the sense of well-defined probability distributions, but in the sense of an ill-defined variety of possible futures, including possible consequences of a given action (2d). Finally, the crisis shows the broad interplay of micro- and macro-processes, both with exogeneous processes that modify the system dynamics (point 3). Altogether, the global financial crisis provides not only one of several paradigmatic examples anchoring the concept of systemic risks formulated in the introduction, it is also perfectly suited to explain the different facets of the concept.

A remarkable coherence of the proposed concept of systemic risks is provided by the way their complex, non-linear, and stochastic features are related to complex dynamic structures first explored in physics and chemistry. These structures are characterized by periods during which they display stable patterns, punctuated by transitions that lead from one such pattern to another one in unpredictable ways. This behavior can be explained by a duality of micro- and macro-states, embedded in states of the environment. The large number of rapidly changing variables characterizing micro-states boils down to a small number of relatively stable variables – known as order parameters – characterizing the macro-states. The stability of the macro-states in turn depends on aspects of the system environment which again can be characterized by a small number of slowly moving variables – known as control parameters. When the control parameters approach critical limits, the system enters a critical transition (Scheffer 2009). In such transitions, the macro-state breaks down until a new one forms. Which one out of several possible macro-states will emerge cannot be known in advance. What can be known, however, is that the new macro-state results from feedbacks that reinforce some micro-processes while dampening others. Systemic risks then arise at critical transitions of the relevant systems. The two concepts are not identical, of course, as many critical transitions in many systems have nothing to do with systemic risks. Still, an important strength of the understanding of systemic risks developed here lies in its connection with critical transitions.

This leads to avenues for further research. We conclude by highlighting four of these. First, there is the question why it is often difficult to predict when a system will suffer a breakdown or collapse. In part, this is due to ripple effects beyond the domain in which the risks originally appear, leading to threats of multiple breakdowns of critical services to society (De Bandt and Hartmann 2000). A major challenge here is that systemic risks defy human intuitions geared to the assumption that causality is linked to proximity in time and space. A second challenge is that, faced with unknown tipping points/areas, you are encouraged to repeat your errors until it is too late. So there are reasons for systemic risks to be underestimated or, at least, under-managed compared to conventional risks. It will be important to expand the fruitful research tradition of comparative studies of risk perception (Boholm 1998) in this direction.

Second, the uncertainty that is characteristic of the bifurcation points involved in systemic risks raises the thorny question about how to make reasonable decisions under deep uncertainty. There is no one-size-fits-all answer to that question, but a range of promising ideas and practical experiences. They include risk governance as a structured procedure of social learning (IRGC 2007; Renn 2008), robust decision-making through enhanced versions of scenario analysis (Lempert and Collins 2007), sequential establishment of threshold resilience, as implemented in the Thames Estuary 2100 project for London (Hinkel et al. 2015), and more.

Third, given the paradigmatic role of the global financial crisis, a key question is whether the concept of systemic risks developed in this paper can help with quantitative and qualitative assessments of global financial risks. Battiston et al. (2016) show that this is the case with quantitative modeling. For stress tests of banks, their position in networks of financial institutions is at least as important as their size. The dynamics of these networks, in turn, are influenced by developments in their broader environment.

With regard to qualitative assessments, an important topic for further research are the long-term perspectives of systemic risks in the financial system, as discussed by Zhou Xiaochuan, governor of the Chinese central bank (Zhou 2009; see also Bergsten 2009; Stiglitz and Members of a UN Commission of Financial Experts 2010; Ussher et al. 2017). Zhou's analysis – related to the macro-economic imbalances between the US and China – is best understood by treating the growing geopolitical rivalry between these nations as a control parameter for the global financial system in the twenty-first century. A sound concept of systemic risks will surely be helpful to understand and reduce some of the systemic risks connected with this rivalry.

Fourth and finally, an important question is how different systemic risks compare with and relate to each other. One may distinguish and investigate some major areas of systemic risks: the growing extent of human intervention in nature (climate change, pollutant emissions, use of land and water); inadequate or ineffective control of central processes in the realms of business and politics (capital markets, corruption, capacity deficits); technological challenges such as cybersecurity; and adverse by-products of globalization and modernization (unequal living conditions, lack of security, loss of identity). Although most people are usually familiar with these kinds of systemic risk, they do not get the same practically effective attention as conventional hazards and risks have been given in the past. This can have disastrous consequences – not only in financial markets.

We close by stressing that research on systemic risks is important not only to avoid catastrophic dangers, but also to seize global opportunities. Indeed, research inspired by the concept of systemic risks developed in this paper should not assume that bifurcation points in global systems are always to be avoided. Some transitions through such bifurcation points will be essential to tackle the challenges of the twenty-first century. Moving from the present, environmentally destructive growth path of the world economy to a path that will allow to overcome global poverty while caring about the planet will definitely imply critical transitions. So will solving other problems global society is faced with. Learning to tackle the challenges of systemic risks is part of the broader task of learning to shape critical transitions in responsible ways.

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