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Perspective

Theory of Systemic Risks: Insights from Physics and Chemistry

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ABSTRACT: Systemic risks, as opposed to conventional risks, bear the danger of destroying entire systems. Their understanding and governance remain a serious challenge. The phenomena of systemic risks show many analogies with those of dynamic structure generation in the systems of nature, technology, and society, including simple model systems of physics and chemistry. By analyzing these model systems, the elementary processes and the generic mechanisms by which they generate macroscopic dynamic structures become evident. Generalizing these insights makes it possible to formulate the basic framework of a theory of systemic risks with elements providing hints for adequate governance strategies. Although these insights cannot be applied to societal processes one by one, they reveal generic patterns and clusters.

KEY WORDS: Complex systems; dynamic structures; governance strategies; homomorphism of patterns

1. INTRODUCTION

While the last four decades have witnessed considerable progress in terms of conventional risk management, the picture becomes less favorable for systemic risks such as those posed, for example, by climate change (IPCC, 2014) or the global financial system (Lo, 2012), growing inequalities between rich and poor (World Economic Forum [WEF], 2017), pandemics as well as the present and urgent local challenges of breakdown of infrastructures (Gheorghe, Masera, De Vries, Weijnen, & Kroger, 2007), destruction of ecosystems, mass migration, and threat to biological diversity.

The notion of systemic risks became prominent in the course of the financial crisis. It was used there to describe the risk of breakdown of the worldwide network of financial institutions, that is, the global financial system, triggered by initially localized and isolated problems in one of its components. It soon became evident that such systemic risks are not limited to the financial world. Rather, the same phenomena can be observed in all systems of nature, technology, and society. More generally, systemic risks then describe phenomena of breakdown of entire systems macroscopically due to reinforcing feedback actions of agents on the microlevel. In natural ecosystems, agents such as harmful chemicals notably used in modern agriculture have recently been shown to interact with the insect population in a way that threatens essential parts not only of the stock but provoking the systemic risk of destroying the welfare of the ecosystem as a whole. Typical examples from the technical world are infrastructures, such as the electrical grid, the water supply, or a complex chemical plant, where the agents may be control and generation units with the systemic risk representing the breakdown of the infrastructure as a whole due to the failure of a single component. A

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recent example of systemic risks in societal systems was the Arab uprising. Here, a seemingly nonsignificant and localized political event, the self-immolation of a small greengrocer in a small village in Tunesia, triggered a widespread political upheaval sweeping away the governments in many parts of the Arab world.

Up to today systemic risks are analyzed on the basis of empirical investigations and statistical evaluations. However, based on the empirically established fact of analogies across the different domains in nature, technology, and society, enough empirical material is available to recommend a closer look into the causal structures. The present contribution attempts to do this by taking advantage of insights from the natural sciences, notably physics and chemistry, about complex systems and their dynamics. The objective is to develop a conceptual approach in order to understand the generic fabrics of systemic risks.

2. NONEQUILIBRIUM DYNAMIC STRUCTURES

The notion of systemic risks is not in common use in physics and chemistry because there is no vulnerability, in the sense the term is used for systems relevant to the society´s welfare. A more general and abstract notion, comprising systemic risks as a special case, is that of dynamic structures, notably nonequilibrium dynamic structures. Nonequilibrium dynamic structures, whether manifesting themselves as systemic risks or not, can be observed in essentially all systems of nature, technology, and society.

Looking at systemic risks as nonequilibrium dynamic structures in an overarching perspective across all domains, a vast body of empirical facts becomes available. A crucial observation is that their phenomenologies show remarkable analogies. In this article, it will be argued that these analogies are deeply rooted in universal elementary mechanisms responsible for the morphology of the macroscopic patterns. We refer to this insight as homomorphicity of dynamic structures and consider it to be an adequate basis of a general theory of systemic risks (Lucas et al., 2018).

A typical example for the emergence of dynamic structures from the technical world is the breakdown of an infrastructure, be that the electricity distribution (Koonce, Apostolakis, & Cook, 2008) or a mobility system such as railway traffic or automobile traffic. An almost everyday experience of railway travelers is the propagation of a localized disturbance, such as the temporary blockade of a railway section, be it by storm damages, human casualties, or other events, over the whole railway network with delays in locations far away from the disturbance and extending over a significant time even after its removal. Quite similar phenomena are frequently observed on automobile highways, where sudden traffic jams appear to occur without any apparent local reason (Helbing, M.Treiber, Kesting, & Schönhof, 2009), as well as in mass panic situations (Hoogendoorn & Daamen, 2005). A deeper look then invariably reveals that the systems were in unstable states, characterized by a high density of trains, cars, or people, respectively. A minor perturbation somewhere in the system is then reinforced and cascaded through the system by internal feedback mechanisms between the agents with the result of a breakdown of the entire system.

In the global financial system, stock market crashes and the global bank crisis are examples of dynamic structures. They are again characterized by the system having been brought into unstable states by an excess of interdependence between the interacting agents, i.e., the financial institutions. Out of such unstable situations the failure of one institution, when interrelated critically to the rest of the system, is able to trigger a sudden phase transition to a new and fatal structure. Here too, it is frequently the cascading effect of an original event over the entire system, similar to epidemic spreading of infections, which characterizes the dynamic process (Battiston et al., 2016, Hurd, Cella, Melnik, & Shao, 2016).

Analogous phenomena of dynamic structure generation can be observed in social systems. The mass migration phenomenon in the aftermath of the Arab uprising follows the same patterns of sudden phase transition out of an unstable societal state (Lucas, 2016). Revolutions are another example of dynamic structure generation within a society (Weidlich, 2000). Many different forms have become historically known. All of them arise due to the perception of unequalness and injustice among large parts of a population with respect to a small elite. The phase transition is preceded by a gradual development toward a critical and unstable situation within the society and is then triggered by some form of fluctuation.

While, on superficial observation, there seems to be no relationship whatsoever between these dynamic structuring processes in the various domains, it is obvious that they follow common patterns. These common patterns point to the existence of common generic mechanisms underlying dynamic structure generation, and thus also systemic risks. In order to scrutinize these detailed mechanisms, a purely empirical and phenomenological analysis is not sufficient. Rather, it is of crucial importance to investigate the physical and mathematical origins of the structure generating processes. For this purpose, systems that lend themselves to such a kind of analysis must be studied.

3. DYNAMIC STRUCTURES IN PHYSISCS AND CHEMISTRY

Particularly simple dynamic structures can be studied in the laboratory for some model systems of physics and chemistry. Here, the generic mechanisms on the microlevel leading to macroscopic dynamic structures can be rigorously formulated in mathematical terms. This makes it possible to gain insight into the essential elementary phenomena resulting in the emergence of macroscopic dynamic structures due to interactions of the agents on the microlevel. It turns out that the rather diverse and chaotic elementary processes of the agents on the microlevel surprisingly order themselves on the macrolevel into widely universal dynamic patterns, which can be formulated in terms of simple macroscopic parameters.

Prototypes of such studies in physics are hydrodynamic structures (Bénard, 1900), chemical structures (Gray & Scott, 1990, Prigogine, 1980; Prigogine & Lefever, 1968), and laser light (Haken, 1977). In analyzing the emergence of macroscopic dynamic structures from the underlying elementary processes, corner stones of a theory become visible. These corner stones, although necessarily qualitative in character, form the basis of a practical and systematic approach that is valuable as an ordering tool for classifying a wide empirical collection of phenomena associated with systemic risks in all domains.

3.1. Hydrodynamic Structures

Hydrodynamic structures are commonplace experience. Clouds in the sky and vortices in rivers can be ubiquitously observed. The agents of the systems are the molecules that communicate with well-defined physical interactions in the dimensions of nanometers. A particularly simple phenomenon of this class of structures are the Bénard free convection cells.

When a liquid, such as oil in a frying pan, is heated from below the system, it is put under stress over its boundaries. Initially, there is only a small temperature difference between the bottom and the top. Then, the heat transfer is put into action through molecular transport. The molecules increase their kinetic energy at the bottom close to the heating surface and communicate this higher energy by impacts with other molecules to the upper regions. The system responds by a heat flow, which depends linearly on the applied temperature difference. It is stable in the sense that molecular fluctuations, which are unavoidable and random, are damped. On continuous increase of the temperature difference, the heat flow gradually increases in a slow process for some time without any macroscopically visible change of the systems state.

However, when the temperature difference surpasses a threshold value, a rapid and dramatic change of the system's behavior results. Then, the linear molecular transport mechanism is no longer adequate to take care of the now much higher heat load at the bottom. The system becomes unstable and highly sensitive. Fluctuations in small regions trigger the formation of local and momentary convection structures, which are no longer damped but rather are stabilized by a positive feedback to the elementary molecular motions. This mechanism, which is of crucial importance in dynamic structure generation, is referred to as circular causality. The macroscopic flow structures thus spread over the whole system. The heat transfer by convection is a typically nonlinear phenomenon in the sense that the heat flux depends on the temperature difference in a higher than linear order.

Highly ordered convection currents result, the so-called Bénard convection cells. The liquid rises parallel to the edge of the pan and perpendicular to against the direction of gravity on one side of the roll, cools down at the top, and moves downward to the bottom in the direction of gravity on the other side of the roll. The generation of structured Bénard rolls is a phenomenon of emergence, i.e., a collective mass phenomenon that cannot be derived from the properties of the agents, here the molecules, since single molecules do not generate structured flow patterns. The resulting structures are macroscopic. So, the molecules must communicate with each other over distances order of magnitudes larger than their sizes and individual ranges of interactions. The structures are not generated by some central control but rather arise by internal self-organization.

Usually, a system in an unstable situation can choose among various different new states, so-called modes. The initial two modes in the Bénard experiment differ by the turning direction of the rolls. The choice between them is made by a random process and the new state can therefore not be predicted. Experimentally it has been found that the rolls are turning left or right with equal probability. After a transition, the system remains in the new state until, in the further course of the experiment under further increase of the temperature difference, further transitions appear, which then depend on the earlier history of the system. The system will thus develop a particular dynamic history, by which later states can only be explained and appreciated when considering this path dependency, i.e., historicity. Eventually, under further increase of the temperature difference, the macroscopically ordered structure breaks apart and gives way to unordered turbulence.

It should be noted that the whole process is characterized by two dramatically different time scales. A rather slow approach to a region of instability on increasing the temperature difference is followed by an instantaneous transition to the new convection state at the threshold. A stability analysis delivers quantitative information about the critical temperature difference in combination with other relevant parameters of the system. This information can be cast into the form of a dimensionless early warning parameter balancing, promoting, and hindering system properties.

3.2. Chemical Structures

In chemical reactions, new substances are generated with new properties, e.g., new colors. Normally, these new properties are distributed evenly over the entire system, resulting, for example, in a uniformly colored solution. However, there are reactions that generate macroscopic patterns over time and space, which in their dimension are a billionfold larger than the molecules as well as their ranges of interactions from which they originate. Such patterns, colored rings or changes in color on a clock-like timed sequence, are examples of dynamic nonequilibrium chemical structures. They can be generated in open system laboratory equipment with substances performing autocatalytic reactions. Catalysis is a process by which a reaction between molecules is speeded up. In autocatalysis, an end product is a catalyst for the reaction considered. By its continuous formation, the reaction is continuously accelerated by positive feedback. Thus, the response of the system to the addition of new substance is an exponential acceleration of the reaction, a typical nonlinear effect. This process has been studied in detail experimentally as well as theoretically. As a result, valuable and generalizable insights have been gained.

In the course of the experiment, substances capable of autocatalytic reactions are fed into the equipment. This process transfers stress over the system's boundaries since now the autocatalytic reactions are continuously induced and the system reacts in a nonlinear, i.e., dramatic way. When the supply exceeds a specific threshold, the system becomes unstable and highly sensitive. Small random fluctuations, irrelevant in stable situations, are no longer damped but rather trigger a transition to a new macroscopic system state.

A pattern once generated, possibly as a local and transient random fluctuation, may spread under favorable conditions over the whole system and generate a new macroscopic picture by circular causality. In this mechanism, a positive feedback, local macroscopic patterns do not decay but rather act back upon the elementary molecular autocatalytic reactions from which they have been generated. The patterns generated are phenomena of emergence. They cannot be derived from the properties of the elementary agents, here the autocatalytic reactants, but are collective mass phenomena. They originate from interactions on the scale of nanometers but spread over macroscopic dimensions. In particular, they are not generated by some external direction but arise through processes of internal self-organization.

Usually, various different patterns are available to the system originating from unstable situations, depending on its internal properties. The system chooses one of them in a random process so that the moment of its emergence as well its particular appearance are not predictable. Once a new state has been chosen, this state may well become unstable again under further increasing external impacts. Thus, the system, starting from the first approach to an unstable regime, will make a random choice of a new state at the first phase transition, then approach a further unstable state depending on the first choice in a deterministic process, again make a random choice at the second phase transition, and so on. The system will thus develop a particular dynamic history, by which later states can only be explained and appreciated when considering this path dependency, i.e., historicity. Under further stress, the system eventually loses its order and gives way to unordered turbulence.

The approach to the unstable state by continuous addition of substances is a slow process while the transition to the new state is instantaneous. So, the whole experiment runs on two different time scales. A stability analysis reveals quantitative statements about the stable concentrations of reactants in dependence on the macroscopic kinetics, which can be used as an early warning indicator of instability.

3.3. Laser Light

In a standard neon lamp, some electrons of the gas atoms are lifted by an influx of energy, e.g., an electrical current, from their normal distribution over the quantum mechanically allowed electronic states to a distribution with more electrons being in higher energy states, so-called activated states. This distorted distribution is referred to as an inversion, analogous to the notion of a nonnormal temperature distribution in weather conditions. From these states the activated electrons tend to fall down again spontaneously to their normal distribution, as long as no further influx of electricity counteracts this tendency. In doing so, they emit light waves of frequencies given by the energy differences between the activated energy levels and the lower levels. Since there is no correlation between these processes, the resulting light is incoherent.

In a laser environment, these physical processes are coordinated by a process of internal self-organization. The interacting agents are the atoms and electrons of the laser medium as well as the photons of the generated light. A crucial addition to the standard neon lamp are two mirrors at the ends of the gas tube. These mirrors transform the neon lamp into a resonant cavity. The laser medium, being in a state of inversion by pumping in energy, is characterized by its electrons being in activated states and trapped there by the quantum selection rules. The light waves resulting from the decay processes now do not leave the tube but rather travel back and forth in the resonant cave except for a minor part passing through one of the mirrors. This has the effect of stimulating nonlinear feedback processes in which the light waves can stimulate the activated electrons to fall back to their ground states and thus emit light of the same quality. The phase and direction of the stimulated emission then match that of the stimulating light, which gives the emitted light the property of coherence and directionality.

As is typical for dynamic structure generation, the transition from microscopically chaotic, i.e., macroscopic incoherent light to laser light results out of an unstable situation by fluctuation processes under the continuous increase of an external stress, here the pumping energy. While the approach to the unstable state is a slow process, the transition is instantaneous. Also, there are different light waves consistent with the construction of the laser, i.e., the distance between the two mirrors. However, the system, based on the internal properties of the laser medium, chooses one particular wave, the laser light, by a process of circular causality, by strengthening its amplitude while those of all others are damped. On further increasing the pumping energy, various forms of coherent laser light are generated until finally the process yield to the production of chaotic, also denoted as turbulent, laser light.

A stability analysis provides a quantitative measure of the pumping energy for the start of laser activity. It can again be cast into a dimensionless parameter balancing promoting and hindering effects.

3.4. Homomorphism

Dynamic structures are generated when open and complex systems reach a state of instability. Openness in the physical and chemical model systems allows the transfer of energy and matter across the system boundaries. Complexity refers to internal properties of the system consisting of many agents, such as molecules, interacting among each other in a way resulting in nonlinear effects with far reaching cause–effect chains.

The study of dynamic structures in some physical–chemical model systems has revealed the underlying elementary mechanisms on the level of the agents, i.e., the molecules, atoms, electrons, photons. While the types of interaction between these agents are obviously rather diverse, it has become clear that in spite of this elementary diversity, universal patterns of macroscopic behavior are generated in these model systems. The dynamics on the microlevel and on the macrolevel proceed on entirely different time scales, in the sense that, the macrodynamics changes much slower than the rapidly changing and rather individual microstates. The system-specific microdynamics may then be considered as fluctuations, which relax to their equilibrium values almost immediately and thus can be neglected in the analysis of the macroscopic dynamics of the system. The macrodynamics of a system can thus be formulated in terms of only a few macroscopic parameters. This accounts for a significant information compression in comparison with the multitude and chaos of interactions on the elementary level of the agents. Due to this information compression, different systems, such as hydrodynamic flows, chemical reactions, and the laser, show remarkable analogies in the elementary processes leading to macrodynamical behavior. This is the formal reason for the many universalities in the basic patterns of dynamic behavior in the various domains with otherwise no relationship between them whatsoever. This phenomenon is referred to here as homomorphism (Lucas et al., 2018).

When the external stress, such as the temperature difference in hydrodynamic structures, the influx of substances in chemical structures, and the pumping energy in a laser, exceeds threshold values, the system is brought into a state of instability. In such states, by responding to small and random perturbations, i.e., fluctuations, the system tests its various intrinsic modes of macroscopic behavior, such as the various forms of Bénard rolls, of chemical patterns or light waves in a laser. A stability analysis then reveals that most modes behave conservatively in the sense that they respond with small changes to small perturbations, without any macroscopic change of the system's state. However, some modes, in competition with the rest, grow exponentially into amplitudes that react back upon the collective dynamics of the system elements, i.e., the agents, by an effect referred to as circular causality and force the system into a new and unpredictable state. Original states thus may collapse in situations of instability. New ordered states then organize themselves on the macrolevel and spread over the whole system.

We here summarize those aspects extracted from the study of the simple model systems, which can maintain general validity and justify the claimed homomorphism as the basis for a theory of systemic risks.

Openness: A fundamental property of the studied systems is their openness. They are in exchange with their environment across their system boundaries. For the model systems, this exchange comprises matter and energy. Thus, the environment takes part in the processes of the system. Perturbations from outside may cross the system boundaries and are able to destabilize it.

Complexity: The dynamic structures generated are due to the properties of and the interactions between the elements of the system, the agents. If these interactions and the other conditions of the experimental set-up are prone to inducing nonlinear effects, such as heat convection, speeding up of reactions or exponential promotion of coherent light waves, small causes may lead to unexpectedly large outcomes, so that the system may become unstable after surpassing a threshold of external stress. The cause–effect chains then become obscure. Random perturbations may transform the system into a new state by a sudden phase transition. This is associated with an unforeseen sensitivity, which in chaotic systems is addressed by the well-known butterfly effect. The dynamics of the system can therefore not be forecasted. Two different time scales become visible: A slow approach to an unstable state is followed by a sudden phase transition of the entire system. Dynamic structures in complex systems are thus generated as a sequence of continuous changes and sudden leaps. They are path dependent, showing historicity, i.e., they are subject to the previous history of the system.

Circular Causality: The generation of macroscopic dynamic structures out of a chaotic multitude of elementary interactions is based on a selection by competition. During this process, one or several macroscopic patterns produced by the actions of the agents act back upon the actions of the agents selectively. This stabilizes these particular structures and allows them to spread over the system while all other structures possibly consistent with the properties of the system are damped and thus do not manifest themselves. This circular causality is constitutive for the dynamic structure generation in all domains.

Early Warning Signals: Unstable states in complex systems are announced by early warning signals. Generally, instability is fostered when the interactions between the elements are stronger than friction effects or when damages to system components arise faster than repair mechanisms, e.g., mitigation measures. Formally, early warning signals can be cast into dimensionless parameters.

Emergence: Complex systems have emergent properties, i.e., they have the ability to generate structures by self-organization that cannot be derived from the isolated properties of the system components. They are coordinated mass phenomena. This makes it impossible in principle to analyze the dynamics of a system by merely studying the system elements.

4. APPLICATION TO SYSTEMIC RISKS

Dynamic structures are overarching phenomena in all domains. In many cases of vulnerability to the societies' welfare, they manifest themselves as systemic risks. Obviously, the insights from physics and chemistry can be transferred to more general systems only at a price of some abstraction. In particular, the transfer to systemic risks in systems with human individuals as agents, in which we are interested here, presents itself as a remarkable challenge. Interactions between human individuals are much more diverse than the physico–chemical interactions studied in the model systems of physics and chemistry. They include nonrational and emotional elements as well as memory effects and may, in notable contrast to those in physico–chemical systems, even be changed by impacts of circular causality. In particular, stochastic elements associated with these interactions play a decisive role in the dynamic evolution of a system. Thus, any system with human individuals as agents is a highly complex nonequilibrium system that changes and develops constantly in an unforeseeable manner. Complexity, multivariability, and contradictoriness in such systems seem to indicate that simplification, reduction, or neglect of the multiplicity of factors determining societal evolution inevitably leads to a multiplication of error and to a significant misunderstanding of the processes under study, thus eliminating any practical value. Still, although it is true that the insights from physics and chemistry thus cannot be generalized one by one, it can be shown that even societal processes reveal the same generic patterns and clusters as the physico–chemical model systems. This supports the thesis of homomorphism of dynamic structures over all domains as the basis of a theory of systemic risks. In the following, we demonstrate this for two systems for which broad empirical evidence is available.

4.1. Breakdown of Technical Infrastructure

A particularly simple example of dynamic structure generation and thus also systemic risks in a system involving human individuals is the phenomenon of traffic jams on a highway. It may serve as a prototype of breakdown of technical infrastructure.

The human individuals in the cars on the highway are the agents of the system. The systemic risk is the disruption of the free flow by a traffic jam (Helbing et al., 2009). The nature of the interactions between the cars depends crucially on their density. At low density, the movements of the cars are proportional to each other, i.e., they communicate in a linear way. Unavoidable and random events of braking and accelerating as well as construction sites have no influence upon the flow of the traffic. The system is stable. This changes dramatically under imported stress over the open boundaries of the system, e.g., increasing density of cars through the inlets. If the density surpasses a threshold, the cars have such a small distance from each other that their communication becomes prone to nonlinear effects. The system enters a region of instability. Sudden and unforeseen traffic jams may develop. Frequently, perturbations such as a construction site, which would be without consequences at low density, are responsible. However, and this is a crucial element of homomorphism, even a small random fluctuation such as a sudden braking process of one car can trigger such a macroscopic change of the system, i.e., a traffic jam. By circular causality, a local and momentary jam phenomenon may act back upon the human agents in neighboring cars stimulating irrational and emotional actions such as braking and acceleration processes or lane changes. The initially local jam is thus stabilized and can spread over a large region of the system far beyond the location of the original perturbing event.

It can easily be seen that all corner stones of the homomorphism of dynamic structures are present even in this still relatively simple system. The system is open since cars can be added or removed via the various inlets and outlets along the route. Its complexity is based on the individual cars and their interactions provoked by the agents of the system, the human drivers. By importing external stress, i.e., increasing the density of cars, the system can be transferred into an unstable situation, which is prone to nonlinear effects. In this situation, the system reacts sensitively to any fluctuation and is easily transformed into a new macroscopic state, such as a traffic jam. Two different time scales become visible: a slow approach to an unstable state is followed by a sudden phase transition of the entire system. Circular causality stabilizes local and momentary risk events. An established early warning signal is the density of the cars which is used to control the traffic in an effort to avoid a jam. The jam itself is a phenomenon of emergence since it owes its generation to a coordinated mass phenomenon of many cars.

4.2. Arab Spring and Mass Migration

Proceeding to systemic risks even more remote from the physico–chemical model systems, we demonstrate the validity of the claimed homomorphism for a recent historical challenge: the mass refugee flows from Arab countries to Europe, notably Germany, after the failure of what has been referred to as Arab spring or rather uprising (Lucas, 2016).

The system under consideration is the North African Arab world together with some other Arab countries. It is obviously an open system, the boundaries of which are permeable for people, information, and material goods, including weapons.

The agents of the system are its human inhabitants. Their interactions among each other and with the system's boundaries are paradigmatically complex in the sense that they promote nonlinear effects. A crucial role in these interactions is played by modern mobile communication technologies, which allow an instantaneous and widespread distribution of information, resulting in rapidly organized mass motions of a large number of people (Hussain & Howard, 2013; Stepanova, 2011; Wilson & Dunn, 2011). These phenomena are evidently emergent in character since they depend on a large number of individuals sharing the information and the associated reactions.

The mass refugee flows came into action following the self-immolation of a grocery trader in a small Tunesian village. This minor yet tragic event would be classified as a fluctuation in the physico–chemical model systems and reflects the high sensitivity typically associated with dynamic structure generation. Clearly, this sensitivity is closely connected to the system being in an unstable regime where the population is unhappy with its living conditions and opportunities of further development. Obviously, the dissatisfaction among society, especially among the young generation, had at that time already surpassed a threshold, the result being that this minor event was able to trigger a widespread revolution (Campante & Chor, 2012; LaGraffe, 2012).

We note the constitutive role of circular causality. While at first only few and local uprisings manifested themselves, these acted back on the many still inactive young people via the massive use of mobile information devices and motivated them to join the movement, thus turning it into a revolution. Instantaneously, the new structure of a mass refugee movement emerged. Clearly, the extent and violence of the uprising and the refugee movement were entirely unforeseen and unpredictable.

The historical path dependency, associated with different time scales, is also quite obvious. The misery of the Arab world is clearly a consequence of its earlier history of suppression by colonialism and subsequent corrupt dictatorships. There was a long process of increasing dissatisfaction over the course of many years until, at the moment of the self-immolation, an isolated event involving a single person, normally probably without much consequence, was able to start a mass revolution, which finally transformed into a mass refugee flow from the Arab countries to Europe (Meijer, 2019).

Clearly, there were early warning signals during all phases of the historical development, all of them woefully neglected. The obvious devotion of many parts of the Arab world to radical Islamic political formations was an early indicator of instability (Ismael & Ismael, 2013). As a counteraction of the autocratic political system, increasing police terror could be observed. A typical parameter as an early warning signal in the forefront of revolutions is the ratio of forbidden actions to police reactions sanctioning them (Schroeter, Jovanovic, & Renn, 2014). If this parameter increases over time, this is an indication that the authorities are no longer able to control the situation and save the system from radical change.

5. ELEMENTS OF GOVERNANCE STRATEGIES

Looking at systemic risks on the basis of the insights from physics and chemistry indicates the nature of the macroscopic phenomena, which are to be expected as well as their microscopic origins. Beyond a general appreciation of the analogies, it is rewarding to make these insights operational in the sense that they provide elements for strategies of governance.

Since the emergence of macroscopic structures appears as an effect of selecting and collective ordering of the elementary processes, any systematic analysis toward successful governance strategies starts with identifying these processes from the empirical knowledge available. Particular system properties are required for dynamic structure generation to take place, such as feedback processes between the elementary processes on the microlevel as well as between the microlevel and the macroscopic field produced by them. The latter effect is referred to as circular causality. Thus, once the system is defined, the analysis with the goal of establishing governance strategies starts with an identification of the agents, of the reasons for nonlinearity, and of the mechanisms of circular causality. Nonlinearity as well as the circular causality are often closely connected to the availability of mobile information systems, including social media. By their speed of dissemination of news, spirits, and emotions, they are able to trigger spontaneous, radical, and irrational actions. Eliminating these services is an effective governance strategy to control the systemic risk of dispersion of local unrest to an area-wide uprising. This is a standard procedure applied by autocratic regimes. In democratic societies, this strategy is not workable. Still, under the systemic risk of becoming divided by some political issue, e.g., the refugee problem in Germany, it can be observed that the mass media, again complemented by the social media with their inclination toward fake news, are widely responsible for the circular causality effects promoting the systemic risk. Appropriate governance strategies in a democratic society aim at controlling the truth contents of these media by democratic authorities and making populist distortions of facts visible. While frequently of limited effectiveness and highly contested, this strategy is pertinent in principle and should be developed toward a better performance.

The collapse of a stationary structure and the emergence of a new system state is triggered by momentary fluctuations, but the deeper reason for it lies in the fact that the system has entered an unstable regime, the origin of which lies in the preceding history of the system. Therefore, any attempts to explain dynamic phase transitions from a local and momentary perspective are bound to fail. They fundamentally have an endogenous historical origin, whereas exogenous forces, even shocks, only serve as triggering factors. The prerequisite of a transition is the system having been moved to an unstable situation in its past history. Appropriate governance strategies therefore set in at times well before the critical instability region is reached. An attempt in this direction is presently visible in the banking sector with the diverse control and stress tests that have been agreed upon. Also, stock market crash events are now better understood by putting them in a historical perspective (Sornette, 2003). Potentially unstable societies should be carefully observed over time with the goal of getting early awareness of an approach to instability.

Associated with this historical perspective, an effective governance strategy aims at looking for early warning signals in the forefront of the emergence of a new system state. While in the systems of physics and chemistry such signals can be found by a mathematical stability analysis, they have to be scrutinized empirically in more general systems. Such parameters are nondimensional in nature and balance enhancing and hindering effects by a suitable combination of external and internal quantities. Examples are the ratio of local uprisings to police interventions in the forefront of revolutions (Schroeter et al., 2014), the size of the economy to the amount of private debt in the onset of a financial crisis (Minsky, 2008), or the index of conflict-related news before the outbreak of war (Chadefaux, 2014).

A frequently underestimated feature of systemic risks with great significance for sensible governance strategies is the suddenness of tipping events. It is universally observed that there is a slow approach to an instability regime, which is then followed by a sudden phase transition. Also, the phase transition is normally triggered by a minor perturbation, which points to the high sensitivity of the system in unstable situations. Typical examples are the sudden tipping phenomena of ecosystems or social upheavals after a long period of enduring stress. Responsible governance then implies a careful and continuous monitoring of a system's evolution under stress even if no indications for a breakdown are yet visible.

6. CONCLUSIONS

The analysis and governance of systemic risks remain issues of challenge. This is due to the fact that in systemic risks, contrary to conventional risks, the entire system as well as its environment participate and the risk-generating event cannot be localized. Instead, an original local perturbation may cascade through the system by elementary nonlinear feedback processes. This nonlinearity and the associated phenomena of circular causality as well as historicity preclude any simple understanding of systemic risks. This has to be accepted as an axiomatic fact and relegates any simple as well as effective control and governance measures into the domain of illusion.

Given this situation, it seems even more important to search for elements of a theoretical concept of systemic risks that is able to provide valuable information about the generic mechanisms of dynamic structure generation. Based on the understanding of these generic mechanisms, a general tool box may be established, which, although qualitative, supports the governance of systemic risks in any domain.

In this contribution, an attempt has been made to scrutinize the generic mechanisms of systemic risks by studying the generation of dynamic structures in simple physico–chemical model systems. Based on the empirically established fact that systemic risks are special cases of dynamic structures and that there is a homomorphism of dynamic structures in all domains, major insights have been gained of great significance for the understanding and even governance of systemic risks. While the insights obtained from physics and chemistry are certainly not sufficient to establish a complete theory of systemic risks, they provide valuable information to be complemented by more detailed empirical knowledge about a particular system under study.

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