Concept Note

# Preparing for Future Catastrophes

## Governance principles for slow-developing risks that may have potentially catastrophic consequences

international risk governance council

# Abbreviations used in the text

| | |
|---|---|
| IRGC | International Risk Governance Council |
| SDCR | slow-developing catastrophic risk |

Cover: Photograph © Phonsawat/FreeDigitalPhotos.net


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# Preface



The IRGC is an independent organisation whose purpose is to help the understanding and governance of emerging global risks that have impacts on human health and safety, the environment, the economy and society at large. The IRGC's mission includes developing concepts of risk governance and recommendations for key decision-makers. Acting as a clearing house of information and practical policy advice about emerging, ignored and neglected risk issues, IRGC brought together an international group of scientists and senior policymakers to discuss "Slow-developing catastrophic risks" in a workshop at the Istituto Veneto di Scienze, Lettere ed Arti in Venice on 24–26 August 2011. This concept note elaborates on the discussions at this workshop.

Following a short introduction to slow-developing catastrophic risks, providing examples and outlining key characteristics, this paper looks at the science behind them and how we can handle them. The importance of focusing holistically on the complex adaptive systems/networks forming our societies, economies and ecosystems is emphasised in developing policy advice, and the numerous issues and difficulties surrounding risk governance of SDCRs are catalogued. The paper concludes with key considerations and a framework for decision-making for both the policymakers and the scientists informing them and the public.

As with all IRGC concept notes, this document has the purpose of providing a summary of some of the issues that IRGC may address in the course of future project work. Comments are welcome on how the IRGC's project on slow-developing catastrophic risks can make a constructive contribution.

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# Executive summary



Many of the serious problems that we face today follow a similar pattern, where the effects of slow, imperceptible change go unheeded until they bring us to a point of rapid, usually irreversible, and often catastrophic, change. This underlying pattern of slow-developing catastrophic risk (SDCR) may be seen retrospectively in recent bank and financial system crashes, in revolutionary social changes such as the "Arab Spring", and in ecosystem collapses such as the desertification of the Aral Sea and large areas of China. Future instances are likely to include the social, economic and ecological effects of biodiversity loss and the dramatic consequences of slow, now probably irreversible, global warming.

Our concerns in this report are:

- To convey the message that the potential for SDCRs is built into the very fabric of our complex socio-political-economic world, just as it is in the ecosystems of which we are a part, and that their occurrence is inevitable;
- To address the question of whether SDCRs can be predicted in time to take practical, effective action to avert them;
- To show that the development of resilient social and economic structures, able to respond and adapt rapidly to sudden change, is the best (and often the only) way to cope effectively with SDCRs; and
- To outline the new thinking and processes that may be needed in order to develop such resilient structures.

## Inevitability of SDCRs

Preparing for the future lies at the heart of politics. One of the hardest pills to swallow for politicians and policymakers is that no amount of planning will forestall the unwelcome appearance of SDCRs at some time in the future.

The intuitive reason is that complex economies, societies and ecosystems are dynamic, constantly evolving systems that contain a great many interacting feedback loops (see Section 2.1). Some of these loops promote stability; others lead to runaway collapse. Planners try to ensure that the stabilising loops prevail, but there is always the possibility of a situation arising where the destabilising loops abruptly take over to produce runaway collapse.

This intuitive reasoning is supported by the many rigorous mathematical models and computer simulations that have been developed over the last decades. It is also supported by practical experience. Crashes and collapses have always been with us, and they always will be.

## Predictability of SDCRs

One use of the models has been in the analysis of real-life complex systems, searching for clues that may help us to predict upcoming SDCRs in time to avert them or, at least, ameliorate their consequences. A number of such clues have emerged, including increasingly rapid oscillations between extreme states (e.g. increasing market or social volatility) and other statistical indicators. Careful analysis of the behaviour of ecosystems prior to collapse has revealed that these indicators can be useful predictive tools, although their application to social and economic change is still at an early stage. It is already clear, however, that most existing social and administrative institutions are simply too cumbersome to respond in an appropriate timescale. By the time that the warning signs have become unambiguous, it is usually too late.

## The value of resilience

On the above grounds alone, we need to develop new institutions and practices that are more responsive to change. All the indications are, however, that responsiveness is not enough. We must anticipate the inevitability of change (and especially the occurrence of SDCRs) by developing new institutions that combine flexibility (the ability to change policy to suit circumstances), adaptability (the ability to change even the institutions themselves) and resilience (planning the socio-economic-ecological system so that it can rapidly find a new position of relative stability following sudden change). One particular difficulty is that some of the new institutions must necessarily be global in nature, because the multiple feedback loops in this modern world are often international in scope, as well as being multi-dimensional in character.

## New political and social strategies

Some governments and executive institutions have already started to move in the directions indicated, but much more remains to be done, and some very difficult political and social choices must be faced if we are to cope effectively (and certainly better than we have in the past) with future SDCRs.

In this report we spell out the practical measures that must be taken if we are to gear the world system and our individual socio-economic-political systems for the inevitable shocks to come. Above all, the administrative and decision-making institutions must be equipped and motivated to take a long-term view – certainly longer than is common in the politics of many Western countries. Such institutions must become more flexible, adaptable, able to plan for resilience and have the power to implement such plans. They must also be equipped and able to address systemic issues, rather than taking piecemeal and often ad hoc decisions.

To obtain such a result, we list ten basic requirements for policymakers and their interaction with the scientists who provide the groundwork of information and understanding. There follows a six-point framework for decision-making that incorporates these requirements.

Our principal message in terms of practical organisation is this:

Today's administrative structures are based on a division of responsibility. The science of complex adaptive networks has revealed the fragilities of such an arrangement, and shows that dealing successfully with SDCRs in any arena requires adopting a holistic approach that transcends traditional administrative boundaries.

We do not know whether it will be possible in practice. What we do know is that it is necessary, and unless we overcome the barriers to such an approach, we will be forever at the mercy of SDCRs, some of which are likely to have severe consequences for our very future.

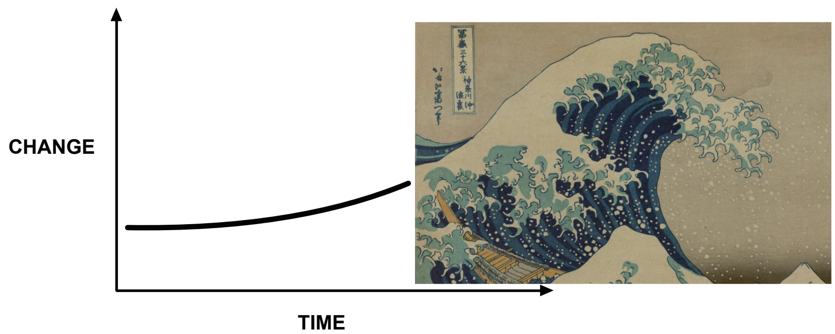
# Introduction

*… reality comprises two cruelly confusing characteristics: on the one hand, continuity and reliability lasting across generations; on the other, unheralded catastrophe.*
**Alain de Botton** ***The Consolations of Philosophy***

*If we don't grab events by the collar they will have us by the throat.*
**Terry Pratchett** ***The Truth***

When economies fail, banking systems crash, ecosystems collapse, or extreme natural events or revolutions disrupt society, the event was often unforeseen, and even apparently unforeseeable. Such events often occur, however, when slowly changing circumstances have brought the system imperceptibly to a point of no return – a tipping point (technically known as a critical transition) where dramatic, sudden and sometimes disastrous change is imminent and unavoidable.

**Box 1. Critical transitions**




Adapted by Len Fisher from Wikimedia Commons "The Great Wave".

1. (After Hokusai) The evolution of a tsunami provides a graphic metaphor for the way in which slow, imperceptible change can eventually lead to a situation of rapid, catastrophic change. A tsunami wave far out to sea may only be one-third of a metre high, though many kilometres long, and will pass unnoticed as a slight swell. Closer to land, and in shallower waters, the wave compresses to grow to enormous height and hits the land with devastating force.

2. Real-life examples of slow-developing risks suddenly culminating in critical change and collapse:


Source: www.Vectorportal.com

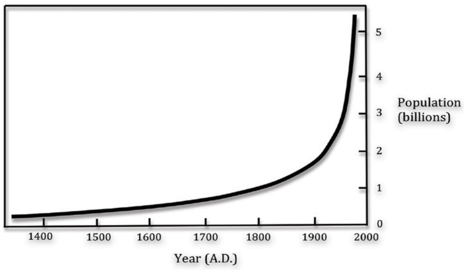
Slow changes in a banking system (e.g. the gradual easing of borrowing restrictions for subprime borrowers prior to the 2008 banking crisis) or an economy (e.g. the emergence of an increasingly elaborate set of financial instruments, intended to optimise returns to individual institutions, prior to the present global financial crisis) can lead to sudden collapse of the system as a whole.


Source: Wikimedia Commons

Slow social change can lead to situations where abrupt social transitions (including revolution and war) occur. Illustrated here is the fall of the Berlin Wall in 1989 following a decade of slow social change in East European Communist countries.

Source: www.animalgalleries.org

One consequence of the slow increase in global temperatures over the past century is the rapid disappearance of Arctic ice over a period of just a few years.




Source: Len Fisher, *Crashes, Crises, and Calamities* (New York, Basic Books, 2011).

Will the exponential increase in world's population over the last decades lead to a situation where Paul Ehrlich's "population bomb" (*The Population Bomb*, New York, Ballantine Books, 1968) may indeed explode?

Such events often catch us unawares, but the development of new approaches and the availability of powerful computers are now allowing scientists to understand and model the processes involved and to work out ways of controlling them or mitigating their effects. Such information promises to be of considerable value in determining the best practical approaches for the governance of such transitions in economics, ecology and society. With this question in mind the IRGC, which acts as a clearing house of information and practical policy advice about emerging, ignored and neglected risk issues, brought together an international group of scientists and senior policymakers to discuss "Slow-developing catastrophic risks" in a workshop at the Istituto Veneto di Scienze, Lettere ed Arti in Venice on 24–26 August 2011.

This concept note[1] is based on those discussions, with further input from several of the participants. There was considerable cross-fertilisation of ideas across the various scientific, economic and social disciplines, with recognition of the essential commonality of the problem. Even more important was the recognition of how the potential governance of these serious long-term problems could be informed by science in new and effective ways, and how the emerging underlying principles might be used to develop practical policy guidelines. These guidelines offer a new and promising tool for policymakers, with the potential to have a very real effect on the ability to predict such catastrophes and to avoid their occurrence or ameliorate their effects.

(1) Following on from the IRGC reports *The Emergence of Risks: Contributing Factors (2010)* and I*mproving the Management of Emerging Risks* (2011).

# 1. Risk and governance



## 1.1. The nature of slow-moving risks

The key characteristics of slow-moving risks with potentially catastrophic consequences are:

- As the name implies, the risk develops slowly, emerging from changes that take place over a long period of time – years, decades or even longer.
- During this period of development/evolution/maturation, it may appear that the system is not only stable, but that it will remain stable indefinitely in its current form. This belief is reflected in such words and phrases as “the balance of nature” (in ecology); “security” (of banking systems and economies); and “social stability” (of societies). All of these concepts are illusory.
- Critically, the potential for sudden, sometimes catastrophic, transitions as a result of slowly evolving changes is built in to all complex economic, ecological and social systems (in technical terms, such risks are endogenous). The risk arises from interactions and consequent changes within the system itself[2], rather than as a result of external factors.
- Long-term planning and rapid adaptability can help to avoid such risks and/or ameliorate their consequences, but the closer that societies get to an endogenous critical transition, the less chance that they have to take effective action. By the time that the warning signs become obvious, it is often too late to act.

## 1.2. The problems of governance

Slow-moving risks with potentially catastrophic consequences are particularly difficult to anticipate. Their governance is complicated by two sets of factors, one scientific, the other socio-political.

### Scientific factors

- The understanding of the mechanisms by which slow changes in complex societies, economies and ecosystems can bring governments, societies or corporations almost imperceptibly to a point of sudden change is still at an early stage, as is the computerised analysis and modelling that is usually required to apply this understanding to specific cases.
- Such modelling also requires a substantive input of real data, which are not always easy to obtain.
- Even so, scientists in various disciplines have come to the conclusion that some important basic principles are common across all fields (social, economic and in the natural world). Workers in these fields still need to communicate more effectively with each other to establish this commonality (one of the aims of this report is to enhance this process).

### Socio-political factors

- Establishing exactly who the stakeholders are – i.e. those who will be most affected by the consequences of the risk, and thus who may be expected to invest most heavily and be involved in its governance.
- Often these stakeholders may not yet have been born. Individuals are often unwilling to change their behaviour and bear the costs of investments today whose returns will not only be in a distant future, but not necessarily of direct benefit to these individuals (this is an important variant of the well-known tragedy of the commons, described by game theory).
- Technological and governance solutions may exist, but may require difficult and unpopular political decisions, and large economic investments. One difficulty with making such investments is that they most often require collective undertaking (the tragedy of the commons again).

(2) This does not mean that all sudden changes are endogenous. Some critical transitions (known as exogenous) are induced by external factors, and it is not always easy to distinguish between the two, even with hindsight (Sornette, 2006). Here, though, we are concerned with endogenous transitions, the insidious possibility of which is often unrecognised by politicians, policymakers and experts in many fields, who are too often wont to lay the blame for abrupt changes and catastrophes on external factors.

- Political and industry leaders are rarely rewarded, or even recognised, for making decisions that lead to long-term gains, where the benefits only arise far in the future. The ultimate benefits can also be difficult to measure, and are sometimes even invisible. Compare the cases of fire prevention and flood prevention. When a flood comes and the dyke holds, the gain from investment is obvious, but when a fire doesn't come, the benefit of earlier investment in preventative measures is much less apparent. Education and public health also may suffer from underinvestment for this reason.
- There may be a head-in-the-sand mentality, or a lack of imagination, where people refuse to believe that endogenous transitions can truly occur.
- This "refusal to believe" may have been exacerbated by previous experience of scientists "crying wolf" or otherwise making exaggerated claims about the level of scientific understanding or the consensus among scientists.
- Vested interests may wish to maintain the status quo, which is serving their interests very well; the conflict between fossil fuel companies and climate change is a current example.

In today's increasingly interconnected world, catastrophes in one place can rapidly affect the lives of those in other places. For example, social unrest may disrupt oil supplies; the crash of a bank or an economy in a distant country can affect the ability of people in another country to borrow money to build businesses or houses; the collapse of an ecosystem due to overexploitation can undermine food supplies as well as the political stability of a community that depends on it for a living, and ultimately the stability of other communities with which that community interacts.

## 1.3. Principal questions to be answered

Based on the above list of issues, the principal questions to be answered are:

1. How can slow and apparently innocuous changes in an economic, social or natural system bring it imperceptibly to a point of no return – a collapse (of an economy, stock market or banking system), a power shift, a destabilisation or a revolution (in a society), a regime change or an extreme natural event (in ecosystems and throughout the natural world)?
2. What warning signs herald the imminence of critical transitions in time for societies to take appropriate action to avoid them or better cope with their consequences?
3. Could systems (economies, societies and even natural ecosystems) be better organised so as to minimise the possibility of critical transitions, and to have stronger resilience if such events do occur?
4. How can the above understanding be converted into practical policy advice for governments and local and international organisations?

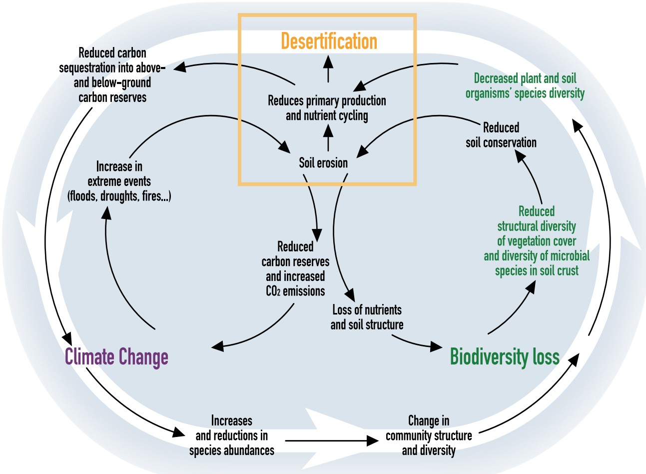
The first two questions are primarily scientific; the third is also scientific, but with strong political implications; the fourth is primarily political, but open to being informed at many points by the science. Section 2 of this concept note outlines how the science has developed and the insights that it has produced in answer to the first three questions, while Section 3 (Policy development) offers concrete analysis of how new scientific insights might be used to help guide the development and implementation of practical policies at the political level. "Practical" does not mean "easy", and the analysis supports the view that some very hard decisions will need to be made if we are to overcome the challenges that slow-moving risks pose to our economies, our societies and the global environment.

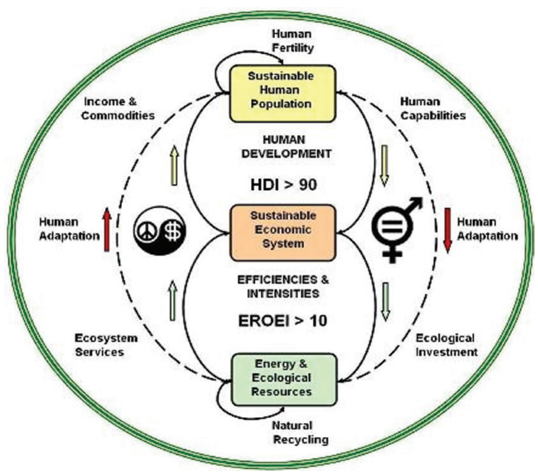
## 2.1. How can slow and apparently innocuous changes in an economic, social or natural system bring it imperceptibly to a point of no return?

From a scientific point of view, the societies, economies and ecosystems that comprise our living world can be viewed as complex adaptive systems, and usually as complex adaptive networks[3]. They are complex because the system as a whole has emergent properties that cannot be predicted or understood just by analysing the behaviour of its individual components. One can't understand how a society works, for example, simply by studying each of the people in it in turn, because a society has global properties that are more than the sum of the local properties.

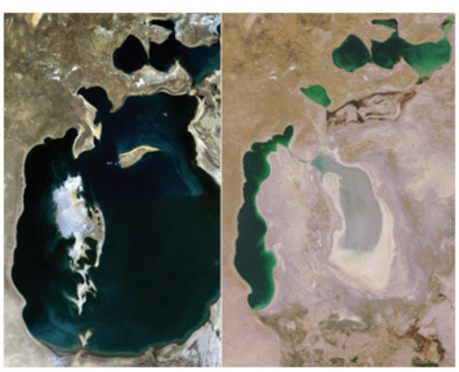
Societies, ecosystems and economies can also be modelled and understood as networks because, reduced to their essentials, they can be modelled as a set of nodes or vertices connected together by links. The nodes are the individual units, which may be people, businesses, countries, animals, plants, physical objects, etc. (all of which are sometimes called actors or agents), or a combination of all of these. The links represent the interactions between individual nodes, i.e. any process by which one node may affect another.

**Box 2. Interacting feedback loops in the real world – ecosystems and the global socio-ecological-economic system**




Sources: Left – United Nations Environment Programme, *The Encyclopedia of Earth.*
Right – *Mother Pelican: A Journal of Sustainable Human Development*, vol. 7, no. 12 (2011).
HDI: Human Development Index; EROEI: energy return on energy investment.



Source: http://en.wikipedia.org/wiki/Aral_Sea

Crashes and catastrophes occur when the balance between stabilising negative feedback loops and destabilising, runaway positive feedback loops gradually shifts until runaway effects take over, as in the rapid shrinkage of the Aral Sea, where the balance between loss of water through evaporation and refilling from river systems was shifted in favour of the former when rivers were diverted for irrigation projects, leading to "one of the planet's worst environmental disasters" (UN Secretary-General Ban Ki-moon, quoted in *The Daily Telegraph*, UK, 5 April 2010).

(3) A massive technical literature on complex adaptive networks covers a wide range of fields. A convenient, non-technical summary of the basic science is given in Nicolis and Nicolis (2009). Some of the major papers from different fields are brought together at http://adaptive-networks.wikidot.com. This website, which is continually updated, aims to "bridge the gap between disciplines and point out related phenomena and results". We make no attempt to summarise those papers here, but focus on a few representative and important ones that are relevant for the development of policy and understanding.

A network is adaptive when the state of the nodes or links can change in response to their previous history, so that the network evolves and changes over time. These changes can be slow, even reversible, but they can also bring the system to a point where sudden, dramatic change becomes inevitable. Such transitions affect the network as a whole, as well as its individual components. The focus of current research, and of this report, is on understanding how such transitions arise in the real-life complex networks of our world and our society, and what we can do about them.

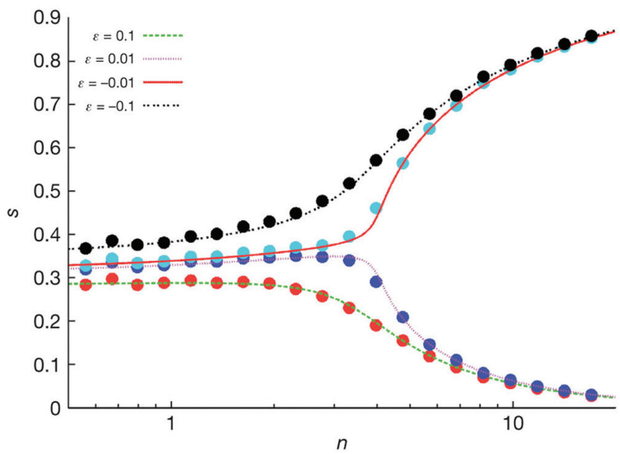
The state and behaviour of such networks is largely determined by the balance between two different sorts of feedback loops:

- Negative feedback loops, which can act to stabilise the system by "pushing back" against change to preserve the system in a status quo, but which can also induce oscillatory instabilities if there is a delay in the system;
- Positive feedback loops, which progressively amplify shifts away from equilibrium to produce runaway change.

Real-life complex adaptive networks have many such loops.

The interaction of multiple feedback loops produces changes that are often counterintuitive, and which cannot be foreseen except by very careful and detailed modelling of the system as a whole. A feature of these changes is that they are usually non-linear; that is, a small change in one part of the system can produce a disproportionately large response in another.

**Box 3. Critical transitions in derivatives trading**




Source: Andrew G. Haldane and Robert M. May, "Systemic risk in banking ecosystems", *Nature* 469 (2011) 351–355 (figure 2).

Average supply of any one derivative *s* as a function of the number *n* of derivatives being traded at competitive equilibrium. Note the sudden instability as the complexity of trading gradually increases for a range of values of the bankers' "risk premium".

In real-life networks the balance between positive and negative feedback processes is constantly evolving. When situations seem stable it is usually because negative feedback processes are dominant. Over time, though, the balance may slowly change until it reaches a point where positive feedback and other runaway processes (Fisher, 2011) take over, producing a critical transition such as those illustrated in Box 1.

The examples in boxes 1, 2 and 3 illustrate the point that the analysis and understanding of complex adaptive networks is not simply an academic exercise, divorced from reality. Rather, it reflects reality, and an appreciation of the underlying principles and outcomes is essential for learning how better to understand and resolve the problems of a complex world. One of the key steps in communication between scientists and politicians is for the former to promote the message that sudden change is an inevitable feature of the complex network structures in our world, where the effects of a change in one part of the system can feed through to other parts, often in a highly non-linear fashion. The inevitable conclusion for the political process is that the governance of such risks requires a systemic approach (even a global one), rather than the piecemeal approach that is all too common.

## 2.2. Can statistical analysis of fluctuations and trends reveal warning signs for upcoming endogenous critical transitions in time for us to take appropriate action?

Using the statistics of the past to predict the behaviour of the future has a long history, and also a massive literature. At the heart of much of this literature lies the assumption that the system will continue to obey the same rules in the future as it has in the past. These rules may come in the form of relationships (e.g. the laws of physics, or the less reliable "rules" of economic or other human behaviour) or in the form of more-or-less consistent patterns and correlations.

The assumption of stability, or more-or-less uniform change, is reasonable if the complex system is in a "slowly changing" state where its behaviour is dominated by negative feedback processes. Makridakis and Taleb (2009) found that this same assumption is false, and can be dangerously misleading, when the system is near a critical transition. They cite many examples, and conclude that "the forecasts of statistical models are … unable to predict changes and turning points, and unable to make predictions for brand new situations." They also conclude from observational evidence that "[human] judgmental forecasts are [even] less accurate. … Forecasters find themselves between Carybdis [sic] and Scylla. On the one hand, they understand the limitations of statistical models. On the other hand, their own judgment cannot be trusted."

These strictures apply to forecasting where statistics and human judgment are used to extrapolate from past events to future possibilities. Authorities such as Taleb (2007, 2010) claim that this is not a useful approach, because many of the most important transitions in economies, ecosystems and society are triggered by highly improbable, unprecedented, and therefore unpredictable events ("black swans").

Taleb does not distinguish between exogenous and endogenous transitions. Here we contend that a significant and vital difference needs to be understood and acted upon by policymakers. The black swan metaphor may well be valid for many exogenous transitions, but there is increasing optimism that the prediction of endogenous transitions (see, for example, Filimonov and Sornette,2012b) may be susceptible to a scientific approach.

This optimism is based on an increasing understanding of the processes that lead to critical transitions in real-life systems, on new approaches to modelling the behaviour of such systems under different conditions, and also on a different use of statistics; not to extrapolate from past experience, but to monitor systems for warning signs of imminent critical transitions. Such warning signs may be identified by their statistical signatures. There have been many academic studies along these lines (see, for example, references in Preis *et al.*, 2011). Here we focus on four particular lines that have important policy implications.

### 2.2.1. Power laws

Many authors have analysed changes in stock market prices with time in terms of power-law correlations in volatility and "fat tails" in probability distribution functions (see references 30–32 in Preis *et al.*, 2011).

In a series of particularly relevant papers (summarised in Johansen and Sornette, 2010) Didier Sornette and his colleagues at ETH-Zurich and elsewhere have identified a statistical signature for upcoming stock market crashes of endogenous origin in the form a log-periodic power law. By applying this and an additional statistical test, they have found that approximately two-thirds of the large-scale drawdowns on the world financial market are endogenous in origin, and that only one-third may be ascribed to the effect of external shocks. The practical implication of this work is that it is possible, at least in principle, to predict the probability of upcoming endogenous stock market transitions from the prior behaviour of the market.

### 2.2.2. Scale invariant fluctuations

The idea that most crashes are endogenous in origin appears to be supported by the work of Preis *et al*. (2011) who have analysed over two billion transactions on the New York Stock Exchange. They find on close examination that the seemingly random fluctuations of stock prices with time actually follow a pattern, where trends that range from "micro" to "macro" all end with a sudden "switch" to a different trend. All of the trends follow a similar pattern, regardless of scale, which leads the authors to the conclusion that "the well-known catastrophic bubbles that occur on large timescales – such as the most recent financial crisis – may not be outliers but single dramatic representatives caused by the formation of increasing and decreasing trends on timescales varying over nine orders of magnitude from very large down to very small."

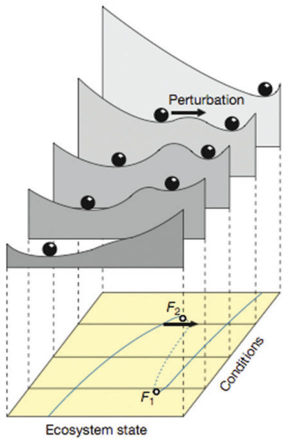
Filimonov and Sornette (2012a) argue that Stanley's analysis is flawed by the use of statistically biased subsets. Their analysis suggests that the so-called "universal switching phenomena" are universal because they occur everywhere, even in simple random walks. Their analysis points up a fundamental difficulty with statistically based prediction. Stanley *et al.'s* original analysis may thus be invalidated, but one of the mechanisms that they suggest – that "switching" may happen when the activities of a few traders against the trend stimulate an avalanche of similar behaviour by other traders – may, as they point out, have important implications for the ability to control such sudden transitions, not only in stock markets, but in many other analogous situations involving complex systems. Two such possibilities are introducing a timelapse in communication, or introducing a cost for a change in behaviour.

### 2.2.3. Critical slowing down

An important new insight has come from the field of ecology, where Scheffer *et al.* (2009), have found that systems that are close to a critical transition have a decreased ability to respond and adapt to change (this is known as critical slowing down or loss of resilience). This change produces a number of characteristic statistical signatures – in particular, an increasing occurrence of extreme states and increasingly rapid swings between extreme states.

The value of this work is three-fold. First, it has a strong theoretical underpinning (Scheffer *et al.,* 2009), which also provides a powerful visual image (see Box 4). Second, Scheffer and others have argued that the result may be applicable well beyond the field of ecology to problems in economics and society as well (Scheffer, 2010). Third, it has been shown to work in practice for ecosystems that include bacteria in laboratory Petri dishes, water fleas in aquaria and fish in Wisconsin mountain lakes.

**Box 4. "Ball in a valley" image for loss of resilience near a critical transition**




As the "valley of attraction" becomes shallower (bottom left to top right) the ball can move further to the left or right under the influence of a small perturbation – that is, it becomes less resilient to small perturbations. When the system is sufficiently close to a critical transition, the resilience becomes so low that a small perturbation can push it over the edge.

This behaviour maps on to a "fold catastrophe" – see Scheffer and Carpenter (2003) and Len Fisher (2011).

Source: Len Fisher, *Crashes, Crises, and Calamities* (New York, Basic Books, 2011).

One of the problems with all statistical approaches is the very large amount of data that can be needed to produce a robust, meaningful calculation (Scheffer, 2010). This can often be a barrier to useful prediction, because by the time enough data are collected the transition is too close for effective action to be taken (Biggs *et al*., 2009).

This time can be greatly reduced by using "smart" data-processing techniques (Scheffer, 2010, references 4, 5, 7) and real-world information about how the system works. Statisticians have been reluctant to do this because it makes their calculations "model dependent". This is not always the case, however, and Lade and Gross (2011) have now shown how to have the best of both worlds, which makes the use of statistical indicators a much more practical proposition. The urgency is great. Barnosky *et al.* (2012), for example, have examined the time-evolution of a range of drivers for potential planetary-scale critical transitions in the biosphere, including landscape fragmentation, increasing ocean "dead zones", changes in reservoirs for biodiversity, and the like. They have concluded that the Earth's biosphere is nearing a critical transition, and that there is an urgent need for detailed data to help detect early warning signs of critical transitions on scales from global to local, highlighting the importance of detecting feedbacks that promote such transitions.

### 2.2.4. Human behaviour

Finally, we draw attention to the possibility of using the analysis of human behaviour as an indicator of upcoming transitions. As an example, Harmon *et al.* (2011) have demonstrated that "the recent economic crises and earlier large single-day panics were produced by high levels of market mimicry – direct evidence of uncertainty and nervousness, and of the comparatively weak influence of external news. High levels of mimicry can be quite a general indicator of the potential for self-organised (i.e. endogenous) crises."

## 2.3. Could real-life complex adaptive networks be better organised so as to minimise the possibility of critical transitions and/or to have stronger resilience if such events do occur?

The short answer to both parts of the above question is "yes", but two important points need to be recognised:

- The science of complex adaptive networks is relatively new, and evolving rapidly, although many important insights have already emerged (particularly during the last decade); and
- In order to use this new science to help develop better and more effective policies, communication and flexibility are the keys – communication between scientists and policymakers to integrate the new understanding into new policies, and flexibility in monitoring the outcomes of policy and being prepared to change policies on the basis of observed effectiveness and advancing scientific insights.

### 2.3.1. The science of real-life networks

Here we list a few important examples of discoveries and insights that have already emerged from network science, and which are relevant to the impact of slowly changing circumstances on the stability of important real-life socio-economic-ecological networks that dominate the world. One particularly important aspect of the configuration of complexity is the "small-world effect", which is illustrated dramatically by "six degrees of separation" – the notion that most of the people on Earth are no more than six steps away, by way of mutual friends, from any other person on Earth. "Small-world" networks arise through the presence of just a few long-range links in an otherwise sparsely connected network where all the links are short range. Such long-range links can greatly accelerate the transmission of information, disease, financial collapse, etc. through an entire network.

It has been pointed out (Dorogovtsev *et al.*, 2008) that the properties of critical phenomena in complex networks are largely determined by the small-world effect, combined with a strong heterogeneity and complex architecture of networks. Understanding the connections within our social, economic and ecological networks is thus vital to being able to foresee and control the effects of critical transitions.

The small-world effect is an example of the effect of network topology on the dynamic processes going on within the network. As pointed out by Gross and Blasius (2008), the mutual feedback between these two processes is fundamental to understanding the evolution of complex adaptive networks, since "the evolution of the topology is invariably linked to the state of the network, and vice versa."

In an early seminal paper, Bornholdt and Rohlf (2000) (see also the review by Caldarelli and Garlaschelli, 2009) pointed out that the feedback between topology and dynamics can drive the system to a steady state that differs from the one obtained when the two processes are considered separately. Ings *et al.* (2009) and Bascompte (2009) offer the more general conclusion that "it is the distribution of interaction strengths and the configuration of complexity, rather than just its magnitude that governs network stability and structure."

A steady, or at least predictable, state is what people often seem to deeply desire, especially for the social and economic networks, but that general observation does not tell the whole story. Studies have shown that subtly different networks can exhibit very different behaviours, so that detailed understanding of the concrete features of individual networks is vital. Here are some examples to illustrate the point with regard to network stability and the possible occurrence of critical transitions:

### a) Epidemic spreading

It is commonly believed that the spread of an epidemic (of infection, rumour or panic, for example) through a network is facilitated by highly connected nodes (called hubs). Examples might be an infected person who comes into contact with many others through their job, or a community gossip-monger who is adept at rumour-spreading. Intuitively, the spread can best be limited or prevented by "vaccinating" such hubs within a population – either by removing them from contact with others, or rendering them safe by treatment (actually vaccinating the infected person, or convincing the rumour-monger that there is no basis to the rumour).

Such a vaccination strategy has often worked well, in cases such as the spread of swine flu, but it is not always successful. In particular, Boguña *et al.* (2003) have shown that it cannot work for a very common sort of network where the distribution of links is described by a mathematical power law. The power law distribution means that most nodes have only a small number of links, while just a few nodes have many more links. Such networks are technically called "scale-free". Real-life examples include the World Wide Web, electricity distribution networks, social networks (real ones as well as those on Facebook), banking networks and many ecological networks (Barabási and Albert, 1999). Boguña *et al.*'s result means that "vaccination" of the highly linked nodes in such networks cannot prevent epidemic-like spreading, and some other strategy is needed. One approach is a voluntary vaccination strategy. Zhang *et al.*, (2010) have shown that such a strategy, where individuals weigh up the risk of infection to themselves versus the risks involved in vaccination, can work to block the spread of infection. It has to be said, though, that the problem is still an open one in many practical cases.

### b) Network stability

In 1972 the mathematical ecologist Robert May demonstrated that large, complex ecosystems could not be stable in the long term if each pair of species interacts with the same probability (i.e. if interactions are random). This basic result remains true (and not just for ecosystems – it applies equally, for example, to economic systems and many social systems), but many subsequent studies have shown that more structured networks can remain stable. To give one recent example, Allesina and Tang (2012) have shown that large predator-prey networks can be stable provided that the predator-prey pairs are tightly coupled in some way. This observation has implications for the stability of social and economic networks as well. Tight coupling of individual pairings and groups within a network (e.g., by promoting mutual dependence within small groups, whether these be groups of people, institutions or species) may be a practical and useful political strategy for maintaining stability of the network as a whole.

### c) Critical thresholds

One measure of network stability is the "critical threshold" – that is, the fraction of nodes that must fail before the whole network fails. When a series of networks becomes interconnected, this critical threshold becomes much lower (Buldyrev *et al.*, 2009), so that the interconnected networks common in today's world (such as the international banking network) have much lower critical thresholds than similar isolated networks. One example cited by Buldyrev *et al.* is the massive blackout that affected much of Italy on 28 September 2003, where the initial failure of some power stations directly led to the failure of nodes in the Internet communication network, which led in turn to further breakdown of power stations in a rapidly growing cascade of failure. A more recent example is the collapse of the Indian power network that affected half the country (Rosen, 2012).

As with the other examples cited so far, detailed understanding is the key to effective policy development for particular cases. Scale-free networks, for example, display a high degree of tolerance to random failures, but this robustness comes at a price – such networks are particularly vulnerable to attack or damage at a few selected points, which can rapidly produce fragmentation and loss of communication between different parts of the network (Albert and Barabási, 2002).

Even when the load previously taken by damaged or lost nodes can be redistributed to other nodes, the possibility of a cascade of overload failures remains and can even be triggered by the loss of a single key node (Motter and Lai, 2002). The fact that many real-life networks are already in a state of imminent fragmentation (Ghedini and Ribeiro,2011) only adds to the problem, although sometimes even small, low-cost alterations to the network structure can dramatically increase the robustness of networks such as the European electricity network and the Internet (Schneider *et al*., 2011; see also IRGC report *Managing and reducing social vulnerabilities from coupled critical infrastructures* (2006) (http://www.irgc.org/-Critical-Infrastructures-.html).

#### d) Critical transitions

As long ago as 1960 the Hungarian mathematician Paul Erdös proved that as one randomly adds links to a network, a sudden point (called a percolation threshold) arrives where there is a path from the great majority of nodes to any other node. Most real-life networks are not random, but the ideas of a percolation threshold (e.g. Newman and Watts, 1999; Gastner *et al.*, 2011), and the occurrence of explosive percolation (Achlioptas *et al.*, 2009; Pan *et al.*, 2011) are central to understanding how connectivity in networks can suddenly change, as for example when YouTube videos “go viral” (Crane and Sornette, 2008).

Many complex adaptive networks evolve and change by constantly switching between highly connected and relatively poorly connected states, both across the whole network and also within smaller sub-networks (Paperin *et al*., 2011). This encompasses networks of many types, including a range of ecosystems and socio-economic systems, and reinforces the view that, in the long term, critical transitions are inevitable in complex adaptive networks.

When a critical transition does occur, the whole network does not necessarily shift to a different state. For example, a network can undergo a “fragmentation transition” (Böhme and Gross, 2010), where the network breaks up into a number of smaller sub-networks (as can happen, for example, when large ecosystems break up into geographically separated patches, or when societies split and divide).

### 2.3.2. Possibilities for network-based governance

#### a) Coping with systemic risk

The clear implication from the scientific advances described above is that policy for the forecasting, control and amelioration of the effects of critical transitions must focus on the network(s) as a whole, and should deal with systemic risk, rather than tackling problems as they arise on an ad hoc,case-by-case basis. This important point was made in an article on “Ecology for bankers” (May *et al.*, 2008) and a later article on “Systemic risk in banking ecosystems” (Haldane and May, 2011).

Haldane and May’s primary recommendations in the case of the banking system include:

- Restructuring the network to reduce its fractal dimensionality (a technical term that roughly equates to the number of independent parameters that are needed to specify it fully) and complexity;
- Learning from epidemiology to seek actively (by regulation) to “vaccinate the super-spreaders” to avert financial contagion; and
- Increasing openness in making information available to planners and the public so that there is sufficient information for the above recommendations to be implemented in practice.

Haldane and May make comparisons between the collapse of banking systems and the collapse of ecosystems. They note the substantive difference between the evolution of ecosystems (the “winnowed survivors of long-lasting evolutionary processes”) and that of banking systems, where “evolutionary forces [including the hand of government] have often meant the survival of the fattest rather than of the fittest.” Following careful analysis of many concrete examples, their two main recommendations are:

- Increased diversity across the system as a whole (as opposed to “diversification” of individual institutions, which actually results in decreased diversification across the system); and

- Breaking the system up into modular units to prevent contagion infecting the whole system in the event of nodal failure.

These suggestions have been the subject of some criticism (Johnson, 2011; Lux, 2011; Sornette and von der Becke, 2011), the main thrust of which is that policy should be based on concrete analysis rather than analogy, and that simple solutions may already exist but have been forgotten or overlooked. This is undoubtedly true, but as Liechty (2012) emphasises, concrete analysis needs concrete information, and banks should "engage with scientists to build the infrastructure needed to price system-wide risk." The same can be said of social and ecological policy development.

### b) Tools for governance

A great deal of effort is now being put in, on the scientific side at least, to garner concrete information that can be used as a basis for policy development. Two particular examples that are being developed are the ambitious FuturICT project "Participatory Computing for our Complex World," which aims to act as a focal point for collecting data as a basis for modelling the global socio-economic-ecological system (see also Helbing and Balietti, 2010) and the Inter-Sectoral Impact Model Intercomparison Project (2012) for modelling climate change.

This information needs to be used within the context of realistic sets of guidelines (with different cultural constraints) that fit with the main principles of network-based governance and open, reliable information. Previous efforts to offer guidelines for policy development, such as the long-running Earth System Governance Project (Biermann *et al*., 2010, 2012), have tended to concentrate on social factors. Ostrom's (2009) General Framework for Analyzing Sustainability of Socio-Ecological Systems was one of the few to mention factors relevant to network-based governance (including an emphasis on appropriate group size) and open information (in the form of shared knowledge), but even these go only part of the way towards addressing the problem.

Policymakers must face the fact that the evolution of complex adaptive networks can sometimes produce a multiplicity of possible outcomes with slight changes in circumstances, and that they may often be called upon to make decisions in an environment of considerable uncertainty. Polasky *et al.* (2011) suggest three possible approaches to help deal with that uncertainty (see also Appendix 1):

- **The thresholds approach**, which uses modelling to determine which actions are most likely to take us dangerously close to a critical threshold/transition, and enables the developing of policies that avoid such actions. At the least, this approach allows ranking of actions according to the likelihood of such risk.
- **Scenario planning**, which conceptualises the future by inventing plausible stories, supported by scientific data and modelling, about how situations might evolve under different conditions if particular human decisions are made and acted on. By examining this range of potential futures, decision-makers can assess the robustness of alternative policies, and also hedge against "worst case" scenarios. According to news reports, this approach is now being used by the UK for contingency planning about the consequences of the Greek debt crisis of 2012.
- **Resilience thinking**, which consists of planning for the future under conditions of limited information and intrinsic uncertainty by ensuring that the system (whether social economic or ecological) has sufficient built-in resilience both to maintain itself under changing external circumstances and to adapt most readily to sudden change if and when it arises. It can be used in combination with the other approaches above, and holds the most promise in the short term for helping us to deal with some of the world's most serious problems.

All of these approaches (the first and third in particular) are more effective when used in conjunction with appropriate complex adaptive network models and/or systems for the monitoring and detection of early-warning signs.

# 3. Policy development

In this section, we address the question of how earlier conclusions about the risks posed by SDCRs, the growing possibilities for timely warnings of critical transitions, and the potential for better organising complex adaptive networks, can be converted into practical policy advice for governments and local/international organisations.

- What examples exist of governments managing strategic risks affecting the prosperity and well-being of populations and environments?
- What additional challenges do SDCRs pose to these kinds of approaches?
- What practical approaches are available to policymakers to minimise unwanted shocks from and resilience to SDCRs? And what roles should science play in that?

## 3.1. What examples exist of governments' use of risk management approaches to avoid or ameliorate disasters?

In theory, governments that have adopted systematic (though not necessarily systemic) risk management approaches (to risks of any kind) have done so to enable their stakeholder populations to exploit the opportunities, and minimise the risks, presented by advances in the scientific world and by globalisation.

In practice, governmental risk management has focused on the risk downside, and on the need to devote resources in the near to mediumterm to mitigate risks and their impacts in a proportionate way.

Reasons for this "precautionary" approach to risk management have included:

- Failure to anticipate or predict past disasters, and a resultant loss of faith in predictions and threat assessments;
- Even where crises have been predicted, failure to anticipate their full outcome in terms of impact on populations, and a need to understand the possible impacts of future events;
- Concern that the accelerating pace of change in science and technology, and the greater connectedness of the world (its economy, communications and infrastructure), will make further failures more likely and their consequences more serious;
- Concern also that a political climate increasingly marked by intolerance of failure to foresee crises, and declining trust in all institutions but in particular government will amplify any failures by government to manage the risks; and
- A need – particularly acute since the financial crisis of 2008 – to use risk management for its traditional purpose: to optimally allocate scarce resources.

Key characteristics of these new risk governance systems are a greater openness, attention to evidence, and greater rigour in devising policy approaches to the treatment of risk. So the UK[4] approach, which has seen increased use of risk assessment to drive policy planning for national resilience planning over the past decade, and more recently to inform the national security strategy and the national climate change adaptation plan, encompasses:

- Attempts to allocate and clarify responsibility for owning and managing elements of risk, catalogued systematically and open to view to the public[5];
- A systematic process of learning from policy failures arising from a failure to identify or correctly assess risks; embedding consideration of risk in core decision-making processes; an enhanced capacity to identify and handle strategic risks, with improved horizon scanning, resilience building, contingency planning and crisis management; and

(4) See Cabinet Office Strategy Unit, November 2002: *Risk: Improving government's capability to handle risk and uncertainty* at http://www.cabinetoffice.gov.uk/media/cabinetoffice/strategy/assets/su%20risk%20summary.pdf
(5) See Cabinet Office: Central Government's Concept of Operations sets out the UK's arrangements for responding to and recovering from emergencies at http://www.cabinetoffice.gov.uk/sites/default/files/resources/lead-government-department-march-2010.pdf

- Improved risk communication, political and senior official/professional leadership and clear objectives to enable confident decision-making on risk and innovation.

## 3.2. What additional challenges do SDCRs pose to these kinds of approaches?

Slowly developing catastrophic risks pose a serious threat to our societies and our world, as illustrated by the following list of examples from widely different sectors of society and nature:

- Evolution of antibiotic-resistant strains of bacteria (Andersson and Hughes, 2011) and multi-drug resistant superbugs in India (Walsh, 2011; Moellering, 2010) and elsewhere;
- Social pressures leading to the loss of cultural diversity in societies, including the loss of languages (Maffi, 2005);
- Environmental tourism increasing pressure on fragile areas and species (Williams and Ponsford, 2009);
- Fragmentation of habitats, leading to loss of biodiversity, and focus on monoculture agriculture, with the potential for large crop losses through disease (Fahrig, 2003);
- Over-extraction of deep aquifers leading to loss of water resource and salination of land (Tularam and Krishna, 2009);
- Exchange of water for food in the globalised water trade network (Dalin *et al.*, 2012);
- Unsustainable national debts (Arghyrou and Tsoukalas, 2011);
- Uncontrollability of financial systems such as the international banking system (Haldane, 2009);
- Increasing income disparities at national and global levels (Meschi and Vivarelli, 2009);
- Demographic imbalances (Cooper, 2008); and
- Increasing Internet security issues (Rose and Gordon, 2003).

Some of these risks are, in principle, covered by the national risk assessments developed by some governments to prioritise planning for the crises that may result. But the risk assessment models used by these governments have tended to focus on nearer term risks, and, in particular, on the more politically “neutral” external threats to national security interests. So, although they provide a basis – a *sine qua non* – for effective risk governance of SDCRs, they have still some way to go before they are up to the task of identifying and weighing longer term, systemic risks. Just as the scientific understanding of complex adaptive networks has made significant advances, so has understanding among governments of the use that can be made of national risk assessments to compare and devise treatments for the most serious risks. But SDCRs present particular challenges because of their systemic nature, long-term horizons and uncertainties, because they are, in political terms, “manufactured risks” (i.e. they are someone’s fault and/or they should be predictable), and because in many cases their international or even global nature make ownership and treatment entirely unclear.

Scientific understanding of such risks can inform policy, but cannot manage it. We do not seek to analyse specific examples here, but to establish general principles by which such risks can realistically be handled in political, scientific and managerial contexts. We do not pretend that the implementation of such principles will be easy, but we do contend that it is possible, as well as being, in many cases, imperative.

The problems that societies face in establishing and implementing general principles by which risks can realistically be handled are of four types: identification and assessment of the risk; information overload; long-term governance and management of the processes; and risk communication.

### 3.2.1. Problems in identification and assessment of SDCRs

- Many risks have multiple causes. It is not always easy, or even possible, to identify and prioritise these, especially since they often interact with and affect each other in complex ways that involve multiple feedback loops. For example, the effect of an ageing population on public debt (pensions, health costs, etc.) may seem to be predicable, but both pensions and health expenditure can in turn affect population demographics, not to mention fiscal and social decisions in other areas, and even social unrest and loss of productivity through economic and social inequity.
- Complex risks may have complex consequences, which need to be understood to build resilience. Analysing the possible consequences of slow-moving risks means understanding the evolution of the relevant complex adaptive networks – a science that is developing rapidly, although much progress remains to be made.
- Analysis usually involves computer modelling of interactions between different processes, whose accuracy depends on having sufficiently detailed information about those processes.
- The uncertainty attaching to changes taking place over decades needs to be characterised in ways that can aid policymaking. Policymakers value the use of scenarios to illustrate possible outcomes (best, worst and most likely) of a risk materialising, and advice on what signs to look out for that will provide strategic warning of change, more than spurious accuracy or embellishment of the possibilities.

### 3.2.2. Problems of information overload

- Digital connections have made everything seem "knowable" and "manageable" because information is routed through smart networks. With few policymakers to really act, this results in bottlenecks in the political decision-making process. There are examples of getting around this, as in some of the risk management offices in governments, but they are rare. The problem now facing policymakers is new – how to make sense out of so much information, much of which is in the public domain. The pressures to act are not only from rational scientific analysis, but also the numerous interested citizens who have vested interests that would be promoted by the action. To make things more difficult there are also pressures from those who have vested interests in keeping the status quo, and so would prefer little or no action to be taken.

### 3.2.3. Problems in governance and management of SDCRs

- Replacing linear thinking (a change in A causes a proportional change in B) with non-linear thinking (many effects are both disproportionate and non-additive) and also systemic thinking (A, B, C, D and E interact with each other in a complex, non-linear way, so we need to develop policies that address changes and disproportionate effects in the system as a whole, rather than adopting a piecemeal approach).
- The tendency to discount costs ("richer societies of the future will pay to deal with the problem"): many SDCRs arise from developments that confer short-term benefits on stakeholders who therefore have a vested interest in maintenance of the status quo.
- Many people extend the (discredited) principle of the "balance of nature" – that systems which are disturbed will tend to return to their initial state by "natural" processes if they are just left to themselves – to encompass the assumption that man-made disturbances are likely to be resolved by new scientific discoveries or unexpected creative solutions. This belief is reinforced by the fact that many societies and natural systems can be surprisingly resilient. History has often shown, though, that such resilience is not to be relied upon, and that the "safety margins" that we rely upon may be illusory. To give one example, the effect of industrially produced carbon dioxide on global temperatures was predicted by the Swedish chemist Svante Arrhenius in 1896, but his predictions were ignored for a century because of the underlying belief that new scientific discoveries were bound to solve the problem; a belief that still exists in some quarters (Etkin and Ho, 2007).

- The "cause(s)" of change, and also their consequences, may not be universally perceived as negative (oil and climate change provide a classic example). Change may produce benefits for some, but difficulties for others. When populations of those "others" (which may be human or environmental) are unpopular or marginalised, the problem for socially responsible policymakers is particularly serious.
- Even where the long-term negative consequences are recognised, policy objectives may differ between key actors; this is a particular problem for global risks where actions to cope with SDCRs may conflict with established political and/or economic interests.
- Identifying owners and stakeholders; assigning responsibility and accountability. Particularly for those risks with an international dimension, a key ingredient for risk management – that someone can be found with responsibility for managing the risk – may be absent.
- Multiple ownership. Addressing the "cause" may be seen as being only partly within or completely outside, the legitimate mandate of government, and may require the creation of totally new political/administrative structures, especially at the international level.
- Effort may be needed over an excessively long period of time, with action to resolve immediate/familiar problems being seen as more important. The political incentive /recognition/reward for averting what may be seen as a hypothetical catastrophe is low, and shifting policy interests may inhibit consistent long-term treatment of risk.

### 3.2.4. Problems in risk communication

- Getting society in general, and policymakers in particular, to understand that the potential for SDCRs is an intrinsic feature of all complex economies, societies and ecosystems, and not usually a consequence of some external force that can conveniently be blamed for their occurrence.
- Getting a public, exposed to too many predictions of catastrophe in different arenas and liable to "risk fatigue", to agree to forego benefits of advances in science etc. for a reduction in the long-term downside risks.
- Some scientists involved with risk prediction are all too easily susceptible to hubris, and to focusing on extreme possibilities in an effort to get their message across. As a consequence, scientists are often seen by politicians as just another pressure group, and their messages may be discounted on this basis (Kassen, 2011; Fisher, 2012).
- Following on from the above, a major problem is that of getting policymakers, the media and scientists to discuss in objective and suitably qualified terms the long-term risks arising from SDCRs. The media in particular have a vital role to play in transmitting accurate information and influencing opinions and behaviours.
- Finally, the ultimate causes of many SDCRs are deeply rooted in human nature, the structure of human societies, and the paradoxes of human decision-making as portrayed by game theory. It is not entirely pessimistic to ask whether it is really worth trying to stop or manipulate history, which can be seen on one level as a succession of risks and reactions.

## 3.3. What practical approaches are available to governments to minimise unwanted shocks from SDCRs?

With these challenges, what are governments/societies going to want from the risk governance process? Given the uncertainty, and that it increases markedly into the future, policymakers want something that will enable them to:

- Estimate where and how to hedge against the long-term risks.This means identifying the top strategic risks in terms of plausible (even if remote or extreme) outcomes affecting key stakeholder groups (populations, businesses) or the environment. Over time, it means having a greater understanding and quantification of the kinds of impact that may be felt if the risk materialises.These are necessary to inform planning for risk treatment, including risk mitigation and resilience strategies.
- Avoid strategic surprise.This means having warning and indicators that the conditions may be present for critical transitions, in time for anticipatory action to be taken. Given the uncertainties over the longer term assessment of risks of SDCR, and the range of possible outcomes, policymakers need to understand how to recognise the symptoms that should provide a trigger for strategic contingency planning.
- Have a coherent basis for information sharing and risk communication, providing an essential basis for persuading people, if necessary, to forego short-term gains for longer term benefits which may in some cases accrue to successor generations and not to themselves.
- Trigger behavioural change. Behavioural change, involving changes in attitudes as well as actions, is probably necessary for dealing with most SDCRs. Exhortations, whether from scientists or policymakers, are not enough. What is needed is: a) a clear agreement between scientists, policymakers and other interested parties about the risks and attitudinal changes that are needed; and b) clear policies (in the form of concrete actions, laws, subsidies and penalties) to make the changes possible. These policies need to be developed and introduced with openness and transparency from the start, and in conjunction with communication and education.
- Incentivise and reward leadership. SDCRs can only be addressed effectively if a substantial proportion of the community understands their importance and is prepared to take individual action towards a common cause. Such actions can be stimulated (especially in the early stages) by appropriate rewards and incentives, with appropriate encouragement and support for individuals to take leadership roles.

One of the most difficult challenges is that political and economic systems which are based on a dynamic balance between conflicting interests are simply not constructed to address problems such as SDCRs, which concern the system as a whole and where a global view needs to be taken. New political and administrative ways need to be found to address such problems. This process will inevitably involve: a) a willingness to examine the respective roles of consensus decision-making versus placing decision-making power in a few hands (at least where SDCRs are concerned); and b) creating an environment of openness where governments can be trusted with the necessary power.

Steering a course for decision-making in uncertain and complex situations is by no means easy. Three major possibilities for alternative criteria were briefly outlined in Section 2.3.2 and in more detail in Appendix 1. These are: the thresholds approach; scenario planning; and resilience thinking. They may be used either in isolation or combination.

## 3.4. Ten basic requirements

The use of these or other techniques to inform long-range strategic thinking about SDCRs imposes separate but complementary challenges for scientists and for policymakers. Science and scientists are nowadays central to policymaking. It is wrong to believe that it is just by making them even more central that more rational, science-based, policymaking would be possible. Invoking more scientific authority in politics is pointless, unless certain improvements can be achieved, both on the side of science and on the side of policy. For scientists, the five basic requirements are:

### 1. Awareness

To understand the potential for a risk-based approach to policymaking and how it differs from more traditional approaches. This implies, in particular, that the normal media-driven obsessions with the immediate past and the immediate future can co-exist in governments with longer term strategising in pursuit of legacy benefits for future generations. And that policymakers are at least as interested in understanding the range of possibilities (what the military call the "left and right of arc") as they are in predictions of what the most probable outcome may be; and that they will increasingly prefer risk assessment to prediction; prefer impact assessment to estimates of probability; and prefer in any case to know what are the harbingers of critical change.

### 2. To look forward as well as back

"Those who cannot remember the past are condemned to repeat it." Santayana's well-known stricture could have been intended for SDCRs, where awareness of the possible consequences of gradual change is an essential first step to dealing with the situation. Lack of awareness has often been a factor in the collapse of economies, societies and ecosystems, for example, Gibbon's analysis of the collapse of the Roman Empire, and the many examples adduced by Malcolm Gladwell in *The Tipping Point* (2002) and by Jared Diamond in *Collapse: How Societies Choose to Fail or Succeed* (2005). Today, for the first time, we can understand the real basis of such historic collapses and learn, not just from experience, but from concrete understanding and analysis. Awareness is the first essential step. But, in particular where human agencies are concerned, it is also true that past performance may not be a reliable indicator of the future. So an understanding of the history of a risk needs to be tempered by a willingness to consider what changes in the risk may arise because of the increasing inter-connectedness of risks. The further ahead we need to look the more we need proven techniques of horizon scanning to estimate the range of possibilities that the future may hold.

### 3. Collaboration

Increasingly, the science of risk requires collaboration: within the science community where the science of complex adaptive networks has shown the need to adopt a holistic approach, just as governmental administrative structures based on a division of responsibility have demonstrated the weakness of "stove-piped" policy or strategy formulation. A cross-disciplinary approach is required despite the fact that such an approach is likely to be both difficult and challenging.

### 4. Avoid predictions (and baffling with science)

Studies have shown (Sarewitz and Pielke, 2000) that "science often becomes ammunition in partisan squabbling, mobilised selectively by contending sides to bolster their positions." Scientists themselves have sometimes contributed to this process by making claims at too early a stage in a research programme, and by naively appealing to the media, whose black-and-white agendas add further distortion.

Scientists need to address this problem, both as individuals and as a group, and re-establish their authoritative, independent position in order to avoid the fate of the mythical Cassandra – that of making true predictions that were never believed until it was too late. Prediction is vital, but in the field of risk assessment and management, and in particular given the uncertainties attaching to long-term SDCRs, scientists should be very careful to spell out the caveats, and not to over-claim. Unfortunately, this carries the hazard of overburdening policymakers who are already at risk of information overload. So the scientist must tread a very fine line in an effort to fulfil Albert Einstein's dictum that "everything should be made as simple as possible, but no simpler".

### 5. Communication between scientists and policymakers

Politicians and other policymakers are liable to see scientists as just another pressure group (Kassen, 2011). This conventional labelling undermines the community's ability to contribute to the understanding of and dealing with SDCRs at a practical level. New ways, and new attitudes, must be found to establish genuine communication. The first step is for each side to understand and respect where the other is coming from. In particular, (Fisher, 2012) scientists must avoid over-claiming, and clearly identify any available short-term benefits of long-term policies (Fisher, 2012).

Scientists also tend to believe that facts will speak for themselves. A more effective approach (Pielke, 2007) is for scientists to act as "honest brokers", integrating scientific knowledge and understanding with stakeholder concerns to provide even-handed advice and information within a policy context (Pielke, 2007). This may require scientists to learn to communicate in terms that are more easily understood by policymakers and use language that will resonate with voters.

The five basic requirements for policymakers are:

### 6. Awareness

Handling risk – both opportunity and threat – is increasingly central to the business of government. The accelerating pace of change in science and technology, and the greater connectedness of the world, are creating new responsibilities and demands, and an expectation that governments will think more strategically about the short-, medium and long-term risks.

### 7. Risk ownership, reward and incentives

Governments need constantly to keep under review where responsibility for managing risk should best sit. It is important as it may often be difficult to identify who can "own" a SDCR. Risk ownership, a term used to describe the fact that only those who have a personal stake in a risk will effectively deal with it, refers to creating links between cause and effect, between risk and reward. Some SDCRs offer opportunities as well as risks.

By identifying a possible reward for those who decide to engage and spend money to mitigate a SCDR (and who will get a return on their investment), by incentivising those who can decide, act and be accountable to the public, the chances of successfully dealing with it will be higher, especially if policymakers establish political and business links between risk and opportunity, and communicate effectively about such opportunities.

### 8. Sound processes and systems

Successful risk handling rests on good judgment supported by sound processes and systems. Action is needed in: systematic, explicit consideration of risk firmly embedded in government's core decision-making processes (covering policymaking, planning and delivery); government should enhance its capacity to identify and handle strategic risks, with improved horizon scanning, resilience building, contingency planning and crisis management; risk handling should be supported by best practice, guidance and skills development.

### 9. Communication with stakeholder communities

A necessary condition for risk to be handled effectively is that those who hold the ultimate power must agree about the significance of the risk. In Western democratic societies, this means that public perception holds the key. In societies with different power structures, the ultimate responsibility may lie in fewer hands. In any case, the key to effective action is first to persuade the power holders that the threat is real and that appropriate action is necessary and possible.

Open communication with stakeholders is especially important because policies for managing and coping with SDCRs often involve a trade-off between groups and individuals with different interests, and mitigation of a primary risk may create secondary risks. There can be a real moral hazard if the secondary risks are borne by vulnerable or less powerful members of a community, or by the members of an entirely different community. Addressing how we might handle such moral hazards is outside the scope of this report, but one suggestion for developing effective policies is to look at how organisations (such as the insurance industry) that habitually deal with this sort of risk manage such situations. In any case, SDCRs should be on the education agenda of all communities, from local to national and global levels. It is especially important to transmit the message that ecological, economic and social SDCRs have a common basis, and can all be understood in a similar way.

### 10. Collaboration and strengthening international policymaking

Today's administrative structures are mainly based on division of responsibility. The science of complex adaptive networks has revealed the fragilities of such an arrangement, and shows that dealing successfully with SDCRs in any arena requires adopting a holistic approach that transcends traditional administrative and political boundaries.

Many if not all of the systemic risks are transnational by nature. International collaboration is a difficult path, mostly because there are often domestic political interests that may be opposed to international coordination. But this is no doubt the only way forward and we must find creative ways to develop the ability to cooperate across nations. There is a great deal of evidence-based history (however, most in times of crises or large-scale disasters) to show that international cooperation can work.

# 4. A framework for decision-making

The key features for establishing an effective framework for decision-making about the problems posed by SDCRs are:

- Decisions must address systemic issues, rather than being taken piecemeal;
- Decisions must be evidence based, with evidence including the results of analysis and modelling, and not just facts and observations;
- Decisions must be flexible, and able to be adapted to the development of new evidence and new understanding over time; and
- Decisions must be effective, with an assurance that individuals and organisations will act on them.

These criteria are best met if scientists, policymakers and other concerned individuals and organisations get together at the earliest possible stage and maintain ongoing communication and policy development. Given these conditions, we propose the following framework for policy development, with a progressive shift from an emphasis on science to an emphasis on policy, although both scientists and policymakers need to be involved at all stages, with flexibility and a willingness to re-address issues in the light of new information. This proposal elaborates from the IRGC risk governance framework (IRGC, 2005, 2008) focusing on the specific challenges posed by slow-developing catastrophic risks.

**Step 1 – Scenario development and horizon scanning,** to identify the "alternative worlds" through analysis of the key drivers for change in the main areas (resources, environment, populations, geo-politics etc.) where change is most likely to be played out in the foreseeable future. And to provide the basis for incentivising evidence-based policy through identification of strategic opportunities as well as risks.

**Step 2 – Identification and characterisation of SDCRs**

- What type of risk are we looking at? Does it fall into a particular class (different types of risk may require different types of approach)?
- What are the key components of the risk? Its representation, its interaction with other risks and factors?
- What timescale are we looking at? Who is going to suffer (or benefit) from the changed circumstances if a critical transition does occur?
- Identification of the "system". Where are its boundaries? Which phenomena are internal and which are external?

**Step 3 – Assessment of current status and possible evolution**

- How will the risk evolve? Deterministic and probabilistic modelling.
- What are its direct and indirect consequences and its inter-relationships with other risks and factors?
- Holistic assessment in social and historical contexts.
- Combined use of the thresholds approach, scenario planning and resilience thinking to assess the potential effects of reaching a tipping point on different sectors and on society as a whole.
- Identification of the "warnings and indicators" of critical transitions.

**Step 4 – Evaluation and judgment**

- Identification of trade-offs with other risks/problems at all stages.
- Making political and business decisions as to whether to engage (or not) in preventative and palliative measures, and if so at what stage (cf. warnings and indicators).

**Step 5 – Development of risk management options**

- Using science as a basis for regulation.
- Policies to effect changes in public and business behaviour, including providing incentives, allocating accountability and attributing risk ownership.
- Developing and changing liability regimes.

**Step 6 – Selecting and implementing governance approaches**

- Deciding about appropriate strategies.
- Developing policies and regulation; implementation and enforcement.

**At all stages – communication, openness and transparency are key to the development of successful and effective policies.** Particular attention needs to be paid to:

- Awareness building;
- Information and dialogue;
- The provision of reliable, trustworthy information – not only observational, but also from correct analytical modelling. Peer reviewed and/or otherwise independently assessed and verified; and
- The development of a risk culture, where people understand the nature of risk (especially SDCRs) and the necessity for monitoring change, predicting its effects and taking sufficiently early action to avoid or ameliorate them.

# Conclusion



Our current understanding of slow-developing catastrophic risks leads us to conclude that the potential for this type of risk is built into the very fabric of our complex socio-political-economic world, just as it is in the ecosystems of which we are a part. Their occurrence is inevitable. This message must be conveyed to decision-makers in the public and private sectors.

The catastrophe that may occur at one stage of the development of a slow-developing risk can be predicted, but often not in time to take practical, effective action to avert it. In such conditions, it is advisable to: a) continue to develop models that enable more accurate anticipation and b) develop resilient social and economic structures, able to respond and adapt rapidly to sudden change. This is the best (and often the only) way to cope effectively with slow-developing catastrophic risks.

This implies that political and social strategies need to support institutions and practices that are more responsive to change, more flexible and adaptable. But above all, it is the relationship between scientists and policymakers that needs to be improved and would benefit from a better reciprocal understanding of each other’s community and rules.

# Appendix 1: Possible approaches to help deal with uncertainty



### The thresholds approach

Complex adaptive systems usually possess multiple basins of attraction, which (to mix a metaphor) act as islands of stability – sometimes veritable continents. The thresholds approach ignores these relatively stable or slowly changing environments, and focuses instead on potential transitions between them.

These transitions, which are labelled as critical transitions or regime shifts, arise because the subtle balance between stabilising negative feedback processes and runaway processes, such as positive feedback, have reached a point where the runaway processes take over, sometimes in dramatic fashion. Inland lakes may suddenly change from turbid to clear, or vice versa. Natural populations may suddenly mushroom, or just as suddenly collapse and even disappear entirely. Technical innovations, from the discovery of fire to the development of the personal computer, can transform our lives in a very short space of time. Banking systems may crash; revolutions may break out; whole societies, ecosystems and economies may suddenly burgeon or just as suddenly collapse. All of these are examples of critical transitions within complex systems, emerging directly from the nature of the system itself.

The thresholds approach offers a screen to rule out actions which modelling and other approaches indicate offer a high risk of crossing a threshold. At the least, it allows us to rank actions according to the likelihood of such risk. Computer modelling of such risk goes back to the Club of Rome 1972 report *The Limits to Growth*, whose predictions, according to a recent study, still largely hold good.

A particularly important application of the thresholds approach lies in the calculation of boundaries for various variables that affect our planetary ecosystem. One recent study, published in the prestigious scientific journal *Nature* under the title "A Safe Operating Space for Humanity", provided conservative calculations for nine variables based on current knowledge, and concluded that three (climate change, the nitrogen cycle and biodiversity) were already close to or (in the case of biodiversity) well beyond the safe limit.

### Scenario planning

Scenario planning is science fiction for the real world. It conceptualises the future by inventing plausible stories, supported by data and modelling, about how situations might evolve under different conditions if particular human decisions are made and acted on. By examining this range of potential futures, decision-makers can assess the robustness of alternative policies, and also hedge against "worst-case" scenarios.

Two contrasting cases illustrate the potential value of this approach to decision-making in complex situations. In the early 1970s, with oil prices low and predicted to remain so, Shell nevertheless considered scenarios where a consortium of oil-producing countries limited production to drive oil prices up. As a result, the company changed its strategy for refining and shipping oil. It was then able to adapt more rapidly than its competitors when the scenario became reality in the mid-1970s, and rapidly rose to become the second-largest oil company in the world.

By contrast, IBM failed to use scenario planning in the 1980s when predicting the market for personal computers, and withdrew from a market that became more than a hundred times larger than its forecasts.

The weakness of scenario planning lies in the difficulty in assessing the likelihood that alternative scenarios will actually arise. Even so, as the above examples illustrate, it can be useful as one of a portfolio of decision-making processes, and has the additional advantage that the stories that it tells can readily be understood by non-technical decision-makers. Perhaps this is why it finds such favour with government committees concerned with disaster planning.

### Resilience thinking

One of the key indicators for the nearness of a critical transition in a complex social, economic or ecological system is a decrease in resilience – that is, a decreasing ability of the system to recover from small perturbations.

Resilience thinking focuses on promoting awareness of such warning signals, and also on the conservation of key processes so that the system is able to adapt most readily to sudden change if and when it arises.

The obvious problem here is that a very wide range of problems and options needs to be considered to make such planning possible. True interdisciplinarity is the key here – not just scientific interdisciplinarity, but social, economic and political too.

A second, major problem is that the timescale of most of the warning signs is unfortunately as short if not shorter than the current timescale of many decision-making processes in society.

The difficult conclusion we are confronted with is that successful planning for our complex future will almost surely require a totally different approach to managing our affairs, and will need new, rapidly adaptive ways of decision-making, such as using the rapid response time of the Internet as a part of the information-collating and decision-making processes. Developing such an approach may require a measure of understanding and good will that is currently beyond us, but the decision criteria above (especially if used in combination) at least suggest that there is light at the end of the tunnel, even if there is a train coming the other way.

# Appendix 2: Themes for governance

The basic principles for the management of emerging risks were spelled out in the IRGC Concept Note *Improving the Management of Emerging Risks* (Geneva, 2011)[6], where 11 specific themes were identified. Discussions at the IRGC-sponsored Venice workshop "Slow-Developing Catastrophic Risks" were not specifically constrained to these themes, but many of the issues that were identified fit comfortably within them as an intellectual framework for the integration of science and policy. In order to provide a link with ongoing IRGC policy development, we briefly place those issues here within the earlier framework, and identify the ways in which these themes are relevant to SDCRs[7] and the unique problems that they can pose[8].

## Risk governance: strategy, management and organisational matters

**1. Risk management as part of overall strategy**

- Assessing indirect consequences and inter-relationships with other risks/factors
- Identification of trade-offs with other risks/problems

**2. Clarification of roles and responsibilities**

- Identification of risk type
- Identification of stakeholders
- Scientists as modellers
- Use of scientists as "honest brokers"
- Development of new administrative structures to handle systemic issues

## Changing the risk culture

**3. Setting explicit incentives and rewards**

- Awareness building
- Provision of reliable, trustworthy information
- Identifying and communicating rewards for long-term, systemic planning, including advising politicians of any short-term political or other benefits for long-term systemic policies

**4. Removing disincentives to long-term planning**

- Restructuring systems (e.g. the banking system) to discourage "short-termism" and provide rewards for long-term planning
- Developing and changing liability regimes to favour long-term systemic planning

**5. Encouraging contrarian views**

- Bring scientists, policymakers and other concerned parties together at an early stage
- Open communication of questions, problems and progress
- Creation of decision-making bodies to develop systemic, holistic policies

## Training and capacity building

**6. Building capacity for surveillance and foresight**

- Support for large-scale data collection and a diverse range of scientific approaches to analysis and prediction
- Creation of "clearing house" administrative structures composed of scientists and policymakers able to integrate relevant material and communicate its significance
- Creation of flexible decision-making bodies that are able to adapt and refine policies in the light of ongoing information and understanding

**7. Improving communication and dialogue**

- Education at school and community levels
- Improved communication between scientists and politicians

**8. Improving cooperation and teamwork**

- Open, transparent communication
- Encouragement and involvement of community leaders

## Adaptive planning and management

**9. Anticipating adverse outcomes**

- Holistic assessment in social and historical contexts
- Use of evidence-based prediction and modelling
- Combined use of the thresholds approach, scenario planning and resilience thinking

**10. Improving flexibility**

- Administrative structures for ongoing interaction between scientists and policymakers
- Avoidance of cumbersome legal measures in favour of open communication and flexible administrative arrangements

**11. Developing strategies for robustness and resilience**

- Development of new administrative structures to handle systemic change and systemic risk
- Combined use of the thresholds approach, scenario planning and resilience thinking

(6) Available on http://www.irgc.org/IMG/pdf/irgc_er2conceptnote_2011.pdf
(7) Example: the metaphors of parturition and death. A striking metaphor for the processes involved in SDCRs is the slow development of a foetus up to the moment of birth – a critical transition that involves a complex interaction between many different physiological, biological and emotional elements. The subsequent growth and development of the new-born baby throughout life provides another striking metaphor, with death as an abrupt, inevitable end point. In both cases, warning signs for the imminent transition may be present, but may not be noticed, and even when they are noticed it may be too late to take appropriate action.
(8) Some of the major questions have been given a public airing in a brief letter to the scientific journal *Nature* ("Shaping policy: Science and politics need more empathy" (Fisher, 2012) and in several talks (Fisher, 2012a; Fisher and Florin, 2012; Florin and Fisher, 2012) where audience response has helped to provide further clarification, as have further discussions between some of the participants from the Venice meeting.

# Glossary

**Agent-based modelling:** simulates the actions and interactions of autonomous agents (both individual and collective entities such as organisations or groups) with a view to assessing their effects on the system as a whole.

**Black swan hypothesis:** a metaphor that describes the disproportionate role of hard-to-predict, high-impact, rare events that are beyond the realm of normal expectations in history, science, finance or technology.

**Complex adaptive network:** where the state of the nodes or links can change in response to their previous communication history, so that the network evolves and changes over time.

**Complex adaptive system:** where the interactions between its component parts lead to emergent behaviours that are characteristic of the system as a whole, so that the system is more than the sum of its parts.

**Critical transition:** sudden, irreversible shift of a complex system from one state to a very different state.

**Emergent behaviour:** one that is a property of a (complex) system as a whole, and which cannot readily be predicted (if at all) from the properties of its individual components – that is, "the whole is more than the sum of its parts".

**Endogenous transition:** a critical transition that arises as a result of changing circumstances within the system itself.

**Exogenous transition:** a critical transition that arises as a result of external triggering forces.

**Game theory:** the study of strategic decision-making between rational agents who seek to make decisions in their own best interests.

**Hubs:** the more highly connected nodes within a network.

**Links:** the connections between nodes in a network.

**Negative feedback:** a process which acts to maintain the equilibrium of a system by responding to deviations from the equilibrium with a restoring force that increases as the deviation increases.

**Nodes:** the individual units within a network.

**Phase transition:** a discrete transition in the state of a physical system.

**Positive feedback:** a runaway process where any deviation from the equilibrium is amplified, with the degree of amplification increasing as the deviation increases.

**Power law:** a relationship between two variables (say x and y) of the form $y = x^n$, where n is the "power".

**Resilience:** the ability of a system to respond to, absorb and recover from perturbations.

**Resilience thinking:** consists of planning for the future under conditions of limited information and intrinsic uncertainty by ensuring that the system (whether social, economic or ecological) has sufficient built-in resilience both to maintain itself under changing external circumstances and to adapt most readily to sudden change.

**Scale-free networks:** those where the connectivity distribution of links to nodes follows a power law, so that a few nodes have many links, while many nodes have fewer links.

**Scenario planning:** conceptualises the future by inventing plausible stories, supported by scientific data and modelling, about how situations might evolve under different conditions if particular human decisions are made and acted on.

**Small-world networks:** those in which most nodes are not neighbours of one another, but where most nodes can be reached from every other by a small number of hops or steps.

**System:** a group of interacting, interrelated or independent elements forming a complex whole.

**Thresholds approach:** uses modelling to determine which actions are most likely to take us dangerously close to a critical threshold/transition, and allows us to rank actions according to the likelihood of such risk.

**Tipping point:** a point in a system at which change becomes irreversible.

**Tragedy of the commons:** a dilemma described by game theory where multiple individuals, acting independently and rationally consulting their own self-interest, ultimately deplete a shared limited resource, even though it is in none of their interests to do so.

**Vertex:** node.

# Annotated selected references

These recent references are a small representative group, selected for their relevance to policy development and implementation and arranged in ascending date order in four sections:

A. Statistics and warning signs
B. Networks
C. Policy and governance
D. General

The purpose of the annotations is to: a) summarise the work and its significance in a clear and understandable way for non-specialists; and b) draw attention to its practical policy implications.

**A. Statistics and warning signs**

Didier Sornette, "Predictability of catastrophic events: material rupture, earthquakes, turbulence, financial crashes and human birth", Proceedings of the National Academy of Sciences the United States of America V99 supp. 1 (2002) 2522–2529 (http://arXiv.org/abs/cond-mat/0107173).

Marten Scheffer and Stephen R. Carpenter, "Catastrophic regime shifts in ecosystems: linking theory to observation", *Trends in Ecology and Evolution*, vol.18 (2003), 648–656.

Didier Sornette, "Endogenous versus Exogenous Origins of Crises", in *Extreme Events in Nature and Society*, Springer (2006) 95–119.

Sornette has examined the origins of critical transitions across areas that include biological extinctions, immune system deficiencies, learning, discoveries, commercial successes and social unrest. His most thorough analysis is of stock market crashes, where he and his co-workers have identified a statistical signature called a "log-periodic power law" (LPPL) for crashes that are endogenous in origin, rather than being precipitated by an external event. Practical implications: we may not be able to do much about exogenous transitions, except to make systems more robust to their effects, but we can at least learn how to identify the warning signs for upcoming endogenous transitions.

Reinette Biggs, Stephen R. Carpenter and William A. Brock, "Turning back from the brink: Detecting an impending regime shift in time to avert it", *Proceedings of the National Academy of Sciences of the United States of America* 106 (2009) 826–831.

The authors conclude that statistical regime-shift indicators "cannot at present be relied upon as a general means for detecting and avoiding regime shifts" because management strategies are not sufficiently well adapted to use the information. To hasten things, they suggest that critical values, rather than the identification of trends, ought to be set as triggers for management action.

Marten Scheffer *et al*., "Early-warning signals for critical transitions", *Nature* 461 (2009) 53–59.

Scheffer and his co-workers modelled critical transitions as "fold" catastrophes, and have identified a key early-warning sign in the form of "critical slowing down". Statistical signatures for critical slowing down include: a decreased ability to recover from small perturbations; increased autocorrelation (i.e. the system develops a "memory"); increased variance (i.e. increasingly frequent fluctuations between different states); and "flickering" between very different states.

John Drake and Blaine Griffen, "Early warning signals of extinction in deteriorating environments", *Nature* 467 (2010) 456–459.

The authors followed the decline in numbers and eventual extinction of populations of the water flea *Daphnia magna* as food supplies were gradually reduced. Long before the final extinction, population fluctuations, as predicted by Scheffer *et al.'s* theory, were observed.

Anders Johansen and Didier Sornette, "Shocks, Crashes and Bubbles in Financial Markets", *Brussels Economic Review* 53 (2010) 201–253.

The authors present an extended analysis of the distribution of drawdowns (runs of losses) in financial markets. Then, they check whether log-periodic power law signatures (LPPS) are present and take the existence of LPPS as the qualifying signature for an endogenous crash. The combination of the two proposed detection techniques provides a novel and systematic taxonomy of crashes further substantiating the importance of LPPS.

Marten Scheffer, "Complex systems: Foreseeing tipping points", *Nature* 467 (2010) 411–412.

An excellent, short, well-illustrated summary of the promise and problems of using statistical warning signs to predict critical transitions.

S.R. Carpenter *et al*., "Early Warnings of Regime Shifts: A Whole-Ecosystem Experiment", *Science* 332 (2011) 1079–1082.

The authors studied two adjacent Wisconsin lakes whose food webs were dominated by small planktivorous fish. They gradually added large-mouth bass to one of the lakes, leaving the other as a control. After several years the large-mouth bass population reached a level where there was an abrupt change in the populations of many species, and the food web structure changed to one where the large-mouth bass were dominant. Beginning 18 months before this, however, there were increasingly rapid fluctuations in the populations of many species, just as Scheffer *et al.'s* (2009) theory had predicted.

Len Fisher, *Crashes, Crises and Calamities: How We Can Use Science to Read the Early-Warning Signs*, New York, Basic Books (2011).
Contains a summary of the different processes that can contribute to sudden critical transitions.

Tobias Preis, Johannes Schneider and H. Eugene Stanley, "Switching processes in financial markets", *Proceedings of the National Academy of Sciences of the United States of America*108 (2011) 7674–7678.
Stanley and his collaborators show that New York Stock Market prices follow trends (ranging from "micro" to "macro") that end with a sudden "switch" to a different trend, with self-similar "scale-free" behaviour across nine orders of magnitude.

Practical implications: a) many stock market crashes may be an unavoidable, intrinsic characteristic of the market structure; b) if the authors' analysis of the causes of "switching" holds up, then appropriate measures may be taken to dampen the process by altering the market structure, e.g. by introducing deliberate delays in communication, or ensuring that there is a cost involved in changing trading behaviour; and c) these principles may be of value in dealing with potential critical transitions in other systems, even non-economic ones.

Anthony D. Barnosky *et al*., "Approaching a state shift in Earth's biosphere", *Nature* 486 (2012) 52–58.
The authors integrate input from palaeontology, macroecology, population biology and ecological network theory to produce a convincing case that the Earth's biosphere is approaching a planetary-scale critical transition. This paper alone provides a sufficiently documented basis for the urgent policy actions that are recommended in this concept note.

Steven Lade and Thilo Gross, "Early Warning Signals for Critical Transitions: A Generalized Modeling Approach", *PLOS Compututational Biology* 8(2) (2012) e1002360.
By incorporating our prior knowledge of a complex system in the form of a simple "generalised model", we can greatly reduce the amount of data that are needed to make a meaningful prediction. The authors support their contention by looking at three real-life cases, with impressive results.

V. Filimonov and D. Sornette, "Spurious trend switching phenomena in financial markets", *European Physical Journal B* 85, 155 (2012a) 1–5.

V. Filimonov and D. Sornette, "Quantifying reflexivity in financial markets: towards a prediction of flash crashes", *Physical Review E* 85 (5): 056108 (2012b).
The authors describe a method whereby one can, for the first time, quantify the level of endogeneity (reflexivity) in financial markets. They are now applying their method to other types of system, including the triggering of conflict and the occurrence of burglaries.

Len Fisher, "Early-warning signs for critical transitions", (2012a).
A talk delivered to Complex Systems Research Institute, Bathurst, NSW, Australia, 22 March 2012.

D. Sornette and G. Ouillon, "Discussion and debate: from black swans to dragon-kings - Is there life beyond power laws?'', *European Physical Journal,* vol. 25, no. 1 (2012) 1–373.
Dragon-kings are defined as extreme events that do not belong to the same population as the other events, in a precise quantitative and mechanistic sense. The hypothesis is that dragon-kings appear as a result of amplifying mechanisms that are not necessary fully active for the rest of the population. This gives rise to specific properties and signatures that may be unique characteristics of dragon-kings.

Annelies J. Veraart *et al*., "Recovery rates reflect distance to a tipping point in a living system", *Nature* 481 (2012) 357–359; Annelies J. Veraart *et al*., "Corrigendum: Recovery rates reflect distance to a tipping point in a living system", *Nature* 484 (2012) 404.
Cyanobacteria use light for energy and require a critical light level to survive and thrive. The authors subjected laboratory populations of cyanobacteria to ever lower light levels and found that the speed at which populations recovered after a high light level was restored became slower as the stressing light level approached the critical level. This confirmed the basic prediction of Scheffer *et al.'s* (2009) theory.

**B. Networks**

P. Erdös and A. Rényi, "On the evolution of random graphs", *Publications of the Mathematical Institute of the Hungarian Academy of Sciences* 5 (1960) 17–61.

Duncan J. Watts and Steven H. Strogatz, "Collective dynamics of 'small-world' networks", *Nature* 393 (1998) 440–442.

Watts and Strogatz show that in sparsely connected networks, where one might expect to need many steps on average to get from one hub to a distant hub, the presence of just a few "short cuts" dramatically reduces the average number of steps that are needed (so that the network becomes a "small-world" network).

Albert-László Barabási and Réka Albert, "Emergence of Scaling in Random Networks", *Science* 286 (1999) 509–512.

M. E. J. Newman and D. J. Watts, "Scaling and percolation in the small-world network model", *Physical Review E* 60 (1999).

Stefan Bornholdt and Thimo Rohlf, "Topological Evolution of Dynamical Networks: Global Criticality from Local Dynamics", *Physical Review Letters* 84 (2000) 6114–6117.

Stefan Bornholdt and Kim Sneppen, "Robustness as an Evolutionary Principle", *Proceedings of the Royal Society of London B* 267 (2000) 2281–2286.

Adislon E. Motter and Ying-Cheng Lai, "Cascade-based attacks on complex networks", *Physical Review E* 66 (2002).

Practical implications: the spread of infectious disease, the collapse of financial systems or any other runaway process of change is dramatically accelerated by the presence of just a few "short-cut" paths in the network.

Réka Albert and Albert-László Barabási, "Statistical Mechanics of Complex Networks", *Reviews of Modern Physics* 74 (2002) 47–97.

The authoritative review of the statistics of network structures and vulnerabilities.

Marián Boguña, Romualdo Pastor-Satorras and Alessandro Vespignani, "Absence of Epidemic Threshold in Scale-Free Networks with Degree Correlations", *Physical Review Letters* 90 (2003).

M. Ángeles-Serrano and Marián Boguña, "Clustering in complex networks", *Physical Review E* 74 (2006).

R. Crane and D. Sornette, "Robust dynamic classes revealed by measuring the response function of a social system", *Proceedings of the National Academy of Sciences of the United States of America* 105 (2008) 15649–15653.

S. N. Dorogovtsev, A. V. Goltsev and J. F. F. Mendes, "Critical phenomena in complex networks", *Reviews of Modern Physics* 80 (2008) 1275–1335.

In this overview of networks in physical systems, the authors conclude that "the brand new appearance of critical phenomena is determined by the combination of two factors – the small-world effect and a strong heterogeneity and complex architecture of networks." In other words, as pointed out by Bascompte and others in the ecological context, to understand the evolution of networks it is necessary to understand the details of their structure and interactions.

Thilo Gross and Bernd Blasius, "Adaptive coevolutionary networks: a review", *Journal of the Royal Society Interface* 5 (2008) 259–271.

Robert May, Simon Levin and George Sugihara, "Ecology for bankers", *Nature* 451(2008) 893–895.

This important article deals with systemic risk. It underlines the fact that the analysis of risk in ecology and economics is too often dealt with on a case-by-case basis (single species in the former, single firms in the latter) rather than the system as a whole. The authors point out that modularity (compartmentalisation) can promote robustness in ecological systems, and prevent damage in one part from spreading to other parts. They argue that the same is true of economic systems, such as the banking system, although "modularity will often involve a trade-off between local and systemic risk." There lies the rub in terms of political decision-making. For a social example, see http://www.eyamplaguevillage.co.uk/, which tells the story of an English village (Eyam) whose inhabitants deliberately isolated themselves from surrounding villages when the village became infested by the plague.

Dimitris Achlioptas, Raissa D'Souza and Joel Spencer, "Explosive Percolation in Random Networks", *Science* 323 (2009) 1453–1455.

Guido Caldarelli and Diego Garlaschelli, "Self-Organization and Complex Networks", *in* Thilo Gross and Hiroki Sayama's *Adaptive Networks: Theory, Models and Applications*, New York, Springer (2009).

An excellent summary (up to 2008) of complex network evolution modelling. The authors' main point is that earlier models tended to focus either on the network structure or on the effects of that

topology on the different dynamic processes within the network. By also considering the effect of the changing dynamics on the network structure, they show that "the feedback between topology and dynamics can drive the system to a steady state that differs from the one obtained when the two processes are considered separately."

Thomas C. Ings *et al*.,"Ecological networks – beyond food webs", *Journal of Animal Ecology* 78 (2009) 253–269;

Jordi Bascompte, "Disentangling the Web of Life", *Science* 325 (2009) 416–419.

The traditional approach to describing and modelling ecological networks has been based on average properties, such as the average number of links ("connectance"). The advent of increasingly powerful computers makes it possible to examine such networks in much more detail, and the authors (Bascompte is also an author on the first paper) show with many concrete examples that this detail is necessary if the models are to reflect the real properties of the network. This is of vital importance if we are to be able to "predict, and eventually mitigate, the consequences of increasing environmental perturbations such as habitat loss, climate change, and invasion of exotic species."

Frank Schweitzer *et al*., "Economic Networks: The New Challenges", *Science* 325 (2009) 422–425.

A warning bell for the dangers of interdependencies and their little understood consequences in the international financial system, with a dramatic presentation of the interconnections among different major financial institutions.

Alessandro Vespignani, "Predicting the Behavior of Techno-Social Systems", *Science* 325 (2009) 425–428.

A call for "network thinking", with the emphasis on three challenges:

- Gathering large-scale data on information spread and social reactions during times of crisis;
- Formulation of models that quantify risk perception and awareness of individuals; and
- Deployment of monitoring infrastructures capable of informing computational models in real time.

Gesa Böhme and Thilo Gross, "Analytical calculation of fragmentation transitions in adaptive networks", arXiv preprint 2010, http://arxiv.org/abs/1012.1213.

A seminal paper on the prediction of fragmentation transitions, but as yet restricted to simple computer models (in this case, the "voter" model of opinion formation).

Sergey Buldyrev *et al*., "Catastrophic cascade of failures in interdependent networks", Nature 464 (2010) 1025–1028; (see also Alessandro Vespignani, "Complex networks: The fragility of interdependence", *Nature* 464 (2010) 984–985).

Network stability and resistance to collapse is measured by a "critical threshold" – the fraction of nodes that must fail before the whole network fails. The authors show that this critical threshold is much lower for interconnected networks (common in today's world) than for isolated networks. A further result concerns heterogeneous networks (e.g. ones where computers and other devices with different operating systems and/or protocols are linked). These are generally thought to be very resilient, but when two such networks are interconnected the authors show that they become less stable.

Haifeng Zhang *et al*., "Hub nodes inhibit the outbreak of epidemic under voluntary vaccination", *New Journal of Physics* 12 (2010).

Michael T. Gastner *et al*., "Changes in the Gradient Percolation Transition Caused by an Allee Effect", *Physical Review Letters* 106 (2011).

Cinari G. Ghedini and Carlos H. C. Ribeiro, "Rethinking failure and attack tolerance assessment in complex networks", *Physica A* 390 (2011) 4684–4691.

Dion Harmon *et al*., "Predicting economic market crises using measures of collective panic", *Social Science Research Network*, (2011) (http://papers.ssrn.com/sol3/papers.cfm?abstract_id=1829224).

Collective panic is a runaway positive feedback process. The authors model its effects in a network of traders who use trend-following mimicry across multiple stocks, finding a) that it closely reflects real-world behaviour; and b) that, when checked against historical crashes of the last decade, "the performance of the predictive pattern is exceptional."

Brian Karrer and M. E. J. Newman, "Competing epidemics on complex networks", *Physical Review E* 84 (2011).

Raj Kumar Pan *et al*., "Using explosive percolation in analysis of real-world networks", arXiv:1010.3171v2 (2011).

Greg Paperin, David Green and Suzanne Sadedin, "Dual phase evolution in complex adaptive systems", *Journal of the Royal Society Interface* 8 (2011) 609–629.

The authors argue that complex adaptive systems evolve and change by constantly switching between highly connected and relatively poorly connected states, both across the whole network and also within smaller sub-networks. Their argument encompasses networks of many types and reinforces the view that, in the long term, critical transitions are inevitable in complex adaptive networks.

Christian M. Schneider *et al.*, "Mitigation of malicious attacks on networks", *Proceedings of the National Academy of Sciences of the United States of America* 108 (2011) 3838–3841.

Stefano Allesina and Si Tang, "Stability criteria for complex ecosystems", *Nature* (2012); see also R. M. May "Will a large complex system be stable?", *Nature* 238 (1972) 413–414.

In 1972 Robert May demonstrated mathematically that large, complex ecosystems could not be stable in the long term if each pair of species interacts with the same probability. This basic result remains true, but Allesina and Tang have now used a similar mathematical approach to show that large predator-prey networks can be stable provided that the predator-prey pairs are tightly coupled in some way. Practical implications: as the authors point out, "these findings are not limited to ecological networks, but instead hold for any [complex network described by a] system of differential equations resting at an equilibrium point". Tight coupling of individual pairings and groups within a network (e.g. by promoting mutual dependence within small groups, whether these be groups of people, institutions or species) may indeed be a practical and useful political strategy for maintaining stability of the network as a whole.

- Andrew Haldane, "Rethinking the Financial Network", (speech delivered at the Financial Student Association, Amsterdam, April 2009), (http://www.bankofengland.co.uk/publications/Documents/speeches/2009/speech386.pdf).
- Andrew Haldane and Robert May, "Systemic risk in banking ecosystems", *Nature* 469 (2011) 351–355; see also Neil Johnson, "Proposing policy by analogy is risky", *Nature* 469 (2011) 302
- Thomas Lux, "Network theory is sorely required", *Nature* 469 (2011) 303.
- Didier Sornette and Suzanne von der Becke, "Complexity clouds finance-risk models", *Nature* 471 (2011) 166.
- John Liechty, "Scientists and bankers – a new model army", *Nature* 484 (2012) 143.

These papers, grouped together here as a series, develop the theme of systemic risk outlined in May *et al.* (2008). Haldane, Executive Director for Financial Stability at the Bank of England, analyses the world financial system as a complex adaptive network, and concludes that "sharp discontinuities in the financial system were an accident waiting to happen." His recommendations include:

- Restructuring the network to reduce its dimensionality and complexity;
- Learning from epidemiology to seek actively (by regulation) to vaccinate the "super-spreaders" to avert financial contagion; and
- Increased openness in making information available to planners and the public.

In the wake of the financial crisis that began in 2007, Haldane and May offer a concrete analysis of systemic risk in the global banking system. They make the point that a substantive difference between the evolution of ecosystems (the "winnowed survivors of long-lasting evolutionary processes") and financial systems, where "evolutionary forces [including the hand of government] have often been survival of the fattest rather than survival of the fittest." Following careful analysis of many concrete examples, their two main recommendations are:

- Increased diversity across the system as a whole (as opposed to "diversification" of individual institutions, which actually results in decreased diversification across the system); and
- Breaking the system up into modular units to prevent contagion infecting the whole system in the event of nodal failure.

Finally, the journalist John Liechty, likening the financial system to a badly balanced ship trying not to capsize in a storm, has emphasised that a key element in restructuring must be for banks and other financial institutions to be much more open with the public and with each other, and to "engage with scientists to build the infrastructure needed to price system-wide risk".

Nick Rosen, "Why India's Power Grid Collapsed", *Energy* (2012), (http://www.off-grid.net/2012/08/05/why-indias-power-grid-collapsed-and-what-to-do-about-it/).

Anna Saumell-Mendiola, M. Ángeles-Serrano and Marián Boguña, "Epidemic spreading on interconnected networks", http://arxiv.org/abs/1202.4087 (2012).

Quirin Schiermeier, "Models hone picture of climate impacts", *Nature* 482 (2012) 286.

A description of the Inter-Sectoral Impact Model Intercomparison Project (ISI-MIP) for modelling future climate change and validating predictions by having more than two dozen groups using different models to make predictions from the same set of data.

The FuturICT project, "Participatory Computing for our Complex World", (http://www.futurict.eu/).
An ambitious focal point for a global programme of modelling and data-collecting of the world's socio-economic-ecological systems.

**C. Policy and governance**

IRGC, *Risk governance – towards an integrative approach*, white paper (2005).

IRGC, *Introduction to the IRGC risk governance framework* (2008).

David Etkin and Elise Ho, "Climate Change: Perceptions and Discourses of Risk", *Journal of Risk Research* 10 (2007) 623–641.
An excellent summary of the issues that affect risk awareness with respect to climate change.

Roger A. Pielke, Jr, *The Honest Broker*, Cambridge, Cambridge University Press (2007).
An excellent exposition of the point of view that scientists must act as independent "honest brokers" in the marriage of science and policy.

William Brock, Stephen Carpenter and Marten Scheffer, "Regime Shifts, Environmental Signals, Uncertainty and Policy Choice", in *Complexity Theory for a Sustainable Future*, Columbia University Press (2008).
"The problem of model uncertainty is fundamental to science-based disagreements about environmental policy" say the authors. "We believe our review of new literature on estimation techniques and dealing with model uncertainty should be useful for both scientists who must report to policymakers and to policymakers who must make demands on scientists to present their results in an understandable manner … together with an honest reporting of the true level of uncertainty." Unfortunately, and perhaps rightly, the authors do not come to any firm conclusion about how best to proceed, except for one key point, "discounting past observations is important to avoid Bayesian posteriors (i.e. expectations based on past information) being frozen by history when the system approaches a bifurcation point. Discounting is important because the distant past contains less information about an impending bifurcation than the recent past. Practical implications: flexible management and policy development are essential to deal with upcoming critical transitions. The possibility of such transitions should also be a signal for an immediate increase in information collecting and assessment.

Stephen Carpenter, Carl Folke, Marten Scheffer and Frances Westley, "Resilience: Accounting for the Noncomputable", *Ecology and Society* 14 (2009).
The authors present a strong argument for the use of information and opinion from multiple diverse sources to anticipate and deal with critical transitions, and offer many real-world examples, including some from ecology where the problem could not have been solved without inputs from illiterate villagers and indigenous fishermen. They point out that "… the dominant models [to understand such transitions in complex situations] are a patchwork of rigorous but fragmented information [and there is] a tendency toward monoculture or the dominance of a few [expert views]." "Perhaps counter-intuitively" they say "[complex] problems may be solved better by a diverse team of competent individuals than by a team composed of the best individual problem solvers." Practical implications: governance is best served by using teams with a real diversity of experience, knowledge and understanding. The practical problems are how to select such teams, bring them together, get them working effectively, and (especially) persuading those responsible for policy to act on the outcome.

Spyros Makridakis and Nassim Taleb, "Decision making and planning under low levels of predictability", *International Journal of Forecasting* 25 (2009) 716–733.
A devastating, evidence-based criticism of the common beliefs among policymakers and the general public alike that accurate forecasting is possible and that errors in forecasting can be reliably assessed.

Elinor Ostrom, "A General Framework for Analyzing Sustainability of Social-Ecological Systems", *Science* 325 (2009) 419–422.
Ostrom lists the requirements for groups of resource users/exploiters to "self-organise" so as to maintain sustainability of the resource and avoid the tragedy of the commons. Specific recommendations include:

- Appropriate group size (dependent on the nature of the resource and the resources needed to manage it);
- Respected leadership;
- Shared moral and ethical standards across the group;
- Shared knowledge of how the socio-ecological system functions;
- A high value of the resource to its exploiters (e.g. users may be dependent on the resource for a substantial portion of their livelihoods, with no obvious alternative on offer); and
- Autonomy at the collective-choice level to craft and enforce rules.

Frank Biermann *et al.*, “Navigating the Anthropocene: the Earth System Governance Project strategy paper”, *Current Opinion in Environmental Sustainability* 2 (2010) 202–208; “Navigating the Anthopocene: Improving Earth System Governance”, *Science* 335 (2012) 1306–1307.

These two pieces are the outcome of the Earth System Governance Project, a ten-year social science based research programme. The major conclusion is that incremental change (the main approach since the 1972 Stockholm Conference on the Human Environment) “is no longer sufficient [was it ever?] to bring about societal change at the level and speed needed to mitigate and adapt to Earth system transformation. It suggests instead seven building blocks for future policy:

- Upgrading of UN environmental agencies and programmes;
- Strengthening the integration of the social, economic and environmental pillars of sustainable development (through creating a high-level UN Sustainable Development Council directly under the UN General Assembly;
- International regulation of emerging technologies;
- Stronger emphasis on planetary concerns in economic governance;
- Majority-based decision-making at the international level;
- Stronger intergovernmental institutions; and
- Equity and fairness in economic distribution between rich and poor countries.

At no point does the report say how these aims might be achieved in practice, nor does it mention the underlying problem of population growth or the problems revealed by game theory (such as the tragedy of the commons) that would disrupt the implementation of almost all of these proposals (see, for example, William A. Brock and Steven N. Durlauf, “Discrete Choice with Social Interaction”, *Review of Economic Studies* 68 (2001) 235–260, (http://www.jstor.org/stable/2695928); Len Fisher, *Rock, Paper, Scissors: Game Theory in Real Life*, New York, Basic Books (2008)).

Dirk Helbing and Stefano Balietti, “Fundamental and Real-World Challenges in Economics”, arXiv:1012.4446v1 (20 December 2010).

In this important article the authors set out a future research programme for economics, analogous to the well-known Hilbert programme in mathematics, which listed the 30 most important unanswered questions at the beginning of the 20th century (27 of which have now been answered!). They argue that traditional economics (based on the mythical Homo economicus) has failed to predict crises, and that future research needs to focus both on real human behaviour and on the emergent properties of complex systems; in particular:

- Multi-disciplinary input and genuine interdisciplinary research;
- Computational modelling, especially agent-based modelling;
- Testable predictions and their empirical or experimental validation;
- Managing complexity and systems engineering approaches to identify alternative ways of organising financial markets and economic systems; and
- Advance testing of economic and organisational innovations for effectiveness, efficiency, safety and systemic impact (i.e. side effects) before they are implemented.

Albert Faber and Floortje Alkemade, “Success or failure of sustainability transition policies. A framework for the evaluation and assessment of policies in complex systems”, DIME Final Conference, Maastricht, arXiv preprint (2011).

The Dutch Government is one of the few to have put in place (since 2001) a policy to facilitate transformation of the socio-economic-ecological system towards one that is more sustainable in the long term. This “transition policy” has so far been evaluated with regard to cost-effectiveness and meeting targets. The authors argue that these traditional evaluation criteria are inappropriate for complex systems because of the systemic character of change (which evokes inherent uncertainties), long time horizons, and multiplicity of actors and processes. They propose an alternative framework (below) that could be used as a model for all policy development in complex systems, with different policy approaches depending on whether the system is in a dynamic stable state, approaching a critical transition or undergoing an “adaptive cycle”.

| Complexity dimension | Conceptual approach | Policy approach | Transition assessment toolbox |
|---|---|---|---|
| **Dynamic stable states** | The use of system options to explore alternative system states | Problem perception | Research, communication and campaigning are important policy tools to support such policy-endorsed erosion of the present regime. For the purpose of our transition evaluation, we will qualitatively aim to identify such activities. |
| | | Developing attractive alternatives; guidance of direction | first, identify and assess the presence of future visions on the transition topic in terms of the three characteristic features. Second, assess the level of policy adherence and articulation of alternative sustainable future visions. |
| | Selection pressures at various levels | selection pressures at landscape level | development and application of fiscal and regulatory instruments. Leverage change on the (landscape) level of the selection environment, rather than the selection mechanism itself |
| | | selection pressures at regime level | support public debate and the use of visions at the regime level. |
| | | selection pressures at niche level | endorse strategic niche management at the niche level. Aim to endorse experimentation at a relatively small scale, and learn from that in terms of innovation as well as policy on a larger scale |
| **Thresholds** | Early warnings | Development of early warning systems | use early warning systems such as scenario studies to explore possible threshold positions and to identify key system drivers |
| | | Recognition of endogenous system rigidities | recognize system rigidities and aim to reduce system tension by developing potential alternatives connections; overcome vested interests by shifting the selection environment. |
| **Adaptive cycle** | Adaptive capacity through resilience | Diversity | account for a transition portfolio that ensures a diversity of strategies in order to maintain options for the future and hence adaptive capacity. |
| | | Distributed decision making | ensure to aggregate grassroots knowledge and participatory governance |
| | Evolutionary policy making | Exploration | stimulate the generation of novely and innovation |
| | | Exploitation | create the development of a proper selection mechanism, that aligns with the long-term transition perspective. Institutionalize policy learning in order to replicate successes and learn from failures |
| | Timing | Time strategy, windows of opportunity | develop a time strategy to recognize and to anticipate on windows of opportunity |

Rees Kassen, “If you want to win the game, you must join in”, *Nature* 480 (2011) 153.

Stephen Polasky *et al*., “Decision-making under great uncertainty: environmental management in an era of global change”, *Trends in Ecology and Evolution* 26 (2011) 398–404.

Classical decision theory is of little use as a guide to policy in complex adaptive systems, since it requires knowing the probabilities and pay-offs for the outcomes of different policies, and can “lead analysts and decision-makers to focus too narrowly on issues with sufficient current data and understanding to permit analysis”. In complex adaptive systems the multiplicity of possible outcomes and the existence of large gaps in our knowledge make this approach virtually impossible in any case. The authors suggest supplementing the classical approach, or even replacing it, with adaptive management, using three guiding principles (see text). These approaches can be used separately or in tandem. All of them can benefit from improved system modelling and/or early detection of warning signs, but can also be implemented independently of these.

Len Fisher, “Shaping policy: Science and politics need more empathy”, *Nature* 481 (2012) 29.

Marie-Valentine Florin and Len Fisher, “Risk governance of slowly developing catastrophic risks”.

A talk delivered to the conference “Planet Under Pressure” (London, 28 March 2012).

Len Fisher and Marie-Valentine Florin, “Risk governance of slowly developing catastrophic risks”.

A talk delivered to the annual conference of the European Society for Risk Analysis (Zurich, 18 June 2012).


### D. General


René Thom, *“Structural Stability and Morphogenesis”*, Massachusetts, Benjamin-Cummings (1973).

Thom identifies seven “elementary” catastrophes as being the only ones possible in a system specified by no more than four variables. These can be represented geometrically, sometimes with evocative names (e.g. “fold”, “cusp”, “swallowtail”) and beautiful images (Salvador Dali used one in *The Swallow’s Tail*). Despite early over-enthusiastic use (especially by sociologists), catastrophe theory remains fundamentally sound, although now largely replaced by non-linear dynamics and bifurcation theory.

Stephen Wolfram, “Complex Systems Theory”, (1984), (http://www.stephenwolfram.com/publications/articles/ca/84-complex/2/text.html).

Wolfram’s argument in this seminal paper (expanded in his book *A New Kind of Science* (Champaign, Illinois, Wolfram Media Science, 2002) is that the many complex systems, especially in the natural world, are “computationally irreducible,” so that to predict their behaviour one can only sit back and watch the evolution of the real system, which effectively acts as its own computer model. “The development of an organism from its genetic code” he offers as an example “may well be a computational irreducible process. Effectively the only way to find out the overall characteristics of the organism may be to grow it explicitly. This would make large-scale computer-aided design of biological organisms, or ‘biological engineering’, effectively impossible: only explicit search methods analogous to Darwinian evolution could be used.” There have been many critical analyses of Wolfram’s arguments, most notably by Leo Kadanoff (arXiv:nlin/0205068v1) and Mohamed Gad-el-Hak (*Applied Mechanics Reviews* 56 (2003) B18–B19). Fortunately, his pessimistic prediction has been overtaken by events, most notably the development of computers sufficiently powerful to analyse realistic models on the basis of realistic assumptions.

Daniel Sarewitz and Roger A. Pielke, Jr, “Breaking the Global Warming Deadlock”, *The Atlantic Monthly* 286 (2000) 54–64.

Malcolm Gladwell, *The Tipping Point*, Back Bay Books (2002).

D. Sornette, *Why Stock Markets Crash (Critical Events in Complex Financial Systems)*, Princeton University Press, Princeton, NJ (2002).

Lenore Fahrig, “Effects of Habitat Fragmentation on Biodiversity”, *Annual Review of Ecology, Evolution, and Systematics* 34 (2003) 487–515.

Chris Rose and Jean Gordon, “Internet Security and the Tragedy of the Commons”, *Journal of Business and Economics Research* vol.1 (11) (2003)67–72.

Didier Sornette, “Critical Phenomena in Natural Sciences, Chaos, Fractals, Self-organization and Disorder: Concepts and Tools”, second edition, Springer Series in Synergetics, Heidelberg (2004).

A reference for critical phenomena applied to many fields of science; a chapter on predictability and precursors of crises.

Luisa Maffi, “Linguistic, Cultural, and Biological Diversity”, *Annual Review of Anthropology* 34 (2005) 599–617.

Nassim Taleb, *The Black Swan* (2007); second edition, Penguin Books (2010).

Famously presents the argument that major changes cannot be foreseen because they arise from rare, unusual and therefore unpredictable events ("black swans"). Practical implications: for endogenous transitions, none, because Taleb is referring by (implication) only to exogenous transitions.

Richard N. Cooper, "Global Imbalances: Globalization, Demography, and Sustainability", *The Journal of Economic Perspectives* 22 (2008) 93–112.

Elena Meschi and Marco Vivarelli, "Trade and Income Inequality in Developing Countries", *World Development* 37 (2009) 287–302.

G. Nicolis and C. Nicolis, "Foundations of Complex Systems", *European Review*, vol. 17 (2009).

An excellent discussion (mainly non-technical) of the ways in which complex adaptive systems involve "the emergence of traits encompassing the system as a whole, that can in no way be reduced to the properties of the constituent parts [and where] order and coherence are ensured by a bottom-up [self-organisation] mechanism rather than through a top-down design and control.

G. A. Tularam and M. Krishna, "Long-term Consequences of Groundwater Pumping in Australia: A Review of Impacts Around the Globe", *Journal of Applied Science in Environmental Sanitation* 4 (2009) 151–166.

Peter W. Williams and Ian F. Ponsford, "Confronting tourism's environmental paradox: Transitioning for sustainable tourism", *Futures* 41 (2009) 396–404.

Robert C. Moellering, "NDM-1 – A Cause for Worldwide Concern", *New England Journal of Medicine* 363 (2010) 277–2379.

Dan I. Andersson and Diarmaid Hughes, "Persistence of antibiotic resistance in bacterial populations", *FEMS Microbiology Reviews* 35 (2011) 901–911.

Michael G. Arghyrou and John D. Tsoukalas, "The Greek Debt Crisis: Likely Causes, Mechanics and Outcomes", *The World Economy* 34 (2011) 173–191.

Jared Diamond, *Collapse: How Societies Choose to Fail or Succeed* (2005); second edition, Penguin Books (2011).

T. R. Walsh *et al.*, "Dissemination of NDM-1 positive bacteria in the New Delhi environment and its implications for human health: an environmental point of prevalence study", *The Lancet* vol. 11 (May 2011).

Carole Dalin *et al.*, "Evolution of the global virtual water trade network", *Proceedings of the National Academy of Sciences of the United States of America* 109 (2012) 5989–5994.

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# About IRGC

The International Risk Governance Council (IRGC) is a non-profit and independent foundation whose purpose is to help improve the understanding and governance of systemic risks that have impacts on human health and safety, on the environment, on the economy and on society at large. IRGC's mission includes developing concepts of risk governance, anticipating major risk issues, and providing risk governance policy advice for key decision-makers. To ensure the objectivity of its governance recommendations, IRGC draws upon international scientific knowledge and expertise from both the public and private sectors in order to develop fact-based risk governance recommendations for policymakers. IRGC operates as an independent think-tank with multidisciplinary expertise and can help bridge the gaps between science, technological development, policymakers and the public. IRGC acts as a catalyst for improvements in the design and implementation of risk governance strategies that can be effective in today's challenging governance environment.

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