# Approaching the tipping point: critical transitions in systems

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## Abstract

*For complex dynamic systems there are a limited number of transition paths to shift from their normal system state into a catastrophic system state. In the present paper, the time development for five generic types of paths have been identified and analyzed. Here, concepts of systems science are linked to observations in human-environment-systems and ecosystems. These generic paths allow analyzing systems from a systemic perspective of how their critical threshold is reached.*

**Keywords**: Catastrophe, Disaster, Transition, Critical Threshold, Tipping Point, Generic Structures, Cybernetics 2nd order

## 1. Introduction

Many complex dynamic systems have critical thresholds where, when a tipping point is passed, the system shifts to another state. In this new state the system either collapses or cannot be sustainable maintained. For instance, after centuries of deforestation of the Easter Islands by its inhabitants there were at one point in time (tipping point) no trees left, which caused a strong population decline after a long period of growth. An up-to-date topic, where a collapse is likely to occur, is the depletion of non-renewable resources such as fossil oil. At one point in time, the resource is depleted and our transportation system (cars, airplanes) that is build on fossil oil changes dramatically.

Current catastrophe exploration mostly concentrates on special catastrophe phenomena caused by forces of *nature*, e.g., volcanic eruptions, storms, epidemics or malfunction of *technical systems*, such as accidents in traffic or transportation (e.g., Kaprun disaster, where a fire in a railway car killed more than 150 people) or industry (e.g., Bhopal disaster, where leaking gas out of a pesticide plant caused the death of several thousand people). Generally, researchers operating in their specific fields concentrate on a special type of catastrophe or a single catastrophic event and do not abstract generic types of how the catastrophe emerges.

There are also several rather interdisciplinary approaches towards catastrophe research. These can be attributed to *social science* and *natural science*.

### *Interdisciplinary catastrophe research in social science*

- The *Sociology of Disaster* [Clausen et al. 2003, Quarantelli 1998] is a special branch of sociology aiming to build a sociological theory of catastrophes. Yet, this theory is limited to social systems and sees catastrophes only as extremely accelerated events. Furthermore, they introduce some questionable concepts, for example a ritualizing factor that describes how far a catastrophe can be seen as a magic incident [Clausen 2003].
- *Economic catastrophe research* [Dacy & Kunreuther 1969, Mileti 1999] is done by, e.g., economists or insurance companies. Yet, their focus lies on modeling techniques to assess the likeliness (in terms of probability) of a catastrophe to happen and the associate costs involved.

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- *Organizational catastrophe research* [Perrow, 1992; Weick 1990; Vaughan 1996] is focused on accidents in high-risk industries that are inevitable consequences as we build and use them. Thus, Perrow [1992] uses the term “normal accidents” to describe them. Yet, the organizational catastrophe research is basically limited to technical systems or where technical systems are being used.

***Interdisciplinary catastrophe research in natural science***

- *Self-organized criticality* [Bak et al. 1987, Turcotte 1999, Ricotta et al. 1999, Seuront and Splimont 2002, With and King 2004] originates as a concept to explain results in a cellular automata model [Wolfram 2002] that analyzed sandpile avalanches. Turcotte [1999] gives the following working definition for self-organized criticality *“a system is in a state of self-organized criticality if a measure of the system fluctuates about a state of marginal stability”* [p.1380]. As an example, he describes for the sandpile model that the input is addition of sand grain and the resulting output is the sand avalanche. The results of self-organized criticality promise similar behavior for broad conditions in case of physical phenomena such as earthquakes or landslides and incidents in biological systems such as epidemics. Yet, for other fields, especially these in social science, the application is controversial as complex interactions, feedbacks and delays between the system elements are insufficiently inherent in the model.
- *Phase transitions* [Kizner et al. 2001, Tainaka 1996] describes the transformation of a thermodynamic system under certain conditions. For example, the heating of water to the boiling point. Beyond the boiling point the water changes into vapor. Yet, this concept of transition is used almost exclusively for physical systems using thermodynamic principles.
- *Catastrophism* is a concept in astronomy, geology and paleontology that describes how our life on Earth is influenced by catastrophic events. Changes do not occur gradually over geological epochs but at fast pace and irreversible. It became popular when Alvarez et al. [1980] showed that around 65 million years ago an asteroid hit the Earth, which led to the extinction of the dinosaurs. Yet, this concept looks exclusively at geological eras.
- Theories of *bifurcations* observe sudden shifts in behavior of systems, which origin from small changes in circumstances. Especially, the so called ‘catastrophe theory’ [Thom 1975, Zeeman 1977] gained popularity. After inappropriate applications, the theory vanished from the scene but regained part of its popularity in recent years [Rosser 2007]. Yet, nowadays people using the theory or special parts of it try to avoid the term as far as possible and use a different terminology. For example Scheffer and Carpenter [2003] talk of ‘catastrophic bifurcations’. The current research in ‘catastrophe theory’ looks for early warning signals for critical transition [Scheffer et al. 2009, Dakos 2009]. Drake and Griffin (2010) show in a controlled experiment with populations of *Daphnia magna* (water fleas) that were subjected to decreasing food levels that a critical slowing down occurs, which *“refers to the decreasing rate of recovery from small perturbations to a population’s expected trajectory in the vicinity of a tipping point”* [p.456]. Supporter of this theory claim that complex dynamical systems such as ecosystem, financial markets or the climate has generic early-warning signals if a critical threshold is approached. Scheffer [2010] suggests, based on the Drake and Griffin study that generic leading indicators should be found to show whether a complex system is soon to collapse or not. Yet, bridging the gap between a simple controlled laboratory experiment and the real world (e.g., determining a stock market crash in advance) is in the fledging stage.

Thus, existing catastrophe research is limited:

1. Most catastrophe research concentrates solely on special catastrophe phenomena (e.g., volcanic eruption),
2. Interdisciplinary catastrophe research is limited to a certain field (e.g., technical systems and thermodynamics) or still in a very early stage and developed theories and concept cannot be applied to complex dynamic systems.
3. Furthermore, on a different level, another problem of existing catastrophe research is that the methods used are often difficult and not intuitively. For example, in order to use bifurcation theory for studying systems a solid mathematical knowledge is needed, which limits the application to a small (scientific) community.

Therefore, concepts and methods of systems science [e.g., Bertalanffy 1984, Forrester 1980] might be a helpful to build general applicable concepts to understand underlying structures why and how catastrophes occur or allow analyzing systems according to their catastrophe potential. Catastrophes are often not caused by a single cause but result by a combination of various causes and can be, especially in social or natural systems, be counter-intuitive [Forrester 1971]. For example, the usage of pesticides might kill the pest harming the crop but may be as well killing or harming animals and humans [Dörner, 2009]. Hence, in the sense of the *philosophy of science,* having generic transition path structures allows deducing from general to specific catastrophe cases – and thus catastrophes can be explored systemically. However, such generic transition paths structures of how catastrophes emerge do not exist.

The present paper aims to present generic transition path of catastrophes from a systemic perspective. The generic transition paths of catastrophes function on a diagnostic as well as strategy and theory building level [Kim 2000]. On a *diagnostic level* the current development of systems towards catastrophe development can be monitored and estimated. On a *strategic level* they allow to look ahead and give clues how our actions might affect the system over time. On a *theory level,* as they are abstracted pictures of reality that are beyond the specifics of an individual case, conceptualizing generic forms of, e.g., catastrophe management, is possible.

Regardless of whether the genesis and development over time towards a catastrophe is man-made or natural, there are only few features to transit from normal system state to the critical threshold and enter the catastrophe system state. This might happen by an individual linear or reinforcing process as well as due to a bifurcation, cascade, or multiple independent events or in a combination of several of them. In a causal system (not based on a symptom level) dealing with (potential) catastrophe situations makes it necessary to know the system structures and dynamics that cause catastrophes to happen. Thus, abstracting the complex emergence of catastrophes to its time-behavior extends existing generic catastrophe research, which might help to formulate a systemic theory of catastrophes in the future.

In order to determine which transition path structure is the underlying one for the observed catastrophe it is necessary to determine the position and time-frame of the observer. For example, the Tōhoku earthquake and tsunami happened on 11. March 2011. For a seismologist observing in a far away area the process towards a tectonic earthquake is normally a long process that happens when at the plate boundaries several plates get cant and stuck and tension builds up over time. In one point in time, the tension exceeds the shearing resistance and gets fitfully released in form of an earthquake. For a person living in that area and being surprised by a sudden earthquake and a tsunami without (or only at very short notice) warning signals and loosing house and property the earthquake is percept very different and far more abruptly. Both, the seismologist and the person hit by the earthquake, are observing the same tectonic earthquake but their time horizon and position of their observation is fundamentally different. Following second-order cybernetics [von Förster, 2003] that investigates systems with the awareness that the observer of the systems has to be explained as well, it is necessary to take these differences into account to determine the transition path structure. Thus, for determining the transition path of a catastrophe it is necessary to determine the observer position and observing time-frame in the forefront.

In order to identify the generic catastrophe transition paths different kinds of catastrophe phenomena were abstracted. Following the *Occam's Razor* principle the "real" observable catastrophes were reduced to main distinctive features to retain for the generic structure building relevant information. For developing and displaying the five different types of transition paths the *reference mode* concept is used. Furthermore, the *cybernetic second order principle* is applied as it is necessary to determine the observer viewpoint to make a statement about the transition type.

There are manifold definitions of what a catastrophe is. Furthermore, there is no clear conceptualized border to the term disaster. In this paper we do not define the meaning of catastrophe but we look at the transition path towards the critical threshold – the shifting of a system from system state normal to system state catastrophic when passing a critical point. The process towards this critical point is the transition path. A system that passed the critical point will either collapse or not exist sustainable in this form. To re-enter the system state normal and get back to the initial system state is either impossible (if the system collapsed) or conjoined with efforts that increase over time.

In the following section, the methodological approach to build the transition paths is described. Section 3 introduces five generic transition paths with examples. Section 4 discusses the findings towards their contribution to understand catastrophes. Section 5 concludes.

## 2. Methodological Approach

The transition paths described show how a system shifts from a normal system state into a catastrophic system state. Figure 1 illustrates the basic principle. To begin a system is stable and holds a position between $t_0$ and $t_1$. Yet, due to some external interfering dynamics that act upon the system state normal, which are not or only hardly visible in the system behavior, the system reaches a critical point (tipping point). If this critical point is passed, the system starts tending away from its stable position (equilibrium), either up (e.g., C1 and C2) or down (e.g., C3 and C4). In the stable position the system is sustainable, in the unstable position the system either collapses or is not lasting sustainable. The moment, the system leaves its equilibrium position, it enters the catastrophic state.

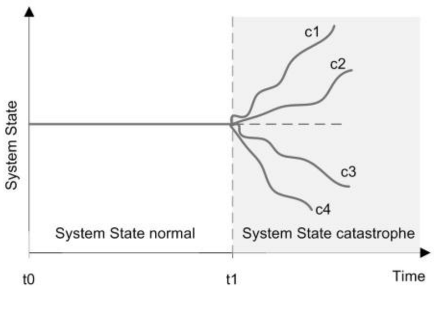

**Figure 1:** Transitions in the System State

To illustrate the transitions, the *reference mode* concept (Figure 1) is used (Wolstenholme 2000, Radzicki 1992, Sterman 2000). This concept allows patterning the behavior over time. In the modeling process, the reference mode gives reference to shape, model boundaries, and, when simulating, verification. The reference mode displays the basic behavior of a system without focusing on a too short time horizon or onto specific events. By looking at the system behavior of time of various catastrophes similarities and differences can be determined that present generic catastrophe transition paths.

When analyzing the transition of a catastrophe the system observing the catastrophe has to be observed as well; this is called second-order cybernetics (v. Foerster 2003). First order cybernetics investigates systems as if these are passively objects that can be fully studied and handle, which might be appropriate for solely technical systems. Second order cybernetics investigates social or natural systems where the system is an agent in its own rights and interacts with some other agent, the observer (Heylighen & Joslyn 2001). Thus, the observer viewpoint has to be set in order to set the transition path structure.

## 3. Results

The following sub sections discuss the five generic types of possible catastrophe transition paths. Box 1 gives an overview of these five transition paths.

**Box 1:** Different types of catastrophe transition paths

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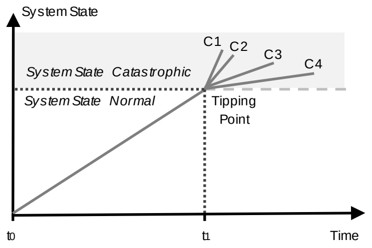
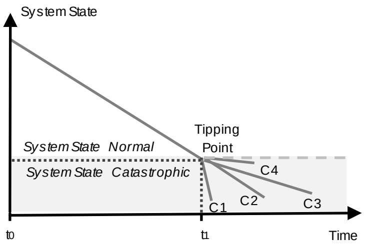
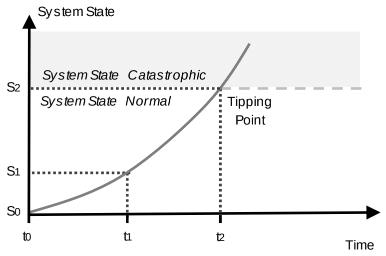
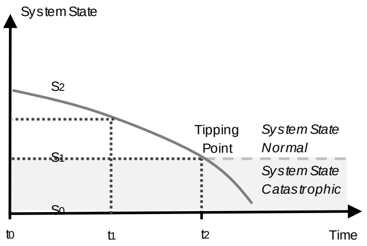
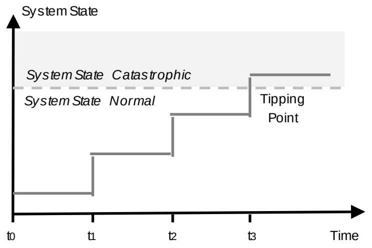
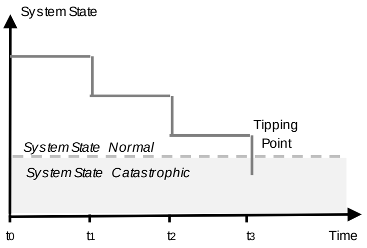
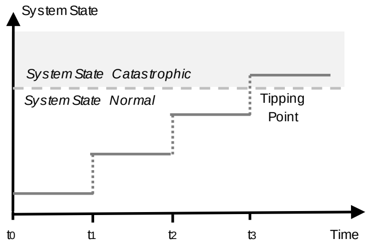
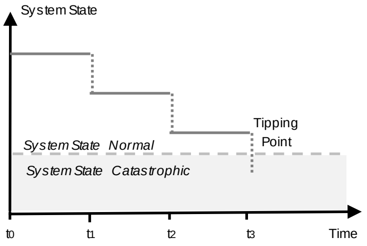
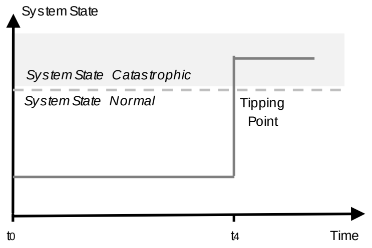
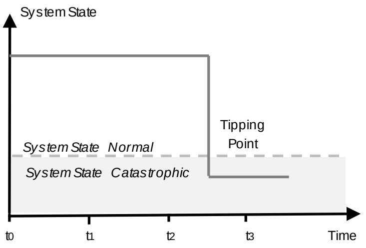
|  |  | **1. Linear**<br>A linear catastrophe transition is a continuous process *without* feedback from the changing system. |
|  |  | **2. Reinforcing**<br>A reinforcing catastrophe transition is a continuous process *with* feedback from the changing system. |
|  |  | **3. Cascade**<br>A cascade catastrophe transition represents a chain of events where each event *builds up on the previous one*. |
|  |  | **4. Multiple Independent**<br>A multiple independent catastrophe transition represents a chain of events where each event *is independent from the other ones*. |
|  |  | **5. Bifurcation**<br>A bifurcation catastrophe transition represents *a single shift*. |

### *1. Linear*

*Description:* Linear growth or decline is a rare and special form of system behavior as there is no feedback from the system towards the net in- or decrease rate. Thus, the net in- or decrease rate is constant. For example, filling a bathtub with water from a faucet (continuous) or cashing up products that have been placed in a market on a conveyor belt (discrete). Yet, normally systems appearing linear to us rather behave exponentially. The main reason that they appear linear to us is because we are looking at them for a too short time horizon and the actual reinforcing behavior is not seen yet (Sterman, 2000). Perrow (1992) describes linear interactions as simple and transparent that can be understood intuitively.

In context of this paper linear behavior refers to a constant (either continuous or discrete) flow of a single element (e.g., water when filling a bathtub) or the measurement of a single indicator (e.g., money when summing up products) that affects the system leading to a catastrophe. Note that there is no feedback from the system state towards increase or decrease rate. In Box 1 the linear catastrophe principle is illustrated. Here, the system state continuously increases linear from $t_0$ to $t_1$. However, at $t_1$ the tipping point is reached and the very moment this point is passed, the system enters the *System State Catastrophic*. The behavior from this point on depends on the observed system; C1, C2, C3, and C4 show possible ways how the system develops then further.

*Example:* A linear indicator growth is the rise in water temperature of rivers or creeks. The rise and decline of temperature is a normal periodic winter-summer phenomenon. However, in recent years there had been extreme heat waves in large parts of Europe that are often associated with climate change. Especially, ecosystems such as glaciers and alpine regions are affected. For example the brown trout population in Alpine rivers and streams has declined from 1990 to 2005 by 50% [Hari et al. 2006]. Increasing water temperature is assumed to be the main factor. Maximum growth rate occurs at temperatures between 13 °C to 14 °C. Population growth declines by temperatures below around 3 °C and above around 19 °C (Elliott & Hurley 2001). At temperatures above 15 °C mortality rises due to an infectious kidney disease [Chilmonczyk et al. 2002]. Brown trout can survive higher temperature shortly. The highest lethal temperature is at around 29 °C, at which brown trout survive for 10 minutes [Elliot 1981, cit. in Hari et al. 2006]. In the brown trout example, two temperature depending critical points can be determined to switch the system from normal to catastrophic system state. Either the temperature falls below 3 °C degree or the water temperature rises above 19°C. In both cases the population size falls.

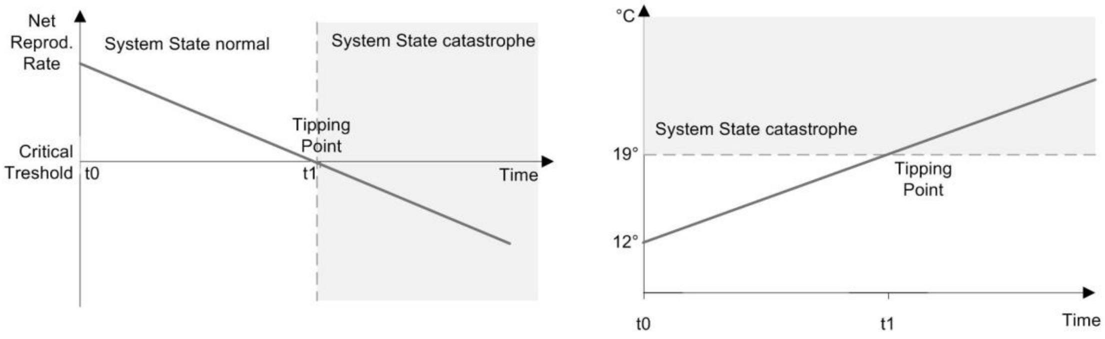


**Figure 2:** Linking rising temperature to net reproduction rate

Figure 2 illustrates the relationship of rising temperature (right) and the sinking of the brown trout net reproduction rate (left). The graph on the right shows the linear increase of water temperature. Starting with 12 °C at $t_0$, the temperature rises constantly within the system state normal. Yet, after a while, the temperature approaches 19 °C at $t_1$. If this temperature is passed the system enters the catastrophic system state since here the net reproduction rate falls below a critical level, where the population cannot be maintained. The graph on the left displays the actual fall of the net reproduction rate. Thus, from $t_0$ to $t_1$, depending on the net reproduction rate, the system is sustainable. As $t_1$ gets passed, the net reproduction rate passes a critical threshold (tipping point) and the system enters from system state normal into system state catastrophic.

### *2. Reinforcing*

*Description:* Reinforcing behavior is due to an enhancing feedback loop in a system. The larger the state of the system, the higher the effect of the net increase rate, and in turn, the net increase rate has a positive effect on the state of the system, which results in a escalating feedback loop. The behavior is not necessarily positive. It can also be negative, as the escalating feedback loop creates a self-reinforcing decline. If there is solely an escalating feedback loop, the system grows exponentially. Exponential growth has one important property: the doubling time. It takes the same amount of time to grow from 1 to 2 as it takes to grow from 1,000,000 to 2,000,000 (Meadows et al. 2004). The second figure in Box 1 shows the escalating growth of a system. Here, the system shifts from $S_0$ to $S_1$ slowly but steadily during the time interval $t_0$ to $t_1$. During the next time interval $t_1$ to $t_2$, which has the same length as the previous, the growth increased due to reinforcing processes in the system.

There are two concepts of an escalation with one major difference (Richardson, 1991). The first one originates from an outside factor that initiates and heats up the escalation. The second one originates from internal dynamic processes that heat up without an external factor. Generally speaking, the reinforcing behavior origins by dominating positive feedback loop that behaves as a “vicious circle” by destabilizing the system (either growth or decline) in an unintended manner. There is not such a thing as origins or unilateral causes but rather causal feedback loops.

### *3. Cascade*

*Description:* A cascade effect (also referred to as chain reaction or domino effect and in case of an upswing referred to as avalanche effect) in our context describes, how different processes gradually build up, whereupon the second process builds up on the first, the third on the second and so on. The meaning originates from the Italian word *cascata* that describes a stepwise waterfall. In Box 1 the general concept of a cascade catastrophe is illustrated. At $t_0$ the system is in equilibrium position. Then at $t_1$ an interference occurs and the system state goes up, yet still in the *System State Normal*. Another upswing occurs at $t_2$ but the system is still in the *Normal System State*. At $t_3$ a further upswing happens and the system state passes the critical point and enters the *System State Catastrophic*.

*Example:* A cascade effect in ecology could be the extinction of a primary species or the introduction of an invasive species that triggers the extinction of secondary species. For example, the over-crowding and collapsing of the mule deer population at the Kaibab Plateau in Arizona that was caused by the (nearly) extinction of predators which in turn lead to a quick increase (irruption) of the prey. Rasmussen [1941] describes that due to an increased usage the Kaibab Plateau resources by livestock such as cattle, sheep and horses in the late 1880s the Grand Canyon Forest Act was signed in 1893 by US President Harrison. Concrete numbers of the amount of mule deer in this time are not available. Nevertheless, in 1905 the deer population was estimated to be about 4,000. The carrying capacity of the Plateau was estimated to be about 20,000 to 25,000 deer [Young 1998]. Advancing the endeavors of his predecessor, in 1906, US President Theodor Roosevelt signed the Grand Canyon National Game Preserve Act in order to protect the deer. Not only was it now prohibited to hunt the mule deer, but it was also attempted to substantially reduce the natural enemies of the deer such as mountain lions, wolves, coyotes and bobcats. From 1922 to 1931 even wild horses were killed in order to increase the food available for domestic animals, including the deer. A further mile stone was the creation of the Grand Canyon National Park in 1919. Both Acts and the formation of the national park formed a unique combination that made it administrative difficult to change the made decisions. As a consequence, the mule deer population exploded. In 1915, it reached around 25,000. The necessity of limiting the number of deer was realized by Forest Service officials. Yet, as this information was made public, a storm of protest arose, since it was an unusual and pleasant view to see so many deer in the Plateau meadows and many people thought that the reports exaggerated. Thus, by 1924, the maximum was reached with around 100,000 deer. This was far above the carrying capacity. The deer were starving and in two successive winters, 60% of the herd died of malnutrition and related causes. As consequence, hunting became permitted and the herd was reduced to 10000 deer in 1939.

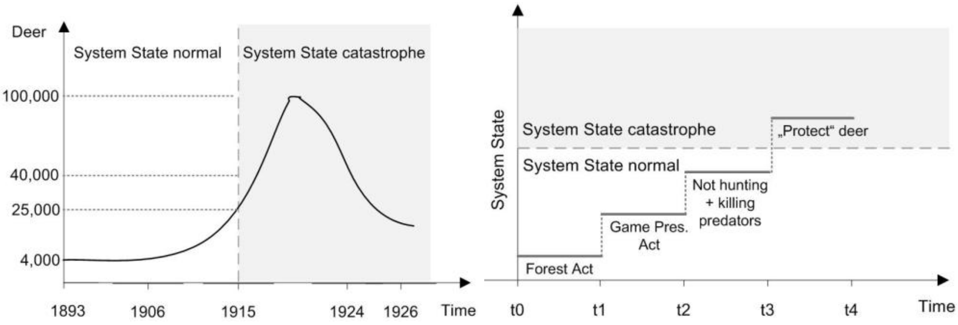


**Figure 3:** Cascade in the Kaibab Plateau

The systemic structure that leads to the overshoot and collapse behavior in the Kaibab Plateau is illustrated in the left part of Figure 3. Here, the development of the deer population in the Kaibab Plateau is shown. After 1906, the amount of deer increased steadily as they were put under protection by law and it was allowed to shoot only their predators. By 1915, they reached their carrying capacity, but due to depletion of resource stock the deer herd could grow until 1925, when they reached around 100,000 deer. Then, the system collapsed.

The right picture of Figure 3 shows the shift from System State Normal to System State Catastrophic. All actions build upon each other. The first action was signing the Grand Canyon Forest Act. The second action was signing the Grand Canyon National Game Preserve Act. The third action was killing the predators and not hunting the deer. Finally, the fourth action – protecting the deer – was responsible for the system to shift from system state normal to catastrophic. The carrying capacity was approached and it became apparent that actions against the growing mule deer herd had to be done. However, the protests against hunting the deer prevented this measurement and the carrying capacity was exceeded. At last, this cascade of events was responsible that a catastrophe happened in the formerly stable system.

### *3. Multiple independent*

*Description:* This transition path structure describes how an incoming of independent new events that do *not* entail each other [Perrow 1992, Rudolph & Repenning 2002] might lead to a catastrophe. Key aspect hereby is that these multiple independent events alone do not have a catastrophic impact, solely the amount of incoming new events leads to a catastrophe as a critical threshold is reached. In Box 1 the concept of this generic structure is illustrated. Here, at point $t_0$ an incident happened, yet the system did not change much towards catastrophic and it is still in its system state normal. At point $t_1$ and $t_2$ independent incidents happen that push the system towards the critical threshold. The system is now close to the catastrophic state. Then, at $t_3$ another incidents occurs and the system switches from system state normal to system state catastrophic.

*Example:* An example is the extinction of a species. Often not a single factor is responsible for the distinctions, but several ones that occur independent to each other. In the following, some prevalent factors are listed:

(1) *Small population*: Factors such as epidemic, fire or a small gen pool affects small populations more heavy than big ones.
(2) *Only Local Existent*: Populations that live solely in one area are more vulnerable against local risks, e.g., droughts.
(3) *Unfamiliar Pressure*: Sensitive species' are more vulnerable to, for example, an extremely hard winter (single event) or disadvantageous climatic change (new permanent condition) than resistant species'.
(4) *New competitor*: Incoming of new species that compete for the same space and food resources.
(5) *Highly specialized*: Many animals are specialized, e.g., some hummingbirds feed off one special flower. If this food source vanishes or decreases heavily so will the specialized species do as well.
(6) *Low fertility*: Animals that have a small reproductively rate need far longer to regain initial population level in case of a previous decrease.

### *5. Bifurcation*

*Description:* A bifurcation [etymologic originating from the Latin words *bi* (double) and *furca* (fork)], describes a qualitative change of a non-linear system through small changes in circumstances. Especially of interest are so called 'catastrophic bifurcations' [Thom 1975] were a catastrophe is the loss of stability in a dynamical system in form of a sudden shift. A well-known example by Zeeman [1977] describes the behavior of a stressed dog, who may respond to provoking action either by becoming cowed or becoming angry. In case of moderate stress, the dog responds in a smooth transition from cowed to angry. In case of high stress, the dog starts cowed and will remain cowed in the face of provoking action, until a fold point ('catastrophic bifurcation') is reached. From this point on, the dog switches into the angry mode and the dog will remain in the angry mode, even if the provoking action gets significantly reduced. Thus, once the catastrophe switch occurred then by just going back to initial conditions is not sufficient to switch the system back; there a two system states for the (basically) same condition set.

Research on early warning signals for sudden shifts [Scheffer et al. 2009; Scheffer and Carpenter 2003] suggests that there is a limited number of possible ways for 'catastrophic bifurcations' that are difficult to detect. Here, we will concentrate on the sudden shift itself. Box 1 shows the general bifurcation behavior. From $t_0$ to $t_1$ the system is in the normal system state. However, due to changes the system reaches a point at which it is highly sensitive. One further little change and the system switches in one step from normal to catastrophic and it stays in this catastrophic state.

*Example:* An example for a bifurcation in an ecosystem is the extinction of the passenger pigeon. Till the 18th century, the passenger pigeon was the most common bird in North America. However, the bird became heavily hunted and the population declined slowly but steadily from 1800 to 1870, followed by an extreme decline between 1870 and 1890 that finally lead to the extinction of the passenger pigeon at the begin of the 20th century. At first no signals of extinction resulted from the falling amount of passenger pigeons. Yet, at one point a minimum population for reproduction was reached, especially as those pigeons were more fertile in big than in small flocks. Killing one more passenger pigeon at this critical point produced a situation that had to lead to the extinction of the bird. Through this ultimate kill, the population of the passenger pigeon finally switched from system state normal to system state catastrophic [Fleissner 2005, Encyclopaedia Smithsonian]. Thus, at the beginning of the 20th century there was hardly a pigeon living in the wild and in 1914 the last pigeon died in Cincinnati zoo. In Figure 4 this shift is illustrated. Even though there is a heavy decline in total population, the system is still in the normal system state as the flock size is big enough to recover. Yet, at one point, here at 1890, the critical amount of pigeons is reached and with the decisive kill, the system switches.

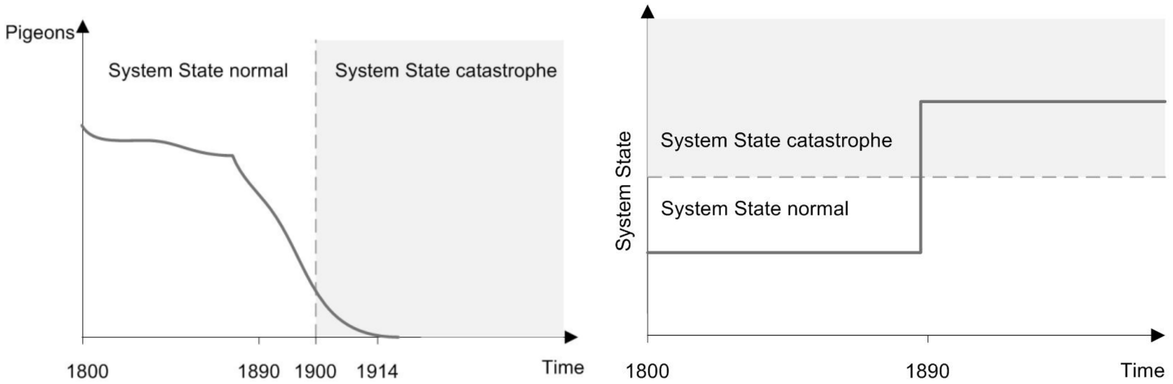


**Figure 4:** Extinction of the passenger pigeon

Extreme decline of populations is not an unique phenomenon. Plants, animals and even humans might perambulate a population bottleneck, where a large amount of the species is killed or cannot reproduce. For example the population of the alpine ibex declined heavily to due hunting to approximately 100 animals beginning of the 19th century. The ibex became protected and the population revived. Today, the population is estimated to be 30.000 to 40.000 animals. Another example is the cheetah's population. The genetic code of all cheetahs is so similar that skin transplantations can be made with only minor repulsion reactions, which is normally only the case by identical twins. Thus, it is assumed that the cheetahs population perambulated around 10.000 years ago through a severe population bottleneck where only very few cheetahs existed.

## 4. Discussion

Models are normally simplified descriptions of our perceived reality that allow us to solve problems. They are clearly focused on a purpose. Thus, models should not display a complete real world system but rather concentrate on the problem to be investigated [Sterman 2000 p.87 et seqq.]. The developed transition paths aim to display generic ways of how catastrophes emerge without concentrating on a real system.

Similarly, systems archetypes [Senge 1990] function that represent generic structures that recur again and again. There exists only a small number of system archetypes (Senge classified nine and Wolstenholme [2003] reduced the amount of archetypes even to four) with different characters and settings, yet they help to unify knowledge across fields and reoccurring plots. For Senge *"purpose of the systems archetypes is to recondition our perceptions, so as to be more able to see structures at play, and to see the leverage in those structures"* [p.95]. Wolstenholme [2004] describes systems archetypes *"as free-standing solutions to complex issues* [qualitative purpose] *and as an aid to quantitative modelling."* [p.342]. For him, *"it is important to recognise that system archetypes are first and foremost a communications device to share dynamic insights"* [Wolstenholme 2003, p.8]. However, the catastrophe transition paths do not show us the structure as the systems archetypes do. The question arises: How can the generic catastrophe transition paths be actually used and what is their purpose?

First, they allow *diagnosing* systems according to their catastrophe potential. The current situation of a system can be compared if it behaves in some manner to one or several of the transition paths. Identifying a certain type of transition in a system can help to look for leverage points in the system to reduce the risk of a catastrophe. For example, in case a cascade transition is identified it tells you to focus on the next step in the cascade and prevent this one, since each step in the cascade is needed to build the catastrophe. Second, they can function more proactively as a strategic tool for *planning*. For example, in case of having few and little effective laws that protect humans and biota from environmental pollution, question like 'what can be the consequences in the future?' or 'how does the pollution build up?' can be better answered with this concept. Thus, the different generic catastrophe paths have potential to allow looking ahead and reveal how our actions may affect the system over time. Third, they can help *building theories* in catastrophe. The paths show simplified pictures of our perceived reality. This allows giving prognoses beyond the specific case, for example, archetypical forms of catastrophe management can be designed.

However, looking at the five paths raises another question: Are there really only five paths or are there more? Basically, with the five indentified paths any type of catastrophe can be assigned to. Different paths either consist of a combination of several of them or are a subtype. One type may be not covered with these five paths: randomness. In case of randomness, we either have too little information about the system so it appears random to us or it is really random, which means if we replicate the starting situation a different end situation can happen. If we have too little information it can be one of the five proposed catastrophe paths. If it is random, there is no generic structure existent and it represents a special case.

An important finding of these generic structures is that the same catastrophe can be associated with different types of generic catastrophe paths – dependent on the viewpoint of the observer. For example, the occurrence of an avalanche in the mountains. There are several key factors for an avalanche to occur, such as gradient, hillside situation, amount of snow, temperature, and canopy that might even weaken or reinforce their impact on each other. However, how the actual avalanche percept is dependent on the viewpoint and the time horizon of perception. The avalanche can be seen as a:

1. *Bifurcation* – nothing happens until suddenly the avalanche occurs,
2. *Cascade* – many intervals of snowfall over several week, where at one point in time the avalanche happens,
3. *Linear process* – seeing the whole snowfall as a linear accumulating process,
4. *Reinforcing process* – likeliness of catastrophe rises exponentially, as snow accumulates,

5. *Multiple independent events* – previous snowfall has nothing to do with snowfall that happened before.

Furthermore, the avalanche can be seen to consist out of several of these paths when concerning different factors that are responsible for a catastrophe to occur. Thus, it is necessary to observe and describe the observing system as well when determining the transition path (development) of a catastrophe. Basically every note, record or picture is the fixation of the observation of an individual person. The view of the person is subjective and bounded to mental models and the description of the observation has an initial position, time-frame, boundaries, and aims. Thus, being aware that the same catastrophe is dependent on the viewers' perspective is important to analyze the catastrophe and find appropriate measures.

## 5. Conclusion and outlook

The approach to form generic transition paths towards catastrophes based on systems science concepts is new and many challenges remain. The paper presents a first step to explore the development of catastrophe from a systemic perspective. There remain open questions and application of the catastrophe paths is needed to verify them and test their real applicability. Current catastrophe research is fairly limited to disciplines and the existing interdisciplinary theories or concepts did not or are also just at the beginning to explore catastrophes according to generic structures and paths. Furthermore, often the methods used in other catastrophe research need previous intensive study and makes their application limited. Therefore, this paper assumes that a systemic perspective on exploring the emergence of catastrophes might help to better understand the transitions of catastrophes and give clues to prevent them to happen in the future.

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