Safety Science 49 (2011) 939–945

Contents lists available at ScienceDirect

Safety Science

journal homepage: www.elsevier.com/locate/ssci

Technical Communication

The complexity of failure: Implications of complexity theory for safety investigations

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ARTICLE INFO

Article history:
Received 4 November 2010
Received in revised form 11 January 2011
Accepted 14 January 2011
Available online 21 February 2011

Keywords:
Complexity theory
Cause
Investigation
Systems thinking
Human error
Newtonian

ABSTRACT

Complexity theory suggests that we see performance as an emergent property, the result of complex interactions and relationships. This can clash, however, with what stakeholders see as legitimate and normal in accident investigations. When systems fail, it is still common to blame components (e.g. human errors) and when they succeed spectacularly, to think in terms of individual heroism (e.g. the A320 Hudson River landing). In this paper, we lay out the contrast between a Newtonian analysis of failure that can be recognized in many efforts at safety analysis and improvement. It makes particular assumptions about the relationship between cause and effect, foreseeability of harm, time-reversibility and the ability to produce the "true story" of an accident. With inspiration from complexity theory, failures are seen as an emergent property of complexity. We explore what that means for safety science and work towards a post-Newtonian analysis of failure in complex systems.

1. Introduction

Complexity is a defining characteristic of today's high-technology, high-consequence systems (Perrow, 1984), and recent submissions to this journal highlight the importance of taking a systems- or complexity view of failure in such systems (Goh et al., 2010). Despite this, single-factor explanations that condense accounts of failure to individual human action or inaction often prevail. An analysis by Holden (2009) showed that between 1999 and 2006, 96% of investigated US aviation accidents were attributed in large part to the flight crew. In 81%, people were the *sole* reported cause. The language used in these analyses also points to failures or shortcomings of components. "Crew failure" or a similar term appeared in 74% of probable causes; the remaining cases contain language such as "inadequate planning, judgment and airmanship," "inexperience" and "unnecessary and excessive, ... inputs." "Violation" of written guidance was implicated as cause or contributing factor in a third of all cases (Holden, 2009).

Single-factor, judgmental explanations for complex system failures are not unique to aviation—they are prevalent in fields from medicine (Wachter and Pronovost, 2009), to military operations (e.g. Snook, 2000), to road traffic (Tingvall and Lie, 2010). Much discourse around accidents in complex systems remains tethered to language such as "chain-of-events", "human error" and questions such as "what was *the* cause?" and "*who* was to blame?" (Douglas, 1992; Catino, 2008; Cook and Nemeth, 2010). The problem of reverting to condensed, single-factor explanations rather than diffuse and system-level ones (Galison, 2000) has of course been a central preoccupation of system safety (Reason, 1997; Maurino et al., 1999; Dekker, 2006), and the difficulty in achieving systemic stories of failure has been considered from a variety of angles (Fischhoff, 1975; Woods et al., 2010).

This paper adds to the literature by critiquing the traditional philosophical–historical and ideological bases for sustained linear thinking about failure in complex systems. We mean by linear thinking a process that follows a chain of causal reasoning from a premise to a single outcome. In contrast, systems thinking regards an outcome as emerging from a complex network of causal interactions, and, therefore, not the result of a single factor (Leveson, 2002). We lay out how a Newtonian analysis of failure makes particular assumptions about the relationship between cause and effect, foreseeability of harm, time-reversibility and the ability to come up with the "true story" of an accident. Whereas such thinking has long been equated with science and rationality in the West, an acknowledgment of the complex, systemic nature of many accidents necessitates a different approach. We take steps toward the development of such an approach, of what we like to call a post-Newtonian analysis, in the second half.

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doi:10.1016/j.ssci.2011.01.008

2. The Cartesian–Newtonian worldview and its implications for system safety

The logic behind Newtonian science is easy to formulate, although its implications for how we think about accidents are subtle and pervasive. Classical mechanics, as formulated by Newton and further developed by Laplace and others encourages a reductionist, mechanistic methodology and worldview. Many still equate "scientific thinking" with "Newtonian thinking." The mechanistic paradigm is compelling in its simplicity, coherence and apparent completeness and largely consistent with intuition and common sense.

2.1. Reductionism and the eureka part

The best known principle of Newtonian science, formulated well before Newton by the philosopher-scientist Descartes, is that of analysis or reductionism. The functioning or non-functioning of the whole can be explained by the functioning or non-functioning of constituent components. Attempts to understand the failure of a complex system in terms of failures or breakages of individual components in it—whether those components are human or machine—is very common (Galison, 2000). The investigators of the Trans World Airlines 200 crash off New York called it their search for the "eureka part": the part that would have everybody in the investigation declare that the broken component, the trigger, the original culprit, had been located and could carry the explanatory load of the loss of the entire Boeing 747. But for this crash, the so-called "eureka part" was never found (Langewiesche, 1998).

The defenses-in-depth metaphor (Reason, 1990; Hollnagel, 2004) relies on the linear parsing-up of a system to locate broken layers or parts. This was recently used by BP in its own analysis of the Deepwater Horizon accident and subsequent Gulf of Mexico oil spill (BP, 2010), seen by others as an effort to divert liability onto multiple participants in the construction of the well and the platform (Levin, 2010).

The philosophy of Newtonian science is one of simplicity: the complexity of the world is only apparent and to deal with it we need to analyze phenomena into their basic components. This is applied in the search for psychological sources of failure, for example. Methods that subdivide "human error" into further component categories, such as perceptual failure, attention failure, memory failure or inaction are in use in for example air traffic control (Hollnagel and Amalberti, 2001). It is also applied in legal reasoning in the wake of accidents, by separating out one or a few actions (or inactions) on the part of individual people (Douglas, 1992; Thomas, 2007; Catino, 2008).

2.2. Causes for effects can be found

In the Newtonian vision of the world, everything that happens has a definitive, identifiable cause and a definitive effect. There is symmetry between cause and effect (they are equal but opposite). The determination of the "cause" or "causes" is of course seen as the most important function of accident investigation, but assumes that physical effects can be traced back to physical causes (or a chain of causes-effects) (Leveson, 2002). The assumption that effects cannot occur without specific causes influences legal reasoning in the wake of accidents too. For example, to raise a question of negligence in an accident, harm must be caused by the negligent action (GAIN, 2004). Assumptions about cause-effect symmetry can be seen in what is known as the outcome bias (Fischhoff, 1975). The worse the consequences, the more any preceding acts are seen as blameworthy (Hugh and Dekker, 2009).

Newtonian ontology is materialistic: all phenomena, whether physical, psychological or social, can be reduced to (or understood in terms of) matter, that is, the movement of physical components inside three-dimensional Euclidean space. The only property that distinguishes particles is where they are in that space. Change, evolution, and indeed accidents, can be reduced to the geometrical arrangement (or misalignment) of fundamentally equivalent pieces of matter, whose interactive movements are governed exhaustively by linear laws of motion, of cause and effect. The Newtonian model may have become so pervasive and coincident with "scientific" thinking that, if analytic reduction to determinate cause-effect relationships cannot be achieved, then the accident analysis method or agency isn't entirely worthy. The Chairman of the NTSB at the time, Jim Hall, raised the specter of his agency not being able to find the Eureka part in TWA 200, which would challenge its entire reputation (p. 119): "What you're dealing with here is much more than an aviation accident... What you have at stake here is the credibility of this agency and the credibility of the government to run an investigation" (Dekker, 2011).

2.3. The foreseeability of harm

According to Newton's image of the universe, the future of any part of it can be predicted with absolute certainty if its state at any time was known in all details. With enough knowledge of the initial conditions of the particles and the laws that govern their motion, all subsequent events can be foreseen. In other words, if somebody can be shown to have known (or should have known) the initial positions and momentum of the components constituting a system, as well as the forces acting on those components (which are not only external forces but also those determined by the positions of these and other particles), then this person could, in principle, have predicted the further evolution of the system with complete certainty and accuracy.

If such knowledge is in principle attainable, then harmful outcomes are foreseeable too. Where people have a duty of care to apply such knowledge in the prediction of the effects of their interventions, it is consistent with the Newtonian model to ask how they failed to foresee the effects. Did they not know the laws governing their part of the universe (i.e. were they incompetent, unknowledgeable)? Did they fail to plot out the possible effects of their actions? Indeed, legal rationality in the determination of negligence follows this feature of the Newtonian model (p. 6): "Where there is a duty to exercise care, reasonable care must be taken to avoid acts or omissions which can reasonably be foreseen to be likely to cause harm. If, as a result of a failure to act in this reasonably skillful way, harm is caused, the person whose action caused the harm, is negligent" (GAIN, 2004).

In other words, people can be construed as negligent if the person did not avoid actions that could be foreseen to lead to effects—effects that would have been predictable and thereby avoidable if the person had sunk more effort into understanding the starting conditions and the laws governing the subsequent motions of the elements in that Newtonian sub-universe. Most road traffic legislation is based on this Newtonian commitment to foreseeability too. For example, a road traffic law in a typical Western country might specify how a motorist should adjust speed so as to be able stop the vehicle before colliding with some obstacle, at the same time remaining aware of the circumstances that could influence such selection of speed. Both the foreseeability of all possible hindrances and the awareness of circumstances (initial conditions) critical for determining speed are steeped in Newtonian epistemology. Both are also heavily subject to outcome bias: if an accident suggests that an obstacle or particular circumstance was not foreseen, then speed was surely too high. The system's user, as a consequence, is always wrong (Tingvall and Lie, 2010).

2.4. Time-reversibility

The trajectory of a Newtonian system is not only determined towards the future, but also towards the past. Given its present state, we can in principle reverse the evolution to reconstruct any earlier state that it has gone through. Such assumptions give accident investigators the confidence that an event sequence can be reconstructed by starting with the outcome and then tracing its causal chain back into time. The notion of *re*construction reaffirms and instantiates Newtonian physics: knowledge about past events is not original, but merely the result of uncovering a pre-existing order. The only thing between an investigator and a good reconstruction are the limits on the accuracy of the representation of what happened. It follows that accuracy can be improved by "better" methods of investigation (Shappell and Wiegmann, 2001).

2.5. Completeness of knowledge

Newton argued that the laws of the world are discoverable and ultimately completely knowable. God created the natural order (though kept the rulebook hidden from man) and it was the task of the investigator to discover this hidden order underneath the apparent disorder (Feyerabend, 1993). It follows that the more facts an analyst or investigator collects, the more it leads, inevitably, to a better investigation: a better representation of "what happened." In the limit, this can lead to a perfect, objective representation of the world outside (Heylighen, 1999), or one final (true) story, the one in which there is no gap between external events and their internal representation.

Those equipped with better methods, and particularly those who enjoy greater "objectivity," (i.e. those who have no bias which distorts their perception of the world, and who will consider *all* the facts) are better positioned to construct such a true story. Formal, government-sponsored accident investigations can sometimes enjoy this idea of objectivity and truth—if not in the substance of the story they produce, then at least in the institutional arrangements surrounding its production. Putative objectivity can be deliberately engineered into the investigation as a sum of subjectivities: all interested parties (e.g. vendors, the industry, operator, unions, professional associations) can officially contribute (though dissenting voices can be silenced or sidelined (Perrow, 1984; Byrne, 2002)). Other parties often wait until a formal report is produced before publicly taking either position or action, legitimizing the accident investigation as original arbitrator between fact and fiction.

2.6. Newtonian bastardization of the response to failure in complex systems

Together, taken-for-granted assumptions about decomposition, cause-effect symmetry, foreseeability of harm, time reversibility, and completeness of knowledge give rise to a Newtonian analysis of system failure. It can be summed up as follows:

- To understand a failure of a system, investigators need to search for the failure or malfunctioning of one or more of its components. The relationship between component behavior and system behavior is analytically non-problematic.
- Causes for effects can always be found, because there are no effects without causes. In fact, the larger the effect, the larger (e.g. the more egregious) the cause must have been.
- If they put in more effort, people can more reliably foresee outcomes. After all, they would have a better understanding of the starting conditions and they are already supposed to know the laws by which the system behaves (otherwise they wouldn't be allowed to work in it). With those two in hand, all future system states can be predicted, harmful states be foreseen and avoided.
- An event sequence can be reconstructed by starting with the outcome and tracing its causal chain back into time. Knowledge thus produced about past events is the result of uncovering a pre-existing order.
- One official account of what happened is possible and desirable. Not just because there is only one pre-existing order to be discovered, but also because knowledge (or the story) is the mental representation or mirror of that order. The *truest* story is the one in which the gap between external events and internal representation is the smallest. The *true* story is the one in which there is no gap.

These assumptions can remain largely transparent and closed to critique in safety work precisely because they are so self-evident and commonsensical. People involved in system safety may be expected to explain themselves in terms of the dominant assumptions; they will make sense of events using those assumptions; they will then reproduce the existing order in their words and actions. Organizational, institutional and technological arrangements surrounding their work don't leave plausible alternatives. For instance, investigators are mandated to find the probable cause(s) and turn out enumerations of broken components as their findings. Technological–analytical support (incident databases, error analysis tools) emphasizes linear reasoning and the identification of malfunctioning components (Shappell and Wiegmann, 2001). Also, organizations and those held accountable for internal failures need something to "fix," which further valorizes condensed accounts. If these processes fail to satisfy societal accountability requirements, then courts can decide to pursue individuals criminally, which also could be said to represent a hunt for a broken component (Thomas, 2007; Dekker, 2009). A socio-technical Newtonian physics is thus often read into events that could yield much more complexly patterned interpretations.

3. The view from complexity and its implications for system failure

Analytic reduction cannot tell how a number of different things and processes act together when exposed to a number of different influences at the same time. This is complexity, a characteristic of a system. Complex behavior arises because of the interaction between the components of a system. It asks us to focus not on individual components but on their relationships. The properties of the system emerge as a result of these interactions; they are not contained within individual components. Complex systems generate new structures internally, they are not reliant on an external designer. In reaction to changing conditions in the environment, the system has to adjust some of its internal structure. Complexity is a feature of the system, not of components inside of it. The knowledge of each component is limited and local, and there is no component that possesses enough capacity to represent the complexity of the entire system in that component itself. The behavior of the system cannot be reduced to the behavior of the constituent components. If we wish to study such systems, we have to investigate the system as such. It is at this point that reductionist methods fail.

3.1. Complicated versus complex

There is an important distinction between "complex" and "complicated" systems. Certain systems may be quite intricate and consist of a huge number of parts, e.g. a jet airliner. Nevertheless, it can be taken apart and put together again. Even if such a system cannot practically be understood completely by a single person, it is understandable and describable in principle. This makes them complicated. Complex systems, on the other hand, come to be in the interaction of the components. Jet airliners become complex systems when they are deployed in a nominally regulated world with cultural diversity, receiver-oriented versus transmitter-oriented communication expectations, different hierarchical gradients in a cockpit and multiple levels of politeness differentiation (Orasanu and Martin, 1998), effects of fatigue, procedural drift (Snook, 2000), varied training and language standards (Hutchins et al., 2002), as well as cross-cultural differences in risk perceptions, attitudes and behavior (Lund and Rundmo, 2009). This is where complicated systems become complex because they are opened up to influences that lie way beyond engineering specifications and reliability predictions.

Complex systems are held together by local relationships only. Each component is ignorant of the behavior of the system as a whole, and cannot know the full influences of its actions. Components respond locally to information presented to them, and complexity arises from the huge, multiplied webs of relationships and interactions that result from these local actions. The boundaries of what constitutes the system become fuzzy; interdependencies and interactions multiply and mushroom.

Complex systems have a history, a path-dependence, which also spills over those fuzzy boundaries. Their past, and the past of events around them, is co-responsible for their present behavior, and descriptions of complexity should take history into account. Take as an example the take-off accident of SQ006 at Taipei where deficient runway and taxiway lighting/signage was implicated in the crew's selection of a runway that was actually closed for traffic (ASW, 2002). A critical taxiway light had burnt out, and the story could stop there. But as only one of two countries in the world (the Vatican being the other), Taiwan is not bound by airport design rules from the International Civil Aviation Organization, a United Nations body. Cross-strait relationships between Taiwan (formerly Formosa) and China, and their tortured post-WWII history (Mao's communists versus Chang-Kai-Shek's Kuomintang Nationalists) and their place in a larger global context are responsible for keeping Taiwan out of the UN and thus out of formal reach for international safety regulations that apply to even the smallest markings and lights and their maintenance on an airport. A broken light and exceptionally bad weather on the night of the SQ006 take-off constituted the small changes in starting conditions that led to a large event in a system that had been living far from equilibrium for a long time—all consistent with complexity.

In describing the macro-behavior (or emergent behavior) of the system, not all its micro-features can be taken into account. The description on the macro-level is thus a reduction or compression of complexity, and cannot be an exact description of what the system actually does. Moreover, the emergent properties on the macro-level can influence the micro-activities, a phenomenon sometimes referred to as "top-down causation." Nevertheless, macro-behavior is not the result of anything else but the micro-activities of the system, keeping in mind that these are not only influenced by their mutual interaction and by top-down effects, but also by the interaction of the system with its environment. These insights have important implications for the knowledge-claims made when analyzing accidents in complex systems. Since we do not have direct access to the complexity itself, our knowledge of such systems is in principle limited. What follows is an outline of the implications of these insights for (the ethics of) system failure, revisiting to the topics used in the section on Newtonian science.

3.2. Synthesis and holism

Perrow pointed out how Newtonian focus on parts as the cause of accidents may sponsored a false belief that redundancy is the best way to protect against hazard (Perrow, 1984; Sagan, 1993). The downside is that barriers, as well as professional specialization, policies, procedures, protocols, redundant mechanisms and structures, all add to a system's complexity. They entail an explosion of new relationships (*between* parts and layers and components) that spread through the system. System accidents result from the relationships between components, not from the workings or malfunctioning of any component part. This insight had already grown out of systems engineering and system safety, pioneered in part by 1950's aerospace engineers who were confronted with increasing complexity in aircraft and ballistic missile systems at that time. The interconnectivity and interactivity between system components made that greater complexity led to vastly more possible interactions than could be planned, understood, anticipated or guarded against (Leveson, 2002).

Newtonian analytic reduction of complex systems not only fails to reveal any culprit part (as broken parts are not necessary to produce system failures) but would also eliminate the phenomenon of interest—the interactive complexity of the system itself that gives rise to conditions that help produce an accident. Sequence-of-events and barrier models can say nothing about the build-up of latent failures, about a gradual, incremental loosening or loss of control that characterizes system accidents (Rasmussen, 1997). The processes of erosion of constraints, of attrition of safety, of drift towards margins, cannot be captured because reductive approaches are static metaphors for resulting forms, not dynamic models oriented at processes of the formation, the evolution of relationships.

3.3. Emergence

System safety has been characterized as an emergent property, something that cannot be predicted on the basis of the components that make up the system (Leveson, 2002). Accidents have similarly been characterized as emergent properties of complex systems (Hollnagel, 2004). They cannot be predicted on the basis of the constituent parts. Rather, they are one emergent feature of constituent components doing their (normal) work. A systems accident is possible in an organization where people themselves suffer no noteworthy incidents, in which everything looks normal, and everybody is abiding by their local rules, common solutions, or habits (Vaughan, 2005). This means that the behavior of the whole cannot be explained by, and is not mirrored in, the behavior of constituent components. Snook (Snook, 2000) expressed the realization that bad effects can happen with no causes in his study of the shoot-down of two U.S. Black Hawk helicopters by two US fighter jets in the no-fly zone over Northern Iraq in 1993:

> "This journey played with my emotions. When I first examined the data, I went in puzzled, angry, and disappointed—puzzled how two highly trained Air Force pilots could make such a deadly mistake; angry at how an entire crew of AWACS controllers could sit by and watch a tragedy develop without taking action; and disappointed at how dysfunctional Task Force OPC must have been to have not better integrated helicopters into its air operations. Each time I went in hot and suspicious. Each time I came out sympathetic and unnerved... If no one did anything wrong; if there were no unexplainable surprises at any level of analysis; if nothing was abnormal from a behavioral and organizational perspective; then what...?"

Snook's impulse to hunt down the broken components (deadly pilot error, controllers sitting by, a dysfunctional Task Force) led to nothing. There was no "eureka part." Again, an accident defied Newtonian logic.

Asymmetry or non-linearity means that an infinitesimal change in starting conditions can lead to huge differences later on. This sensitive dependence on initial conditions removes proportionality from the relationships between system inputs and outputs. The evaluation of damage caused by debris falling off the external tank prior to the fatal 2003 Space Shuttle Columbia flight can serve as an example (CAIB, 2003; Starbuck and Farjoun, 2005). Always under pressure to accommodate tight launch schedules and budget cuts (in part because of a diversion of funds to the international space station), certain problems became seen as maintenance issues rather than flight safety risks. Maintenance issues could be cleared through a nominally simpler bureaucratic process, which allowed quicker Shuttle vehicle turnarounds. In the mass of assessments to be made between flights, the effect of foam debris strikes was one. Gradually converting this issue from safety to maintenance was not different from a lot of other risk assessments and decisions that NASA had to do as one Shuttle landed and the next was prepared for flight—one more decision, just like tens of thousands of other decisions. While any such decision can be quite rational given the local circumstances and the goals, knowledge and attention of the decision makers, interactive complexity of the system can take it onto unpredictable pathways to hard-to-foresee system outcomes.

This complexity has implications for the ethical load distribution in the aftermath of complex system failure. Consequences cannot form the basis for an assessment of the gravity of the cause (or the quality of the decision leading up to it), something that has been argued in the safety and human factors literature (Orasanu and Martin, 1998). It suggests that everyday organizational decisions, embedded in masses of similar decisions and only subject to special consideration with the wisdom of hindsight, cannot be fairly singled out for purposes of exacting accountability (e.g. through criminalization) because their relationship to the eventual outcome is complex, non-linear, and was probably impossible to foresee (Jensen, 1996).

3.4. Foreseeability of probabilities, not certainties

Decision makers in complex systems are capable of assessing the probabilities, but not the certainties of particular outcomes (Orasanu and Martin, 1998). With an outcome in hand, its foreseeability becomes quite obvious, and it may appear as if a decision in fact *determined* an outcome, that it inevitably led up to it (Fischhoff and Beyth, 1975). But knowledge of initial conditions and total knowledge of the laws governing a system (the two Newtonian conditions for assessing foreseeability of harm) is unobtainable in complex systems.

That does not mean that such decisions are not singled out in retrospective analyses. That they do is but one consequence of Newtonian thinking: accidents have typically been modeled as a chain of events. While a particular historical decision can be cast as an "event," it becomes very difficult to locate the immediately preceding "event" that was *its* cause. So the decision (the human error, or "violation") is cast as the aboriginal cause, the root cause (Leveson, 2002).

3.5. Time-irreversibility

The conditions of a complex system are irreversible. The precise set of conditions that gave rise to the emergence of a particular outcome (e.g. an accident) is something that can never be exhaustively reconstructed. Complex systems continually experience change as relationships and connections evolve internally and adapt to their changing environment. Given the open, adaptive nature of complex systems, the system after the accident is not the same as the system before the accident—many things will have changed, not only as a result of the outcome, but as a result of the passage of time.

This also means that the any predictive power of retrospective analysis of failure is limited (Leveson, 2002). Decisions in organizations, for example, to the extent that they can be described separately from context at all, are not the single beads strung along some linear cause-effect sequence that they may seem afterward. Complexity argues that they are spawned and suspended in the messy interior of organizational life that influences and buffets and shapes them in a multitude of ways. Many of these ways are hard to trace retrospectively as they do not follow documented organizational protocol but rather depend on unwritten routines, implicit expectations, professional judgments and subtle oral influences on what people deem rational or doable in any given situation (Vaughan, 1999).

*Re*constructing events in a complex system, then, is impossible, primarily as a result of the characteristics of complexity. The system that is subjected to scrutiny after the fact is never the same system that produced the outcome. It will already have changed, partly because of the outcome, and partly because of passing time and the nature of complexity. But psychological characteristics of retrospective investigation make it so too. As soon as an outcome has happened, whatever past events can be said to have led up to it, undergo a whole range of transformations (Fischhoff and Beyth, 1975; Hugh and Dekker, 2009). Take the idea that it is a sequence of events that precedes an accident. Who makes the selection of the "events" and on the basis of what? The very act of separating important or contributory events from unimportant ones is an act of construction, of the creation of a story, not the reconstruction of a story that was already there, ready to be uncovered. Any sequence of events or list of contributory or causal factors already smuggles a whole array of selection mechanisms and criteria into the supposed "re"-construction. There is no objective way of doing this—all these choices are affected, more or less tacitly, by the analyst's background, preferences, experiences, biases, beliefs and purposes. "Events" are themselves defined and delimited by the stories with which the analyst configures them, and are impossible to imagine outside this selective, exclusionary, narrative fore-structure (Cronon, 1992).

3.6. Perpetual incompleteness and uncertainty of knowledge

The Newtonian belief that is both instantiated and reproduced in official accident investigations is that there is a world that is objectively available and apprehensible. An independent world exists to which investigators, with proper methods, can gain objective access. Observer and the observed are separable, knowledge is a mapping of facts from one to the other. Investigation, in this belief, is not a constitutive or creative process: it is merely an "uncovering" of distinctions that were already there and that are simply waiting to be observed (Heylighen et al., 2006).

Complexity, in contrast, suggests that the observer is not just the contributor to, but in many cases the creator of, the observed (Wallerstein, 1996). Cybernetics acknowledged the intrinsically subjective nature of knowledge, as an imperfect tool used by an intelligent agent to help it achieve its goals. Not only does the agent not need an objective mapping of reality, it can actually never achieve one. Indeed, the agent does not have access to any "external reality": it can merely sense its inputs, note its outputs (actions) and from the correlations between them induce certain rules or regularities that seem to hold within its environment. Different agents, experiencing different inputs and outputs, will in general induce different correlations, and therefore develop different knowledge of the environment in which they live. There is no objective way to determine whose view is right and whose is wrong, since the agents effectively live in different environments (Heylighen et al., 2006).

Different descriptions of a complex system, then (from the point of view of different agents), decompose the system in different ways. It follows that the knowledge gained by any description is always relative to the perspective from which the description was made. This does not imply that any description is as good as any other. It is merely the result of the fact that only a limited number of characteristics of the system can be taken into account by any specific description. It is not that some complex readings are "truer" in the sense of corresponding more closely to some objective state of affairs (as that would be a Newtonian commitment). Rather, the acknowledgment of complexity in safety work can lead to a richer understanding and thus it holds the potential to improve safety and help to expand the ethical response in the aftermath of failure. Examples of alternative accounts of high-visibility accidents that all challenged the "official" readings include the DC-10 Mount Erebus crash (Vette, 1984), the Dryden Fokker F-28 icing accident (Maurino et al., 1999), the Space Shuttle Challenger launch decision (Vaughan, 1996), and the fratricide of two Black Hawk helicopters over Northern Iraq (Snook, 2000). All such revisionist accounts, generated by a diversity of academics, system insiders, and even a judge, have offered various audiences the opportunity to embrace a greater richness of voices and interpretations. Together, they better acknowledge the complexity of the events, and the systems in which they happened, than any single account could. In complexity there is no procedure for deciding which narrative is correct, even though some descriptions will deliver more interesting results than others—depending of course on the goals of the audience. The selection of "causes" (or "events" or "contributory factors") is always an act of construction by the investigation or a revisionist narrative. There is no objective way of doing this—all analytical choices are affected, more or less explicitly, by the author's own position in a complex system. The most interesting "truth" about an accident, then, may lie in the diversity of possible accounts, not in the coerciveness of a single one (Hoven, 2001; Cilliers, 2010).

3.7. A post-Newtonian analysis of failure in complex systems

Complexity and systems thinking denies the existence of one objective reality that is accessible with accurate methods. This has implications for what can be considered useful and ethical in the aftermath of failure (Cilliers, 2005):

- An investigation must gather as much information on the event as possible, notwithstanding the fact that it is impossible to gather "all" the information.
- An investigation can never uncover one true story of what happened. That people have different accounts of what happened in the aftermath of failure should not be seen as somebody being right and somebody being wrong. It may be more ethical to aim for diversity, and respect otherness and difference in accounts about what happened as a value in itself. Diversity of narrative can be seen as an enormous source of resilience in complex systems, not as a weakness. The more angles, the more there can be to learn.
- An investigation must consider as many of the possible consequences of any finding, conclusion or recommendation in the aftermath of failure, notwithstanding the fact that it is impossible to consider all the consequences.
- An investigation should make sure that it is possible to revise any conclusion as soon as it becomes clear that it has flaws, notwithstanding the fact that the conditions of a complex system are irreversible. Even when a conclusion is reversed, some of its consequences (psychological, practical) may remain irreversible.

4. Conclusion

When accidents are seen as complex phenomena, there is no longer an obvious relationship between the behavior of parts in the system (or their malfunctioning, e.g. "human errors") and system-level outcomes. Instead, system-level behaviors emerge from the multitude of relationship and interconnections deeper inside the system, and cannot be reduced to those relationships or interconnections. Investigations that embrace complexity, then, might stop looking for the "causes" of failure or success. Instead, they gather multiple narratives from different perspectives inside of the complex system, which give partially overlapping and partially contradictory accounts of how emergent outcomes come about. The complexity perspective dispenses with the notion that there are easy answers to a complex systems event—supposedly within reach of the one with the best method or most objective investigative viewpoint. It allows us to invite more voices into the conversation, and to celebrate their diversity and contributions.

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