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E. Talen

Accidents, Normal

Normal Accident Theory (NAT) applies to complex and tightly coupled systems such as nuclear power plants, aircraft, the air transport system with weather information, traffic control and airfields, chemical plants, weapon systems, marine transport, banking and financial systems, hospitals, and medical equipment (Perrow 1984, 1999). It asserts that in systems that humans design, build and run, nothing can be perfect.

Every part of the system is subject to failure; the design can be faulty, as can the equipment, the procedures, the operators, the supplies, and the environment. Since nothing is perfect, humans build in safeguards, such as redundancies, buffers, and alarms that tell operators to take corrective action. But occasionally two or more failures, perhaps quite small ones, can interact in ways that could not be anticipated by designers, procedures, or training. These unexpected interactions of failures can defeat the safeguards, mystify operators, and if the system is also 'tightly coupled' thus allowing failures to cascade, it can bring down a part or all of system. The vulnerability to unexpected interactions that defeat safety systems is an inherent part of highly complex systems; they cannot avoid this. The accident, then, is in a sense 'normal' for the system, even though it may be quite rare, because it is an inescapable part of the system.

Not all systems are complexly interactive, and thus subject to this sort of failure; indeed, most avoid interactive complexity if they can, and over time become more 'linear,' by design. (The jet engine is less complex and more linear than the piston engine.) And not all complexly interactive systems are tightly coupled; by design or just through adaptive evolution they become loosely coupled. (The air traffic control system was more tightly coupled until separation rules and narrow routes or lanes were technically feasible, decoupling the system somewhat.) If the system has a lot of parts that are linked in a 'linear' fashion the chances of unanticipated interactions are remote. An assembly line is a linear system, wherein a failure in the middle of the line will not interact unexpectedly with a

<i>Complex systems</i>	<i>Linear systems</i>
Proximity	Spatial segregation
Common-mode connections	Dedicated connections
Interconnected subsystems	Segregated subsystems
Limited substitutions	Easy substitutions
Feedback loops	Few feedback loops
Multiple and interacting controls	Single purpose, segregated controls
Indirect information	Direct information
Limited understanding	Extensive understanding
<i>Tight coupling</i>	<i>Loose coupling</i>
Delays in processing not possible	Processing delays possible
Invariant sequences	Order of sequences can be changed
Only one method to achieve goal	Alternative methods available
Little slack possible in supplies, equipment, personnel	Slack in resources possible
Buffers and redundancies are designed-in, deliberate	Buffers and redundancies fortuitously available
Substitutions of supplies, equipment, personnel limited and designed-in	Substitutions fortuitously available

Figure 1

Characteristics of the two major variables, complexity and coupling

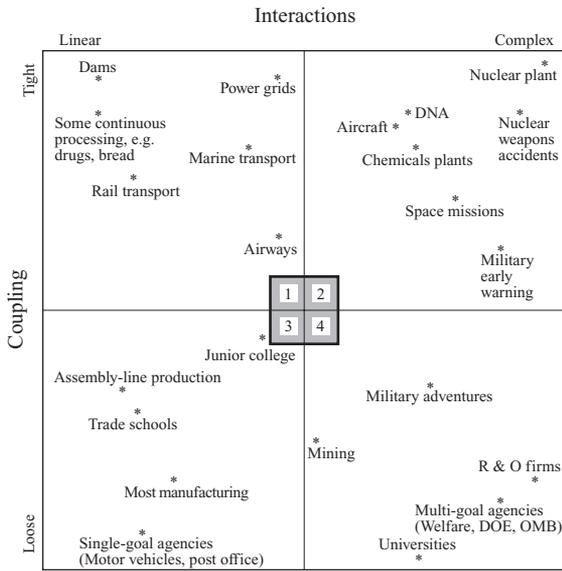


Figure 2
Interaction/coupling chart showing which systems are most vulnerable to system accidents

failure near the end, whereas a chemical plant will use waste heat from one part of the process to provide heat to a previous or later part of the process. A dam is a linear system; a failure in one part is comprehensible and though it may be one that is not correctable, making an accident inevitable, the system characteristics are not the cause of the failure; a component simply failed. But a dam is tightly coupled, so the component failure cannot be isolated and it precipitates the failure of other components. A university is an example of a complexly interactive system that is not tightly coupled. Substitutes can be found for an absent teacher, another dean for an absent dean, or to retract or delay a mistaken decision, the sequencing of courses is quite loose and there are alternative paths for mastering the material. Unexpected interactions are valued in a university, less so in the more linear vocational school, and not at all in the business school teaching typing. Figure 1 summarizes some of the characteristics of the two major variables, complexity and coupling.

NAT has a strong normative content. It emerged from an analysis of the accident at the Three Mile Island nuclear power plant in Pennsylvania in 1979. Much of the radioactive core melted and the plant came close to breaching containment and causing a disastrous escape of radioactivity. The catastrophic potential of that accident, fortunately not realized, prompted inquiry. It appeared that elites in society were causing more and more risky systems with catastrophic potential to be built, and just trying harder was not going to be sufficient to prevent

catastrophes. Though people at all levels in the company running the Three Mile Island plant did not appear to have tried very hard to prevent accidents, the more alarming possibility was that even if they had, an accident was eventually inevitable, and thus a catastrophe was possible. Other systems that had catastrophic potential were also found to be both complexly interactive and tightly coupled. Figure 2 arrays these two variables in a manner that suggests which systems are most vulnerable to system accidents. The catastrophic potential of those in the upper right cell is evident. The policy implications of this analysis is that some systems have such extensive catastrophic potential (killing hundreds with one blow, or contaminating large amounts of the land and living things on it), that they should be abandoned, scaled back sharply to reduce the potential, or completely redesigned to be more linear in their interactions and more loosely coupled to prevent the spread of failures.

Normal Accidents reviews accidents in a number of systems. The Three Mile Island (TMI) accident was the result of four failures, three of which had happened before (the fourth was a failure of a newly installed safety device), all four of which would have been handled easily if they had occurred separately, but could not when all four interacted in unforeseen ways. The system sent correct, but misleading, indications to the operators, and they behaved as they had been trained to do, which made the situation worse. Over half of the core melted down, and had it not been for the insight of a fresh arrival some two hours into the accident, all of the core could have melted, causing a breach of containment and extensive radioactive releases. Several other nuclear power plant accidents appear to have been system accidents, as opposed to the much more common component failure accidents, but were close calls rather than proceeding as far as that at TMI. Several chemical plant accidents, aircraft accidents, and marine accidents are detailed that also fit the definition, and though there were deaths and damages, they were not catastrophic. In such linear systems as mining, manufacturing, and dams the common pattern is not system accidents but preventable component failure accidents.

One of the implications of the theory concerns the organizational dilemma of centralization versus decentralization. Some processes still need highly complex interactions to make them work, or the interactions are introduced for efficiency reasons; tight coupling may be required to ensure the most economical operation and the highest throughput speed. The CANDU nuclear reactors in Canada are reportedly more forgiving and safer, but they are far less efficient than the 'race horse' models the USA adopted from the nuclear navy. The navy design did not require huge outputs with continuous, long-term 'base load' operation, and was smaller and safer; the electric power plant scaled up the design to an unsafe level to achieve economies of scale.

Tight coupling, despite its associated economies, requires centralized decision making; processes are fast and invariant, and only the top levels of the system have a complete view of the system state. But complex interactions with uncertainty call for decentralized decision making; only the lower-level operators can comprehend unexpected interactions of sometimes quite small failures. It is difficult, and perhaps impossible, to have a system that is at the same time centralized and decentralized. Given the proclivities of designers and managers to favor centralization of power over its decentralization, it was a fairly consistent finding that risky systems erred on the centralization side and neglected the advantages of decentralization, but it was also clear that immediate, centralized responses to failures had their advantages. No clear solution to the dilemma, beyond massive redesign and accompanying inefficiencies, was apparent.

A few noteworthy accidents since the 1984 publication of *Normal Accidents* have received wide publicity: the Challenger space shuttle, the devastating Bhopal (India) accident in Union Carbide's chemical plant, the Chernobyl nuclear power plant explosion in the former USSR, and the Exxon Valdez oil tanker accident in Alaska. (These are reviewed in the Afterword in a later edition of *Normal Accidents* (Perrow 1999).) None of these were truly system accidents; rather, large mistakes were made by designers, management, and workers in all cases, and all were clearly avoidable. But the Bhopal accident, with anywhere from 4,000 to 10,000 deaths, prompted an important extension of Normal Accident Theory. Hundreds of chemical plants with the catastrophic potential of Bhopal have existed for decades, but there has been only one Bhopal. This suggests that it is very hard to have a catastrophe, and the reason is, in a sense, akin to the dynamics of system accidents. In a system accident everything must come together in just the right way to produce a serious accident; that is why they are so rare. We have had vapor clouds with the explosive potential to wipe out whole suburbs, as in the case of a Florida suburb, but it was night and no cars or trucks were about to provide the spark. Other vapor clouds have exploded with devastating consequences, but in lightly populated rural areas, where only a few people were killed. The explosion of the Flixborough chemical plant in England in 1974 devastated the plant and part of the nearby town, but as it was a Saturday few workers were in the plant and most of the townspeople were away shopping.

Warnings are important. There was none when the Vaiont dam in Italy failed and 3,000 people died; there was a few hours warning when the Grand Teton dam failed in the USA and only a few perished. Eighteen months after Bhopal another Union Carbide plant in West Virginia, USA, had a similar accident, but not as much of the gas was released, the gas was somewhat less toxic, and few citizens were about (though some

100 were treated at hospitals). (Shortly before the accident the plant had been inspected by the Occupational and Safety and Health Administration and declared to be very safe; after the accident they returned and found it to be 'an accident waiting happen' and fined Union Carbide.) Such is the role of retrospective judgment in the accident investigations Perrow 1999.)

To have a catastrophe, then, requires a combination of such things as: a large volume of toxic or explosive material, the right wind direction or presence of a spark, a population nearby in permeable dwellings who have no warning and do not know about the toxic character of the substance, and insufficient emergency efforts from the plant. Absent any one of these conditions and the accident need not be a catastrophe. The US government, after the Union Carbide Bhopal and West Virginia accidents, calculated that there had been 17 releases in the US with the catastrophic potential of Bhopal in 20 years, but the rest of the conditions that obtained at Bhopal were not present (Shabecoff 1989). The difficulty of killing hundreds or thousands in one go may be an important reason why elites continue to populate the earth with risky systems.

A number of developments appear to have increased the number of these 'risky systems' and this may account for the attention the scheme has received. Disasters caused by humans have been with us for centuries, of course, but while many systems started out in the complex and coupled quadrant, almost all have found ways to increase their linearity and/or their loose coupling, avoiding disasters. We may find such ways to make nuclear power plants highly reliable in time, for example. But the number of risky systems has increased, their scale has increased; so has the concentration of populations adjacent to them; and in the USA more of them are in privatized systems with competitive demands to run them hotter, faster, bigger, and with more toxic and explosive ingredients, and to operate them in increasingly hostile environments. Recent entries might be global financial markets, genetic engineering, depleted uranium, and missile defenses in outer space, along with others that are only now being recognized as possibilities, such as hospital procedures, medical equipment, terrorism, and of course, software failures.

NAT distinguishes system accidents, inevitable (and thus 'normal') but rare, from the vastly more frequent component failure accidents. These could be prevented. Why do component failure accidents nevertheless occur even in systems with catastrophic potential? Three factors stand out: the role of production pressures, the role of accident investigations that are far from disinterested, and the 'socialization of risk' to the general public. The quintessential system accident occurs in the absence of production pressures; no one did anything seriously wrong, including designers, managers, and operators. The accident is

rooted in system characteristics. But the opportunities for small failures that can interact greatly increases if there are production pressures that increase the chances of small failures. These appear to be increasing in many systems, and not just in complex/tightly coupled ones, as a result of global competition, privatization, deregulated markets, and the failure of government regulatory efforts to keep up with the increase in risky systems. Accidents have been rising in petrochemical plants, for example, apparently because their growth has not included growth of unionized employees. Instead, work is contracted out to non-union contractors with inexperienced, poorly trained and poorly paid employees, and they do the most risky work at turnaround and maintenance times. The fatalities in the contractor firms are not included in safety statistics of the industry, but counted elsewhere (Kochan et al. 1994).

A second reason preventable accidents are not prevented in risky systems is the 'interested' nature of the investigations. Operators—those at the lowest level, though this includes airline pilots and officers on the bridge of ships—are generally the first to be blamed, though occasionally there is a thorough investigation that moves the blame up to the management and the design levels. If operators can be blamed then the system just needs new or better trained operators, not a thorough overhaul to change the environment in which operators are forced to work. Operators were blamed at TMI for cutting back on high pressure injection, but they were trained to do that; the possibility that 'steam voids' could send misleading information and there could be a zirconium–water interaction was not conceived by designers; indeed, the adviser to the senior official overseeing the recovery effort, the Governor of Pennsylvania, was told it would not happen. Furthermore, if conditions A and B are found to be present after the accident, these conditions are blamed for it. No one investigates those plants that had conditions A and B but did not have an accident, suggesting that while A and B may be necessary for an accident, they are sufficient; unrecognized condition C may be necessary and even sufficient, but is not noted and rectified.

A third reason for increases in accidents may be the 'socialization of risk.' A large reinsurance company found that it was making more money out of arbitraging the insurance premium it was collecting from many nations: making money by transferring the funds in the currency the premium was paid in to other currencies that were slightly more valuable. They enlarged the size of the financial staff doing the trading and cut the size of their property inspectors. The inspectors, lacking time to investigate and make adequate ratings of risk on a particular property, were encouraged to sign up overly risky properties in order to increase the volume of premiums available for arbitraging. More losses with risky properties occurred, but the losses were more than covered by the

gains made in cross-national funds transfers. The public at large had to bear the cost of more fires and explosions ('socializing' the risk). Insurance companies have in the past promoted safe practices because of their own interest in not paying out claims; now some appear to make more on investing and arbitraging premiums than they do by promoting safety. Open financial markets, and the speed and ease of converting funds, appear to interact unexpectedly with plant safety.

Normal Accident Theory arose out of analyzing complex organizations and the interactions of organizations within sectors (Perrow 1986). Recent scholarship has expanded and tightened the organizational aspects of the theory of normal accidents. Scott Sagan analyzed accidents and near misses in the United States' nuclear defense system, and pointed to two aspects of NAT that needed emphasis and expansion: limited or bounded rationality, and the role of group interests (Sagan 1993).

Because risky systems encounter much uncertainty in their internal operations and their environments, they are particularly prone to the cognitive limits on rationality first explored by Herbert Simon, and elaborated by James March and others into a 'garbage can' model of organizations, where a stream of solutions and problems connect in a nearly random fashion under conditions of frequent exit and entry of personnel and difficult timing problems (March and Olsen 1979). Sagan highlights the occasions for such dynamics to produce unexpected failures that interact in virtually incomprehensible ways.

The second feature that deserved more emphasis was the role of group interests, in this case within and among the many organizations that constitute the nuclear defense system. These interests determined that training was ineffective, learning from accidents often did not occur, and lessons drawn could be counterproductive. Safety as a goal lost out to group interests, production pressures, and 'macho' values. In effect, Sagan added an additional reason as to why accidents in complex/coupled systems were inevitable. The organizational properties of bounded rationality and group interests are magnified in risky systems making normal safety efforts less effective.

A somewhat competing theory of accidents in high-risk systems, called High Reliability Theory, emphasizes training, learning from experience, and the implanting of safety goals at all levels (Roberts 1990, La Porte and Consolini 1991, Roberts 1993). Sagan systematically runs the accidents and near misses he found in the nuclear defense system by both Normal Accident Theory and High Reliability Theory and finds the latter to be wanting. Sagan has also developed NAT by exploring the curious association of system accidents with redundancies and safety devices, arguing that redundancies may do more harm than good (Sagan 1996).

NAT touched on social-psychological processes and

cognitive limits, but this important aspect of accidents was not as developed as much as the structural aspects. Building on the important work of Karl Weick, whose analysis of the Tenerife air transport disaster is a classic (Weick 1993), Scott Snook examines a friendly fire accident wherein two helicopters full of UN peacekeeping officials were shot down by two US fighters over northern Iran in 1991 (Snook 2000). The weather was clear, the helicopters were flying an announced flight plan, there had been no enemy action in the area for a year, and the fighters challenged the helicopters over radio and flew by them once for a preliminary inspection. A great many small mistakes and faulty cognitive models, combined with substantial organizational mismatches and larger system dynamics caused the accident, and the hundreds of remedial steps taken afterwards were largely irrelevant. In over 1,000 sorties, one had gone amiss. The beauty of Snook's analysis is that he links the individual, group, and system levels systematically, using cognitive, garbage can, and NAT tools, showing how each contributes to an understanding of the other, and how all three are needed. It is hard to get the micro and the macro to be friends, but he has done it.

Lee Clarke carried the garbage can metaphor of organizational analysis further and looked at the response of a number of public and private organizations to the contamination by dioxins of a 18-story government building in Binghamton, NY (Clarke 1989). Organizations fought unproductively over the cause of the accident, the definition of risk involved, the assignment of responsibility, and control of the cleanup. While the accident was a simple component failure accident, the complexity of the organizational interactions of those who could claim a stake in the system paralleled the notion of interactive complexity, and their sometimes tight coupling led to a cascade of failures to deal with it satisfactorily. An organizational 'field' can have a system accident, as well as an organization. Clarke followed this up with an analysis of another important organizational topic related to disasters (Clarke 1999). When confronted with the need to justify risky activities for which there is no experience—evacuating Long Island in New York in the event of nuclear power plant meltdown; protecting US citizens from an all-out nuclear war; protecting sensitive waterways from massive oil spills—organizations produce 'fantasy documents' based on quite unrealistic assumptions and extrapolations from minor incidents. With help from the scientific community and organizational techniques to co-opt their own personnel, they gain acceptance from regulators, politicians, and the public to launch the uncontrollable. It is in the normative spirit of *Normal Accidents*.

Widespread remediation apparently saved us from having a world-wide normal accident when the year 2000 rolled around and many computers and embedded chips in systems might have failed, bringing about interactive errors and disasters. But even while exten-

sive remediation saved us, something else was apparent: the world is not as tightly coupled as many of us thought. Though there were many 'Y2K' failures, they were isolated, and the failures of one small system (cash machines, credit card systems, numerous power plants, traffic lights and so on) did not interact in a catastrophic way with other failed systems. A few failures here and there need not interact in unexpected ways, especially if everyone is alert and watching for failures, as the world clearly was as a result of all the publicity and extensive testing and remediation. It was a very reassuring event for those who worry about the potential for widespread normal accidents.

One lesson is that NAT is appropriate for single systems (a nuclear plant, an airplane, or chemical plant, or part of world-wide financial transactions, or feedlots and live-stock feeding practices) that are hard-wired and thus tightly coupled. But these single systems may be loosely coupled to other systems. It is even possible that instead of hard-wired *grids* we may have a more 'organic' form of dense *webs* of relationships that overlap, parallel, and are redundant with each other, that dissolve and reform continuously, and present many alternative pathways to any goal. We may find, then, undersigned and even in some cases unanticipated alternatives to systems that failed, or pathways between and within systems that can be used. The grid view, closest to NAT, is an engineering view; the web is a sociological view. While the sociological view has been used by NAT theorists to challenge the optimism of engineers and elites about the safety of the risky systems they promulgate, a sociological view can also challenge NAT pessimists about the resiliency of large system (Perrow 1999).

Nevertheless, the policy implications of NAT are not likely to be challenged significantly by the 'web' view. While we have wrung a good bit of the accident potential out of a number of systems, such as air transport, the expansion of air travel guarantees catastrophic accidents on a monthly basis, most of them preventable but some inherent in the system. Chemical and nuclear plant accidents seem bound to increase, since we neither try hard enough to prevent them nor reduce the complexity and coupling that make some accidents 'normal' or inevitable. New threats from genetic engineering and computer crashes in an increasingly interactive world can be anticipated. Lee Clarke's work on fantasy documents shows how difficult it is to extrapolate from experience when we have new or immensely enlarged risky systems, and how tempting it is to draw ridiculous parallels in order to deceive us about safety (Clarke and Perrow 1996, Clarke 1999).

It is also important to realize how easily unwarranted fears can be stimulated when risky systems proliferate (Mazur 1998). Formulating public policy when risky systems proliferate, fears abound, production pressures increase, and the costs of accidents can be 'socialized' rather than borne by the systems, is

daunting. We can always try harder to be safe, of course, and should; even civil aviation has seen its accident rate fall, and commercial air travel is safer than being at home, and about as safe as anything risky can be. But for other systems—nuclear plants, nuclear and biological weapons, chemical plants, water transport, genetic engineering—there can be policy attention to internalizing the costs of accidents, making risk taking expensive for the system; downsizing operations (at some cost to efficiency); decoupling them (there is no engineering need for spent fuel rod storage pools to sit on top of nuclear power plants, ready to go off like radioactive sparklers with a power failure or plant malfunction); moving them away from high-population areas; and even shutting some down. The risks systems to operators may be bearable; those to users and innocent bystanders less so; those to future generations least of all.

NAT was an important first step for expanding the study of accidents from a ‘operator error,’ single failure, better safety, and more redundancy viewpoint that prevailed at the time *Normal Accidents* was published. It questioned all these and challenged the role of engineers, managers, and the elites that propagate risky systems. It has helped stimulate a vast literature on group processes, communications, cognition, training, downsizing, and centralization/decentralization in risky systems. Several new journals have appeared around these themes, and promising empirical studies are appearing, including one that operationalizes effectively complexity and coupling for chemical plants and supports and even extends NAT (Wolf and Berniker 1999). But we have yet to look at the other side of systems: their resiliency, not in the engineering sense of backups or redundancies, but in the sociological sense of a ‘web-like’ interdependency with multiple paths discovered by operators (even customers) but not planned by engineers. NAT, by conceptualizing a system and emphasizing systems terms such as interdependency and coupling and incomprehensibility, and above all, the role of uncertainty, should help us see this other, more positive side.

See also: Islam and Gender; Organizational Behavior, Psychology of; Organizational Culture, Anthropology of; Risk, Sociological Study of; Risk, Sociology and Politics of

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C. Perrow

Accountability: Political

Political accountability is the principle that governmental decision-makers in a democracy ought to be answerable to the people for their actions. The modern doctrine owes its origins to the development of institutions of representative democracy in the eighteenth century. Popular election of public officials and relatively short terms of office were intended to give the electorate the opportunity to hold their representatives to account for their behavior in office. Those whose behavior was found wanting could be punished by their constituents at the next election. Thus, the concept of accountability implies more than merely the tacit consent of the governed. It implies both