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The Vulnerable System: An Analysis of the Tenerife Air Disaster

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The Tenerife air disaster, in which a KLM 747 and a Pan Am 747 collided with a loss of 583 lives, is examined as a prototype of system vulnerability to crisis. It is concluded that the combination of interruption of important routines among interdependent systems, interdependencies that become tighter, a loss of cognitive efficiency due to autonomic arousal, and a loss of communication accuracy due to increased hierarchical distortion, created a configuration that encouraged the occurrence and rapid diffusion of multiple small errors. Implications of this prototype for future research and practice are explored.

There is a growing appreciation that large scale disasters such as Bhopal (Shrivastava, 1987) and Three Mile Island (Perrow, 1981) are the result of separate small events that become linked and amplified in ways that are incomprehensible and unpredictable. This scenario of linkage and amplification is especially likely when systems become more tightly coupled and less linear (Perrow, 1984).

What is missing from these analyses, however, is any discussion of the processes by which crises are set in motion. Specifically, we lack an understanding of ways in which separate small failures become linked. We know that single cause incidents are rare, but we don't know how small events can become chained together so that they result in a disastrous outcome. In the absence of this understanding, people must wait until some crisis actually occurs before they can diagnose a problem, rather than be in a position to detect a potential problem before it emerges. To anticipate and forestall disasters is to understand regularities in the ways small events can combine to have disproportionately large effects.

The purpose of the following analysis is to suggest several processes that amplify the effects of multiple small events into potentially disastrous outcomes. These processes were induced from an analysis of the Tenerife air disaster in

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which 583 people were killed. The processes include, the interruption of important routines, regression to more habituated ways of responding, the breakdown of coordinated action, and misunderstandings in speech-exchange systems. When these four processes occur in the context of a system that is becoming more tightly coupled and less linear, they produce more errors, reduce the means to detect those errors, create dependencies among the errors, and amplify the effects of these errors.

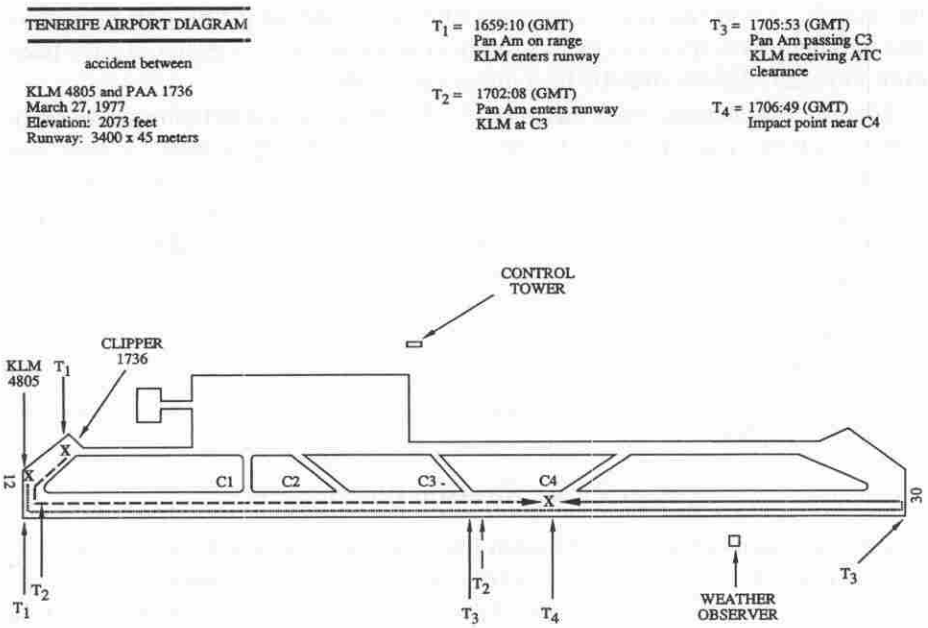
These processes are sufficiently basic and widespread that they suggest an inherent vulnerability in human systems that, up until now, has been overlooked. The processes suggest both a research agenda for the 90s as well as a managerial agenda.

Description of Tenerife Disaster[1]

On March 27, 1977, KLM flight 4805, a 747 bound from Amsterdam to the Canary Islands, and Pan Am flight 1736, another 747 bound from Los Angeles and New York to the Canary Islands, were both diverted to Los Rodeos airport at Tenerife because the Las Palmas airport, their original destination, was closed because of a bomb explosion. KLM landed first at 1:38 PM, followed by Pan Am which landed at 2:15 PM. Because Tenerife is not a major airport, its taxi space was limited. This meant that the Pan Am plane had to park behind the KLM flight in such a way that it could not depart until the KLM plane left. When the Las Palmas airport reopened at 2:30, the Pan Am flight was ready to depart because its passengers had remained on board. KLM's passengers, however, had left the plane so there was a delay while they reboarded and while the plane was refueled to shorten its turnaround time at Las Palmas. KLM began its taxi for takeoff at 4:56 PM and was initially directed to proceed down a runway parallel to the takeoff runway. This directive was amended shortly thereafter and KLM was requested to taxi down the takeoff runway and at the end, to make a 180 degree turn and await further instruction.

Pan Am was requested to follow KLM down the takeoff runway and to leave the takeoff runway at taxiway C3, use the parallel runway for the remainder of the taxi, and then pull in behind the KLM flight. Pan Am's request to hold short of the takeoff runway and stay off it until KLM had departed, was denied. After the KLM plane made the 180 degree turn at the end of the takeoff runway, rather than hold as instructed, it started moving and reported, "we are now at takeoff." Neither the air traffic controllers nor the Pan Am crew were certain what this ambiguous phrase meant, but Pan Am restated to controllers that it would report when it was clear of the takeoff runway, a communique heard inside the KLM cockpit. When the pilot of the KLM flight was asked by the engineer, "Is he not clear then, that Pan Am?" the pilot replied "yes" and there was no further conversation. The collision occurred 13 seconds later at 5:06 PM. None of the 234 passengers and 14 crew on the KLM flight survived. Of the 380 passengers and 16 crew on the Pan Am plane, 70 survived, although 9 died later, making a total loss of 583 lives.

A brief excerpt from the Spanish Ministry of Transport and Communication's investigation of the crash, describes interactions among the KLM crew members



immediately before the crash. These interactions, reconstructed from the KLM cockpit voice recorder (CVR), are the focus of the remainder of our analysis.

As the time for the takeoff approached, the KLM captain "seemed a little absent from all that was heard in the cockpit. He inquired several times, and after the copilot confirmed the order to backtrack, he asked the tower if he should leave the runway by C-1, and subsequently asked his copilot if he should do so by C-4. On arriving at the end of the runway, and making a 180 degree turn in order to place himself in takeoff position, he was advised by the copilot that he should wait because they still did not have an ATC clearance. The captain asked him to request it, and he did, but while the copilot was still repeating the clearance, the captain opened the throttle and started to takeoff. Then the copilot, instead of requesting takeoff clearance or advising that they did not yet have it, added to his read-back, "We are now at takeoff."

The tower, which was not expecting the aircraft to take off because it had not been given clearance, interpreted the sentence as, "We are now at takeoff position." (When the Spanish, American and Dutch investigating teams heard the tower recording together and for the first time, no one, or hardly anyone, understood that this transmission meant that they were taking off.) The controller replied: "O.K.,...stand by for takeoff...I will call you." Nor did the Pan Am, on hearing the "We are now at takeoff," interpret it as an unequivocal indication of takeoff. However, in order to make their own position clear, they said, "We are

still taxiing down the runway." This transmission coincided with the "Stand by for takeoff...I will call you," causing a whistling sound in the tower transmission and making its reception in the KLM cockpit not as clear as it should have been, even though it did not thereby become unintelligible.

The communication from the tower to the PAA requested the latter to report when it left the runway clear. In the cockpit of the KLM, nobody at first confirmed receiving these communications until the Pan Am responded to the tower's request that it should report leaving the runway with an "O.K., we'll report when we're clear." On hearing this, the KLM flight engineer asked, "Is he not clear then?" The captain did not understand him and he repeated, "Is he not clear that Pan American?" The Captain replied with an emphatic "Yes." Perhaps influenced by his great prestige, making it difficult to imagine an error of this magnitude on the part of such an expert pilot, both the copilot and flight engineer made no further objections. The impact took place about 13 seconds later (*Aviation Week,* 1978b: 71).

Tenerife as a Stressful Environment

Stress is often defined as a relation between the person and the environment, as in Holyroyd's and Lazarus's (1982) statement that "psychological stress requires a judgment that environmental and/or internal demands tax or exceed the individual's resources for managing them" (22). Their use of the word *judgment* emphasizes that stress results from an appraisal that imposes meaning on environmental demands. Typically, stress results from the appraisal that something important is at stake and in jeopardy (McGrath, 1976).

There were several events impinging on people at Tenerife that are likely to have taxed their resources and been labeled as threatening. These events, once appraised as threatening, had a cumulative, negative effect on performance (George, 1986). After we review some of the more prominent of these events, we look more closely at which concepts used in the stress literature help us most to make sense of the Tenerife disaster. It is these concepts that deserve closer attention in subsequent research on how crises are mobilized. The concepts to be discussed include size of discrepancy between demands and abilities, regression to first learned responses, and interruption as the occasion for stress. First, however, we review the demands at Tenerife.

Environmental Demands at Tenerife

The KLM crew felt growing pressure from at least three sources: Dutch law, difficult maneuvers, and unpredictable weather. Because the accident took place near the end of March, members of the KLM crew were very near the limits of time they were allowed to fly in one month. This was more serious than a mere inconvenience because in 1976 the Dutch enacted a tough law on "Work and Rest Regulations for Flight Crews" (Roitsch, Babcock, & Edmunds, 1979: 14) that put strict limits on flight and duty time. The computation of these limits was complex and could no longer be done by the captain nor did the captain have any discretion to extend duty time. Therefore, the KLM crew faced the possibility of fines, imprisonment, and loss of pilot license if further delays materialized. The

crew was informed that if they could leave Las Palmas by 7 PM their headquarters thought they could make it back to Amsterdam legally, but headquarters would let them know in Las Palmas.

Further pressure was added because the maneuver of turning a 747 around (backtracking) at the end of a runway is difficult, especially when that runway is narrow. It takes a minimum width of 142 feet to make a 180 degree turn in a 747 (Roitsch et al., 1979: 19) and the Tenerife runway was 150 feet wide.

Finally, the weather was unpredictable, and at Tenerife that creates some unique problems. Tenerife is 2073 feet above sea level and the sea coast is just a few miles away. This means that clouds rather than fog float into the airport. When KLM's crew backtracked, they saw a cloud 3000 feet down the runway moving toward them at 12 knots (Roitsch et al., 1979: 12), concealing the Pan Am plane on the other side. Pan Am was taxiing inside this cloud and passed its assigned runway exit because it could not see it. KLM entered that same cloud 1300 feet into its takeoff roll and that is where the collision occurred. The tower did not see the collision or the resulting fire because of the cloud, nor could the firefighters find the fire at first when they were summoned. The density of the cloud is further shown by the fact that when the firefighters started to put out the fire on one plane, the KLM plane, they didn't realize that a second plane was on fire nearby because they couldn't see it (*Aviation Week*, 1978a: 117-119).

The KLM crew was not the only group that was under pressure. Las Palmas airport had reopened for traffic at 2:30, barely 15 minutes after Pan Am had landed at Tenerife. Pan Am was ready to leave Tenerife immediately except that they were blocked by KLM 4805 and continued to be blocked for another 2-1/2 hours. Reactions of the Pan Am crew to the lengthening delays undoubtedly were intensified by the fact that they had originally asked to circle over Las Palmas because they had sufficient fuel to do so, a request that was denied by Spanish controllers. The Pan Am crew also saw the weather deteriorating as they waited for KLM to leave. They had been on duty 11 hours, although they were not close to the limits of their duty time.

Controllers at Tenerife were also under pressure because they were shorthanded, they did not often handle 747's, they had no ground radar, the centerline lights on the runway were not operating, they were working in English (a less familiar second language), and their normal routines for routing planes on a takeoff and landing were disrupted because they had planes parked in areas they would normally use to execute these routines.

Research Leads to be Pursued

The events at Tenerife provide a pretext to think more carefully about discrepancy size, regression, and interruption as components of stressful environments. These three concepts figure prominently in the events we have just reviewed, and by implication, they may also be a source of system vulnerability in other environments.

McGrath (1976) has shown that the traditional formulation of stress as a discrepancy between demands and ability operates differently from what most people thought. The highest arousal occurs when abilities are only slightly less than

what is demanded and there is a chance that the person can cope. Small discrepancies create the most intense stress.

Despite all of the pressures operating at Tenerife, and despite all of the ways in which demands were mounting, the people involved were nearly able to cope successfully. Abilities almost matched demands. When the KLM captain saw the Pan Am plane in front of him on the runway, he pulled back fully on the control column in an attempt to fly over it. The tail of his plane scraped the runway and left a 66 foot long streak of metal embedded in the runway. It was only the KLM's wheels that hit the right wing and rear cabin of the Pan Am plane (which the Pan Am pilot had almost been able to steer off the takeoff runway) (Roitsch et al., 1979: 13), and when the KLM settled back on the runway after the collision, it was intact. Ignition of the extra fuel taken on to speed up departure from Las Palmas caused the KLM fatalities.

Tenerife is important, not just because it illustrates that small discrepancies can have large effects, but even more important because it seems to be an usually clear example of the much discussed, but seldom pursued idea that stress can produce regression to first learned responses (Allnutt, 1982: 11; Barthol & Ku, 1959). If there is a key to understanding the Tenerife disaster, it may lie in this principle.

The pilot of KLM 4805 was Head of the Flight Training Department of KLM. He was a training captain: the flights he was most familiar with were those which followed a script, had fewer problems, and were shorter in duration. Furthermore, he had not flown on regular routes for 12 weeks. The importance of this background becomes evident in the context of a footnote in the Spanish Ministry's report:

> "Although the captain [KLM captain] had flown for many years on European and intercontinental routes, he had been an instructor for more than 10 years, which relatively diminished his familiarity with route flying. Moreover, on simulated flights, which are so customary in flying instruction, the training pilot normally assumes the role of controller: that is, he issues takeoff clearances. In many cases no communications whatsoever are used in simulated flights, and for this reason takeoff takes place without clearance" (*Aviation Week*, 1978a: 121).

Pressure leads people to fall back on what they learned first and most fully. In the case of the KLM pilot, this was giving himself clearance to takeoff. Giving clearance is what he had done most often for the last 10 years when sitting at the head of a runway and it is the response he may have reverted to as pressures mounted at Tenerife.

Both the Pan Am crew and the air traffic controllers seem also to show evidence of regression. The Pan Am captain wanted to hold short of the active runway, but he was asked to proceed down the active runway by a ground controller who spoke with a heavy accent and who did not seem to comprehend fully what Pan Am was requesting. Rather than attempt a potentially more complex negotiation to get permission to hold short, the Pan Am captain chose the more overlearned option of compliance with the controller's directive. Controller commu-

niques also became more cryptic and harder to understand as controllers tried to cope with too many aircraft that were too big. These pressures may have made their use of English, a language which they used less frequently, more tenuous and increased the likelihood that more familiar Spanish language constructions would be substituted.

The more general implication of the disruptive effects of regression is that more recently learned complex rationales and complex collective responses are all more vulnerable to disruption than are older, simpler, more overlearned, cultural and individual responses. Requisite variety (Zeleny, 1986) is much harder to achieve than it looks. When people acquire more complex responses so that they can sense and manage more complex environments, they do not become more complex all at once. Instead, they develop their complexity serially. Under pressure, those responses acquired more recently and practiced less often, should unravel sooner than those acquired earlier, which have become more habitual. Thus, requisite variety may disappear right when it is most needed. Hypothetically, the KLM pilot had high requisite variety because he was both a training pilot and a line pilot. In reality, however, his more recent habits of line flying disappeared under pressure and were replaced by his older habits of flying under training conditions.

Among the many theories of stress that could be applied to the incidents at Tenerife, one of the most fitting is Mandler's (1982) because it encompasses so many properties of Tenerife, including interruption, limited information processing, cognitive narrowing, interpretation, plans, and autonomic arousal.

The centerpiece of Mandler's theory is the idea that interruptions trigger activity in the autonomic nervous system. This autonomic activity absorbs information processing capacity, which then decreases the efficiency of complex thought processes. By way of background, the autonomic nervous system is the branch of the peripheral nervous system that regulates the body's internal environment and maintains homeostasis. The sympathetic branch of the ANS, through the secretion of adrenaline and noradrenaline, mobilizes the common symptoms of stress such as accelerated heart rate, increased blood pressure, and increased glucose secretion. (Frankenhauser, 1986).

In Mandler's theory, autonomic activity is triggered by interruption, which he defines as "Any event, external or internal to the individual, that prevents completion of some action, thought sequences, plan, or processing structure" (92). Both action structures and intrapsychic cognitive structures can be interrupted, either when an expected event fails to occur or an unexpected event occurs.

The degree of autonomic activity that occurs following an interruption depends on two factors: first, the degree of organization of the action or thought process that is interrupted (invariant, habituated actions with high degree of expectancy among parts create a sharp increase in autonomic activity when interrupted); and second, the severity of interruption (high external demand to complete an action, coupled with repeated attempts to restart the action and repeated interruptions combine to facilitate arousal).

The autonomic activity triggered by an interruption focuses attention on two things, both of which consume considerable information processing capacity. At-

tention is focused on the interrupting event, and if it is not altered, on the internal autonomic activation itself. When autonomic arousal consumes scarce information processing capacity, this reduces the number of cues that can be processed from the activity that was underway at the time of the interruption.

In Mandler's model, stress is an interruption that signals an emergency and draws attention to events in the environment. In the short run, this signalling is adaptive and improves coping. Autonomic activity alerts people to the existence of threatening events, but if the threat is not dealt with and the arousal continues, then it registers in consciousness and interferes with ongoing cognitive activity. Thus, consciousness becomes the arena for troubleshooting, but unless the diagnosis and coping is swift, and the response being interrupted is weak in its organization, the troubleshooting consumes information processing capacity and this leads to the omission of important cues for task performance and an increase in cognitive inefficiency.

If we apply Mandler's concepts to the situation of the KLM pilot, we pay closer attention to such aspects as the following. The diversion to Los Rodeos was an interruption of the plan to get back to Amsterdam legally. And the cloud moving down the runway toward the KLM plane represents a potential interruption of a lower order plan to leave Las Palmas. Because neither interruption can be removed directly, autonomic arousal increases, displaces more information processing capacity, and decreases attention to peripheral cues such as radio transmissions. The severity of the interruption should be substantial because a well organized takeoff routine is interrupted, but most of all because there is a continuing, intense demand to complete the interrupted action (there is no realistic substitute activity that will get the passengers to Las Palmas unless they leave Los Rodeos on KLM 4805).

The pilot's potential focus on the interruption created by the diversion to Los Rodeos and on the consequent lengthening of duty time, coupled with potential awareness of his own internal agitation (which would be hard to label as "pleasure" but easy to label as "frustration" or "fear"), all use up information processing capacity. This leaves little remaining capacity for the immediate task of taxiing the plane to a difficult takeoff position and then flying it safely off the runway. Furthermore, there would appear to be little remaining capacity available to process cryptic, non-standard, sometimes noisy transmissions from the tower and other aircraft.

Thus, to use Mandler's phrase, consciousness became "the arena for troubleshooting," but the troubleshooting was devoted to the question of a legal return to Amsterdam, a higher order plan, rather than to the immediate plan of leaving Los Rodeos. Attention devoted to interruption of the higher order plan used up the major share of attention that could have been allotted to the lower order, more immediate plan.

The point I want to demonstrate is that crises in general typically involve the interruption of plans or cognitive structures or actions that are underway. Because interruption is a generic accompaniment of crisis, a theory of stress and emotion

that uses interruption as the point of departure is ideally suited for further investigation and application to settings involving crisis. Furthermore, susceptibility to interruption is an important predictor of system vulnerability.

The Breakdown of Coordination Under Stress

The phrase "operator error" is misleading in many ways, but among the most subtle problems is the fact that the term is singular (Hayashi, 1985). An operator error is usually a collective error (e.g., Gardenier, 1981), but it is only recently that efforts have been made to understand the ways in which team interaction generates emergent potentialities for and remedies of local failures (e.g, Hirokawa, Govran, & Martz, 1988). The crew in the KLM cockpit provides a unique glimpse of some ways in which crises become mobilized when crew interaction breaks down.

Individualism in the Cockpit

The setting in the KLM cockpit was unusual, not only because the captain was the head of flight training and a member of the top management team, but also because this captain had given the co-pilot (first officer) his qualification check in a 747 just 2 months earlier. This recently certified first officer made only two comments to try to influence the captain's decision during the crucial events at the head of the runway. The ALPA report of the crash describes those comments this way:

> The KLM first officer was relatively young and new in his position and appeared to be mainly concerned with completing his tasks so as not to delay the captain's timing of the takeoff. He only made two comments in order to try to influence the captain's takeoff decision. When the captain first began pushing up the thrust levers, he said, "Wait a minute, we do not have an ATC clearance." The captain, rather than admitting to an oversight, closed the thrust levers and responded by saying, "No, I know that, go ahead ask." The second occurrence was at the end of the ATC clearance readback. The KLM first officer observed that the captain had commenced the takeoff and finished the ATC clearance readback by stating, "We are, uh, taking off" or "We are at takeoff" over the radio. After many hours of replaying the tapes, it is difficult to be sure what statement the first officer made. For this reason, we assume that neither the approach controller nor the Pan Am crew were positive about what was said. The Study Group believes that this ambiguous statement by the first officer was an indication that he was surprised by the KLM captain's actions in commencing the takeoff. We believe the first officer thought something was wrong with the takeoff decision by the captain, and tried to alert everyone on frequency that they were commencing takeoff. The KLM captain did not comment on his first officer's radio transmission but rather became immediately involved in setting takeoff power and tracking the runway centerline. (Roitsch et al., 1979: 18).

The first officer is not the only person acting in a manner that is more individual than collective (Wagner & Moch, 1986). The same was true for the engineer.

The flight engineer was the First and current President of the European Flight Engineers Organization. There is an odd statement about him in the ALPA documents. It says that he was not in favor of integrating the functions of the engineering position with those of the pilot crewmembers, such as communication, navigation, and general monitoring of the operation of the flight. "He is said to have felt that flight engineering should consist of specialized emphasis on powerplant and systems analysis and maintenance consideration" (Roitsch et al., 1979: 5). Recall that the engineer was the last point where this accident could have been prevented when he asked, "Is he not clear then, that Pan Am?" Recordings suggest that he made this statement in a "tentative manner" (Roisch et al., 1979: 22) just as the plane entered the thick cloud and the pilots had their hands full keeping the plane on the runway.

Research Leads to be Pursued

These several observations suggest that the KLM crew acted less like a team (Hackman, 1987) than like three individuals acting in parallel. That difference becomes important in the context of an important generalization suggested by Hage (1980): "Micro-sociological hypotheses usually require limits. The human scale is much smaller than the organizational one—at least as far as hypotheses are concerned. Beyond this the "world" of the individual appears to be dominated by normal curves where too much of a good thing is as bad as too little. In contrast, linearity appears to be a good first approximation in the organizational 'world' " (202).

We should expect that most microhypotheses are curvilinear and most macrohypotheses are linear. McGuire's (1968) model of individual persuasion, for example, is curvilinear and predicts that people with moderately high intelligence are more persuasible than are those who are higher or lower in intelligence. Dailey (1971) argues that individual perceptual accuracy is curvilinear and reflects a tradeoff between increasing confidence in one's own judgment and decreasing openness to new information.

When we move from individual to group, we move from micro in the direction of macro and should expect to find fewer curvilinear relationships and more linear relationships. For example, the recurrent finding that the relationship between stress and performance is curvilinear, holds for individuals, but when it is examined as a group phenomenon, the relationship is found to be more linear (Lowe & McGrath, 1971). Thus, as we move from individual to group, increases in stress should lead to increases in performance, not decreases. However, this shift is dependent on whether individuals coalesce into a team that is a distinctive entity exhibiting distinctive functional relationships or whether they merely act in the presence of another and respond and fall apart, more like individuals than like groups.

A KLM crew that is not a team is subject to curvilinear relationships, whereas a crew that is a team is more subject to linear relations. It is conceivable that more stress improves team performance but degrades individual performance, because teamwork lowers task complexity. A well functioning team may face a simpler task than does a poorly functioning team. And research on the Yerkes-Dodson (e.g., Bregman & McAllister, 1982) law shows that performance of simple tasks

is less susceptible to the disruptive effects of arousal than is performance of complex tasks.

What Hage describes resembles what Hackman (1987) seems to have in mind when he describes group synergy: synergy "refers to group-level phenomena that (1) emerge from the interaction of group members, and (2) affect how well a group is able to deal with the demands and opportunities in its performance situation" (324). Group synergy creates outcomes that "may be quite different from those that would be obtained by simply adding up the contributions of individual members" (321-322). Synergy can be either positive or, as appears to be the case with the KLM crew, negative: negative synergy is described as "a failure of coordination within the group so severe that *nobody* knows what he or she is supposed to be doing" (322). Although it is true that the plane was accelerating in a mechanically correct manner and the crew had in hand a clearance routing them to Las Palmas, lingering uneasiness about pilot judgments was neither voiced nor resolved until it was too late. What is unclear is whether the KLM crew represents a case of negative synergy with a defective group interaction process, or a case of three individuals who never became a group in the first place, or a case where a group became transformed into a collection of separate individuals when stress led the three people to fall back on dissimilar idiosyncratic ways of responding (Lazarus & Folkman, 1984; 104).

Hackman's model seems to suggest that the KLM crew in the Tenerife disaster is an example of a group where there was a slight deficiency of knowledge and skill (pilot unfamiliar with route flying, first officer recently certified on 747) but mainly a deficiency in the performance strategies (328-331) they adopted to review their design and their process and to alter it to fit the abnormal demands created by the diversion.

Helmreich's continuing research on flightcrew behavior has direct relevance to our understanding of the Tenerife disaster. As part of this program, Helmreich has assessed the managerial aspect of flight operations using a 25-item "Cockpit management attitudes survey" (Helmreich, 1984). The instrument, administered to more than 5000 pilots, has been validated on pilots classified as high and low in resource management (Helmreich, Foushee, Benson, & Russini, 1985) and covers such topics as personal reactions to stress (e.g., "pilots should feel obligated to mention their own psychological stress or physical problems to other flight-crew personnel before or during a flight"), interpersonal communication (e.g., "the pilot flying the aircraft should verbalize his plans for maneuvers and should be sure that the information is understood and acknowledged by the other pilot"), and crew roles (e.g., "There are no circumstances [except total incapacitation] where the first officer should assume command of the ship").

The items in the survey are of special interest in the context of Tenerife. It was found (Helmreich, 1984: 586) that Captains and First Officers differed significantly in their answers to item 5, which read, "First officers should not question the decision or actions of the captain except when they threaten the safety of the flight." The first officers agreed with the contention significantly more often than did the captains. However, on item 6, which read "Captains should encourage their first officers to question procedures during normal flight operations and in

emergencies,'' captains were significantly less enthusiastic about encouraging input than were first officers. Thus, the idea of coordinated activity and coordinated decision making in the cockpit is a source of ambivalence and a potential source of errors that could enlarge.

These two items remained diagnostic in the validation study, because they were 2 of the 6 items that discriminated most sharply between 114 pilots rated below average or outstanding by evaluators, who actually rode with these pilots and evaluated their flight crew performance. Pilots evaluated as outstanding felt more strongly that first officers should be encouraged to question their decisions and that the first officers should question decisions other than those that threaten the safety of the flight. Pilots with below average performance held the opposite attitudes. Parenthetically, it should be noted that the item that discriminated most sharply between the outstanding and the below average was the item that read, ''My decision-making ability is as good in emergencies as in routine flying situations.'' Below average pilots agree with this item; outstanding pilots disagree with it. Thus, not only do the outstanding pilots realize that their ability to make decisions can change under stress, but in realizing this, they may become more receptive to inputs from others that will help the crew cope.

Speech-exchange Systems as Organizational Building Blocks

KLM as an airline is in large part constituted by its speech exchanges. When people employed by KLM talk among themselves and with outsiders, not only do they communicate within an organization, they also construct the organization itself through the process and substance of what they say. As their talk varies, the solidity and predictability of the organization itself varies. Conversations with headquarters about duty time, conversations with the KLM agent at Las Palmas about ways to hasten the departure, conversations (or the lack of them) among crew members that construct the hypothesis that the runway is empty, all are the building blocks of the order and disorder that is the hallmark of organized activity.

The unfolding of the Tenerife disaster reminds us that macroprocesses such as centralization are made up of repetitious microevents that occur frequently and in diverse locations. Organizations are built, maintained, and activated through the medium of communication. If that communication is misunderstood, the existence of the organization itself becomes more tenuous.

The Tenerife disaster was built out of a series of small, semi-standardized, misunderstandings, among which were the following:

1. KLM requested 2 clearances in one transmission (we are now ready for takeoff and are waiting for ATC clearance). Any reply could be seen as a comment on both requests.

2. The controller, in giving a clearance, used the words ''after takeoff'' (''maintain flight level niner zero right after takeoff proceed with heading zero four zero until intercepting the three two five radial from Las Palmas''), which could have been heard by the KLM crew as permission to leave. The ATC Manual (7110.650, October 25, 1984) clearly states, under the heading ''Departure Terminology'' that controllers should, ''Avoid using the term 'takeoff'' except to ac-

tually clear an aircraft for takeoff or to cancel a takeoff clearance. Use such terms as 'depart,' 'departure,' or 'fly' in clearances when necessary'' (heading 4-20: 4-5). Thus, the Tenerife controller could have said ''right turn after departure'' or ''right turn fly heading zero four.''

3. As we have seen, the phrase ''We are now taking off'' is non-standard and produced confusion as to what it meant.

4. When the controller said to KLM, ''Okay...stand by for takeoff...I will call you,'' a squeal for the last portion of this message changed the timbre of the controller's voice. This may have led the KLM crew to assume that a different station was transmitting and that the message was not intended for them.

5. The controller did not wait to receive an acknowledgement (e.g., ''Roger'') from KLM after he had ordered them to ''standby for takeoff.'' Had he done so, he might have discovered a misunderstanding (Hurst, 1982: 176).

6. Shortly before the collision, for the first and only time that day, the controller changed from calling the Pan Am plane ''Clipper 1736'' to the designation ''Pappa Alpha 1736.'' This could sound like the controller is referring to a different plane (Roitsch et al., 1979: 22).

The point to be emphasized is that speech exhange and social interaction is an important means by which organization is built or dismantled. This is not to say that social interaction is a local, self-contained production that is unaffected by anything else in the setting. There clearly are ''noninterpretational foundations of interpretation in social interaction'' (Munch & Smelser, 1987: 367). The interpretation process itself is shaped by shared language, authority relationships that assign rights of interpretation, norms of communication, and communication. The meanings that actors co-construct are not self-created. So microanalysis cannot go it alone without macroinput. As Mead put it, people carry a slice of society around in their heads (Alexander & Giesen, 1987: 9). But to acknowledge that slice, is also to acknowledge the carrier and the fact that the slice is realized, made visible, and given shape, in discourse.

Research Leads to be Pursued

We have already discussed several issues regarding communication and here will merely supplement those by suggesting that (a) communication is necessary to detect false hypotheses and (b) crises tend to create vertical communication structures when, in fact, lateral structures are often more appropriate for detection and diagnosis of the crisis.

In any crisis situation, there is a high probability that false hypotheses will develop and persist. It is largely through open exchange of messages, independent verification, and redundancy, that the existence of false hypotheses can be detected. There are at least four kinds of situations in which false hypotheses are likely to occur and in which, therefore, there is a premium on accuracy in interpersonal communication (O'Reilly, 1978). These four, identified by Davis (1958), are the following:

1. Expectancy is very high. If a pilot hears a distorted message and knows the tower would not say something meaningless, then the pilot tries to fill in the gaps, and hears the message he or she ''should'' have heard. This tendency increases the likelihood that a dubious hypothesis will be preserved. Applied to Tenerife,

because the crew was expecting takeoff clearance and because they wanted to hear takeoff clearance, it is probable that when the tower said, "Okay, stand by for takeoff, I will call you," and when a squeal accompanied the middle portion of that message, they could have heard "OK, takeoff," which is what they expected to hear.

2. The hypothesis serves as a defense. People interpret communiques in ways that minimize anxiety. In nuclear power plant control rooms, for example, "it is easy for each operator to assume the other knows best, and, in being a good fellow, to reinforce the other's misperceptions. Thus error probabilities for people working together may be better or worse than error probabilities for individuals working independently and not communicating" (Sheridan, 1981: 23). Occasionally, a pilot's seniority and status "may be an even greater bar to admitting his mistakes—and he will only publicly reject his false hypothesis when it is too late" (Allnutt, 1982: 9). Applied to Tenerife, the hypothesis that there is no one on the runway, given the limited amount of current information present in the radio traffic that had been processed, could easily be bolstered if the pilot and the first officer both assumed that, if there were someone on the runway, surely the head of Flight Training would know it.

3. Attention is elsewhere. We have already encountered this explanation in the context of Mandler's theory. Allnutt (1982: 9) supplements the earlier discussion when he notes that, "if a pilot has a number of immediate tasks, and if one of those requires special attention, he is likely to be less critical in accepting hypotheses about other components of the work load." Thus a person may ignore information that conflicts with the prevailing hypothesis when it comes from instruments that are on the periphery of attention. Applied to Tenerife, the pilot was undoubtedly more focussed on the takeoff including the approaching cloud, the difficult backtrack maneuver, and tracking the centerline on the runway without the help of lights than he was on the radio communiques that were being handled by the first officer.

4. It is after a period of high concentration. There is often a let-up near the end of a journey, when the most difficult part of the procedure has been completed. False hypotheses can persist in the face of this decreased attentiveness. Applied to Tenerife, the Spanish Ministry report of the accident actually raised this possibility: "Relaxation—after having executed the difficult 180-degree turn, which must have coincided with a momentary improvement in the visibility (as proved by the CVR, because shortly before arriving at the runway approach they turned off the widescreen wipers), the crew must have felt a sudden feeling of relief which increased their desire to finally overcome the ground problems: the desire to be airborne" (*Aviation Week,* 1978a: 121). The false hypothesis that the runway was clear was something the crew expected to be true, something they wanted to be true, something they dimly felt might not be true, but in the context of hierarchical communications was something they jointly treated as if it were true.

The likelihood that crises impose hierarchical constraints (Stohl & Redding, 1987) on speech-exchange systems is a straightforward extrapolation from the finding that stress leads to centralization (see Staw, Sandelands, & Dutton,

1981). This finding traditionally has been interpreted in a way that masks a potentially key cognitive step that allows us to understand Tenerife more fully. Before stress creates centralization, it must first increase the salience of hierarchies and formal authority, if it is to lead to centralization. It is the increased salience of formal structure that transforms open communication among equals into stylized communications between unequals. Communication dominated by hierarchy activates a different mindset regarding what is and is not communicated and different dynamics regarding who initiates on whom. In the cockpit, where there is a clear hierarchy, especially when the captain who outranks you is also the instructor who trained you, it is likely that attempts to create interaction among equals is more complex, less well-learned, and dropped more quickly in favor of hierarchical communication, when stress increases.

What is especially striking in studies of communication distortion within hierarchical relationships (Fulk & Mani, 1985), is that the "types of subordinate message distortion [to please the receiver] are quite similar to the strategies used to address message overload. They include gatekeeping, summarization, changing emphasis within a message, withholding, and changing the nature of the information" (Stohl & Redding, 1987: 481). The similar effects of hierarchy and overload on communication suggests that one set of distortions can solve two different problems. A mere change in emphasis in a communication upward can both reduce message overload and please the recipient. These mutually reinforcing solutions to two distinct problems of crises—overload and centralization—should exert continuing pressure on communication in the direction of distortion and away from accuracy.

Interactive Complexity as Indigenous to Human Systems

As the day unfolded at Tenerife after 1:30 in the afternoon, there was a gradual movement from loosely coupled events to tightly coupled events, and from a linear transformation process to a complex transformation process with unintended and unnoticed contingencies. Human systems are not necessarily protected from disasters by loose coupling and linear transformation systems, because these qualities can change when people are subjected to stress, ignore data, regress, centralize, and become more self-centered.

Thus it would be a mistake to conclude from Perrow's (1984) work that organizations are either chronically vulnerable to normal accidents or chronically immune from them. Perrow's (1984:63) structural bias kept him from seeing clearly that, when you take people and their limitations into account, susceptibility to normal accidents can change within a relatively short time.

Several events at Tenerife show the system growing tighter and more complex:

1. Controllers develop ad hoc routing of 2 jumbo jets on an active runway because they have no other place to put them. (Roisch et al., 1979: 8).

2. Controllers have to work with more planes than they have before, without the aid of ground radar, without a tower operator, and with no centerline lights to help in guiding planes.

3. Controllers keep instructing pilots to use taxiway "Third Left" to exit the active runway, but this taxiway is impossible for a 747 to negotiate. It requires a

148 degree left turn followed by an immediate 148 degree right turn onto a taxiway that is 74 feet wide (Roisch et al., 1979: 19). Thus, neither the KLM pilot nor the Pan Am pilot are able to do what the controller tells them to do, so both pilots assume that the controller really means for them to use some other taxiway. Nevertheless, the KLM pilot may have assumed that the Pan Am pilot had exited by taxiway third left (Roisch et al., 1979: 24).

4. The longer the delay at Tenerife, the higher the probability that all hotel rooms in Las Palmas would be filled, the higher the probability that the air corridor back to Amsterdam would be filled with evening flights, occasioning other air traffic delays, and the greater the chance for backups at Las Palmas itself, all of which increased the chances that duty time would expire while the KLM crew was in transit.

5. Throughout the afternoon there was the continuing possibility that the terrorist activities that had closed Las Palmas could spread to Tenerife. In fact, when the tower personnel heard the KLM explosion, they first thought that fuel tanks next to the tower had been blown up by terrorists (Roisch et al., 1979: 8).

Research Leads to be Pursued

Stress paves the way for its own intensification and diffusion because it can tighten couplings and raise complexity. Each of the several effects of stress that we have reviewed up to this point either increases dependencies among elements within the system or increases the number of events that are unnoticed, uncontrolled, and unpredictable. For example, the same stress that produces an error due to regression paves the way for that error to have a much larger effect by increasing the complexity of the context in which the error first occurred. As stress increases, perception narrows, more contextual information is lost, and parameters deteriorate to more extreme levels before they are noticed, all of which leads to more puzzlement, less meaning, and more perceived complexity. Not only does stress increase the complexity, it also tightens couplings. Threat leads to centralization, which tightens couplings between formal authority and solutions that will be influential, even though the better solutions may be in the hands of those with less authority. Notice how the same process that produces the error in the first place, also shapes the context so that the error will fan out with unpredictable consequences.

Normally, individual failures stay separate and unlinked if they occur in a linear transformation system where they affect only an adjacent step and if they occur in a loosely coupled system where that effect may be indeterminate (Perrow, 1984: 97, characterizes "airways" as linear, modestly coupled systems). If the couplings become tighter (e.g., slack such as excess duty time is depleted) and if the linear transformation process becomes more complex through the development of a greater number of parallel events having unknown but multiple logical entailments (Douglas, 1985: 173), then more failures can occur and they can affect a greater number of additional events.

Cost cutting at the Bhopal plant prior to the disastrous gas leak illustrates the subtle way in which minor changes can tighten couplings and increase complexity:

> "When cost cutting is focused on less important units [in Union Carbide], it is not just decreased maintenance which raises susceptibility to crisis. Instead, it is all of the indirect effects on workers of the perception that their unit doesn't matter. This perception results in increased inattention, indifference, turnover, low cost improvisation, and working-to-rule, all of which remove slack, lower the threshold at which a crisis will escalate, and increase the number of separate places at which a crisis could start. As slack decreases, the technology becomes more interactively complex, which means there are more places where a minor lapse can escalate just when there are more minor lapses occurring." (Weick, 1988: 313)

The point of these details is that "normal accidents" may not be confined to obvious sites of technical complexity such as nuclear power plants. Instead, they may occur in any system that is capable of changing from loose to tight and from linear to complex. As we have suggested, any system, no matter how loose and linear it may seem, can become tighter and more complex when it is subjected to overload, misperception, regression, and individualized response.

Implications and Conclusions

Although we have examined closely only a single incident, we have done so in the belief that Tenerife is a prototype of system vulnerability in general. Among the generic properties of Tenerife that are likely to be found in other systems, we would include the interruption of important routines among and within interdependent systems, interdependencies that become tighter, a loss of cognitive efficiency due to autonomic arousal, and a loss of communication accuracy due to increased hierarchical distortion. This configuration of events seems to encourage the occurrence and rapid diffusion of multiple errors by creating a feedback loop which magnifies these minor errors into major problems.

Implications for both research and practice of the processes observed in this prototype have been scattered throughout the preceding account and I conclude by reviewing some of those which seem especially important. The concepts that I found most helpful were concepts that have been around for some time. The good news is that much of the old news about crises and behavior remains viable news. What I have basically done is gather these bits and pieces of understanding in one place, sort through them for their relevance to a single dramatic event, and then propose that the resulting assemblage represents a plausible configuration that explains the genesis of a large crisis from small beginnings. The account I have assembled is as much a reminder of tools already in hand as it is a set of speculations about new variables.

Nevertheless, in assembling, editing, and reformulating existing ideas, several themes for future research were identified and I review seven of them below.

First, the concept of temporary systems (e.g., Bryman, Bresnen, Beardsworth, Ford, & Keil, 1987; Goodman & Goodman, 1976; Miles, 1964) has been around for some time, but seems worth resuscitating because air crews, task forces and project teams are both plentiful and doing increasingly consequential work. It is not just air crews with their constantly changing personnel that form an odd mix of the mechanistic and the organic. Any group with a transient pop-

ulation is subjected to some of the same dynamics (e.g., see Gaba, Maxwell, & DeAnda, 1987 on mishaps during anesthesia administration). Thus, it would be instructive to learn to what extent parallels of Tenerife occur in the larger category of organizational forms called temporary systems.

Second, it goes without saying that we must continue to refine and make more precise the concept of stress. The concept plays an important role. It blends together emotion, anxiety, strain, pressure, and arousal. This blending can be troublesome because of the resulting ambiguity, but the global concept of stress nevertheless serves the important function of reminding investigators that affect is a vital part of experience and the human condition (Kemper, 1987). That reminder is worth whatever terminological distress it may occasion.

Third, there appears to be an important but little understood tradeoff between cohesion and accuracy in groups (e.g., Weick, 1983). Janis's (1982) important research on groupthink demonstrates the many insidious ways that sensing and criticism can be sacrificed in the service of group maintenance. Tenerife reminds us again of how delicate this balance can be and of the necessity to see the conditions under which the dilemma can be accommodated.

Fourth, in a related vein, we may need to restudy the possibility that pluralistic ignorance (Miller & McFarland, 1987) is a potential contributor to early stages of crisis. Pluralistic ignorance applied to an incipient crisis means I am puzzled by what is going on, but I assume that no one else is, especially because they have more experience, more seniority, higher rank. That was the error with the Enterprise at Bishop Rock (Robert, in press) (i.e., "surely the captain knows that is a rock just ahead") as well as with the KLM takeoff (i.e., "surely the captain knows that the runway may not be clear").

The first officer, who is reluctant to take off for Las Palmas but assumes no one else is, may not be all that different from the person who is reluctant to ride to Abilene (Harvey, 1974) on a sticky Sunday afternoon, but assumes no one else is. The conditions under which that paradox gets resolved before damage is done remain important to articulate.

Fifth, if the elements that form the pre-crisis context become tightly coupled and more complex, then failures occur more often because of complexity and spread farther and more quickly because of tighter couplings. That is important, but fairly obvious. What is less obvious, and what the analysis of Tenerife suggests, is that persistent failures (those that remain unresolved and lead to a buildup of autonomic arousal) can also tighten couplings and increase complexity. Failures use up information processing capacity. With less information processing capacity, people ignore more central cues, invoke simpler mental models that leave out key indicators, and become more tolerant of unexplained and unpredicted entailments. Failures make authority structures, divisions of labor, and assigned responsibilities more salient. This can tighten the coupling between assigned roles and role behavior in the crises, even though such in-role behavior may be dysfunctional. Notice that this tightening between assigned pre-crisis roles and action during crisis is especially likely if those pre-crisis roles are overlearned. Even though improvisation might reduce the impact of a crisis, it is difficult when arousal is high and when, as Helmreich (1984) demonstrated, cap-

tains are wary of the idea that there are times when first officers should override their judgment. This wariness surely does not get lost on ambitious first officers.

Special attention should be directed at systems that are either loose/linear, loose/complex, or tight/linear, because they all are potentially vulnerable to small failures that are difficult to contain. The fact that so many systems are included within these three categories is the basic point being emphasized.

If tightening and complication of systems can be blocked, slowed, or dampened, or if people can be trained and rewarded to redesign the performance strategies when both their context and their structure become tighter and more complex, then failures should stay small and local.

Sixth, we need to see whether, as group interaction improves, task complexity (Wood, 1986) decreases? If so, we then need to see if this is a plausible means by which cohesive groups are less susceptible to disruption from stress than are uncohesive groups? This may be one means by which cohesive groups continue to function productively even though they are subjected to very high levels of stress.

And seventh, we need to see whether an increment in stress increases the salience of formal structure and authority relations. If so, this may be a considerable deterrent to expertise rather than position controlling the content of an early diagnosis. Given the tendency for communication among equals to turn hierarchical under stress, it would appear necessary that those at the top of the hierarchy explicitly legitimate and model equal participation, if they are to override that salience of hierarchy.

Implications for Practice

Again, the implications for practice that emerge from an analysis of Tenerife are not unusual, but they bear repeating because we are likely to see many more situations in the future that assume the outlines of Tenerife.

First, part of any job requirement must be the necessity for talk. Strong, silent types housed in systems with norms favoring taciturnity can stimulate unreliable performance because misunderstandings are not detected. Of the four implications for managerial practice derived by Sutton and Kahn (1987) in their influential stress review, three concern talk: be generous with information, acknowledge the information functions of the informal organizations, do not hold back bad news too long. LaPorte, Rochlin, and Roberts (e.g., LaPorte & Consolini, 1989) find that reliable performance and amount of talk exchanged co-vary.

What our analysis of Tenerife has uncovered is the possibility that with communication a complex system becomes more understandable (you learn some missing pieces that make sense of your experience) and more linear, predictable, and controllable.

The recommendation that people should keep talking is not as simple as it appears, because one of the problems at Three Mile Island was too many people in the control room talking at one time with different hunches as to what was going on. The din created by tense voices plus multiple alarms, however, would make it all but impossible to single out talk as uniquely responsible for confusion, misdiagnosis, and delayed responding. The crucial talk at TMI should have occurred in hours before the control room got cluttered, not after.

If things do not make sense, speak up. This is the norm that needs to be cre-

ated. Only by doing so can you break pluralistic ignorance (i.e., "you too, I thought I was the only one who didn't know what was going on").

Second, cultivate interpersonal skills, select people on the basis of their interpersonal skills, and devote training time to the development of interpersonal skills (Helmreich, 1983), As technologies become more complex than any one person can comprehend, groups of people will be needed to register and form collective mental models of these technologies. Requisite variety is no longer an individual construct; it must be viewed as a collective accomplishment (Orton, 1988). But to create collective requisite variety, leaders must create a climate in which trust, doubt, openness, candor, and pride can co-exist and be rewarded.

Third, remember that stress is additive, and that off the job stressors cumulate with those that arise on the job. Encourage norms that people under stress should alert others who are dependent on them that their performance may be sub-par. That norm is hard to implant in a macho culture where coping is perceived as grounds for promotion and an admission of problems is seen as grounds for being plateaued.

Fourth, treat chaos as a resource and reframe crises into opportunities to demonstrate and reaffirm competence as well as to enlarge response repertoires. One of the most important contributions of chaos theory (e.g., Gleick, 1987) as well as the counsel to "thrive on chaos" (Peters, 1987) is that they suggest that disorder contains some order; therefore, prediction, if not control, is possible. If chaos theory is not convincing on those instrumental grounds, then at least it suggests that chaos is indigenous, patterned, normal, and to be expected. Appreciation of those aspects of chaos may cushion the arousal that occurs when it becomes the source of interruption. Any response is seen as susceptible to interruption: one never becomes wedded to a single strategy but instead, repeatedly cultivates options and alternative routes by which projects can be completed.

Fifth, controllability makes a difference (Karasek, 1979; Sutton & Kahn 1987), which means discretion must be generously distributed throughout the system. The removal of the KLM pilot's discretion to extend duty hours increased the severity of the interruption occasioned by the diversion to Tenerife and may have produced more cognitive narrowing than would have occurred had the effects of that interruption been bypassed by an extension of duty time.

Sixth, if a strong case can be made that new complex skills should be learned to replace old skills that are no longer appropriate, then the new skills should be overlearned, but with a clear understanding of the tradeoffs involved. It is important to overlearn new skills to offset the tendency for that skill to unravel in favor of earlier learning under pressure of stress. But, overlearning is a mixed blessing. It reduces the likelihood of regression, but in doing so it heightens the disruptive effects of an interruption because overlearning makes the sequence of the response more invariant. The remedy would seem to be to give people more substitute routes by which an interrupted response can be carried to completion and inoculate people against the disruptive qualities of interruption. Help them expect interruption and give them a mindset and actions to cope with interruption.

And seventh, forewarn people about the four conditions under which they are especially vulnerable to false hypotheses. Remind people to be mindful when

they are most tempted to act in a mindless fashion (i.e., when they expect something, when they want something, when they are preoccupied with something, and when they finish something).

In conclusion, small details can enlarge and, in the context of other enlargements, create a problem that exceeds the grasp of individuals or groups. Interactive complexity is likely to become more common, not less so in the 90s. It is not a fixed commodity, nor is it a peculiar pathology confined to nuclear reactors and chemical plants. It may be the most volatile linkage point between micro and macro processes we are likely to find in the next few years.

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