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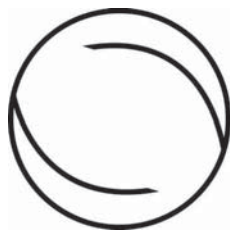
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# Distributed Knowledge and Indeterminate Meaning: The Case of the Columbia Shuttle Flight

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## Abstract

We explore the processes that unfolded during NASA's ill-fated Columbia shuttle flight, as members of the mission team struggled to understand the significance of an unexpected foam-shedding event. It was difficult to categorize this event in real time, as two different criteria — a concern for safety and a concern for meeting schedules — were being used. Using in-depth data gathered on the Columbia shuttle flight, we describe the sensemaking processes that unfolded and discuss the implications for organizations.

**Keywords:** data indeterminacy, distributed knowledge, decision making, sensemaking, Columbia Shuttle, accidents

On 1 February, 2003, the incoming Columbia Shuttle Flight STS-107 started reentry into the earth's atmosphere. At 8:54:24, Mission Management noticed that the hydraulic sensors on the left wing had failed. The spacecraft, traveling at Mach 23 and wing temperatures of up to 2,800°F, was committed to reenter the earth's atmosphere. Mission Management watched as the spacecraft disintegrated.

An investigative board highlighted the significance of a technical event during the shuttle launch, i.e. a large block of insulation foam quite possibly more than 1,000 cu. in. (16,400 cm<sup>3</sup>) in size fell off the external tank and struck the underside of the orbiter's left wing, compromising its thermal coating skin. When the spacecraft reentered the earth's atmosphere, flows of hot plasma gas then set off chain reactions that destroyed the shuttle and its crew. An investigatory report compiled by a board of eminent evaluators (The Columbia Accident Investigation Board Report — CAIB) concluded:

'Management decisions made during Columbia's final flight reflect missed opportunities, blocked or ineffective communications channels, flawed analysis, and ineffective leadership. Perhaps most striking is the fact that management — including Shuttle Program, Mission Management Team, Mission Evaluation Room, and Flight Director and Mission Control — displayed no interest in understanding a problem and its implications.' (CAIB 2003: 170)

In analyzing another disaster where two F-15 pilots shot down two friendly helicopters, Snook (2000) suggested that an analytic frame that considers individuals as the primary determinants of decisions oversimplifies the situational complexities to such an extent that fundamental attribution errors arise (see also Allison, 1971). Similarly, in her analysis of the Challenger disaster, Vaughan (1996:393)

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highlighted what she labeled as the ‘politics of blame’ noting, ‘as long as we see organizational failures as the result of individual actions our strategies for control will be ineffective, and dangerously so’. In the conclusion of her analysis of the September 11th World Trade Center terrorist attacks, Sutcliffe (2005) also drew attention to problems that emerge when we assume that an incident ought to have presented itself with the clarity that hindsight affords analysts. As she stated:

‘although large-scale failures and disasters are investigated frequently, they are not fully understood — if only because, by definition, inquiries and studies of catastrophes investigate well-structured problems *after the fact* [emphasis added] as defined and revealed by the disaster, and not the problem that caused the disaster as it presented itself to those involved beforehand.’ (Turner, 1976: 393; Sutcliffe 2005: 423)

### **Inquiry Frame**

How we evaluate the efficacy of sensemaking (Weick et al. 2005) and decision-making (March 1997) processes depends on the perspectives that we use to assess organizations and on the roles we believe that individuals play within them. One perspective views organizations as information-processing systems (Galbraith 1974; Huber 1982) driven by individuals operating under norms of rationality (Thompson and Tuden 1959). Driving decision making is the ‘logic of consequences’, i.e. ‘actions are chosen by evaluating their probable consequences for the preferences of the actor’ (March and Simon 1993: 8). To the extent that one uses this perspective, ‘inappropriate’ decisions can occur if biases creep into human decision-making processes, and the attribution of blame for suboptimal outcomes falls squarely on the shoulders of the individuals involved, which is exactly what the CAIB report (2003) concluded.

March (1997) noted, however, that organizational processes are far more complex than what can be within the reach of any one individual. Given bounds to the norms of rationality, individuals are driven not just by the logic of consequences, but also by the ‘logic of appropriateness’. As March and Simon (1993: 8) pointed out: ‘Actions are chosen by recognizing a situation as being of a familiar, frequently encountered type and matching the recognized situation to a set of rules.’ From this perspective, decisional problems occur because inappropriate organizational rules are triggered in response to an emergent situation.

While there has been considerable progress in gaining an appreciation of the decision-making processes that unfold within organizations, March (1997: 26) pointed out that much work still needs to be done. Specifically, pre-decisional processes are fraught with challenges, as they involve integrating the views of multiple actors, each bringing to bear a different perspective (see also Tsoukas 1996; Weick et al. 2005; Bowker and Star 1999). These difficulties arise from an inability to easily make sense of the situation that one confronts given ‘an ecology of inconsistent preferences and identities’ March (1997: 26).

To understand the gray zone, when organizations first attempt to make sense of emergent events, which is what Weick et al. (2005) label as sensemaking, we adopt an inquiry frame that considers sensemaking as emerging from the interactions of different pieces of organizational knowledge distributed across artifacts, people, metrics, and routines (Weick and Roberts 1993; Hutchins 1995; Tsoukas 1996;

Ocasio 1997). Sensemaking around emergent events occurs as these distributed knowledge resources become interwoven into 'action nets' (Czarniawska 2004: 779–784). Such a constructivist perspective is very different from the other two perspectives, which assume that events present themselves consistently and clearly so that people can easily identify them and so make decisions.

We use this inquiry frame to identify the processes that unfolded during the Columbia incident at NASA. Research has already uncovered some of the problems that make it difficult for organizations to address unexpected events. These include, for example, organizational processes that accept deviations that could pose safety problems as normal (Vaughan 1996),<sup>1</sup> and the emergence of an associated 'vocabulary of organizing' that obscures inherent risks (Ocasio 2005). Challenges also arise because the information content around a situation may continue to change, leading to situations with unclear significance due to 'variable disjunction of information' (Reeves and Turner 1972; Turner 1978).<sup>2</sup>

Our study draws attention to an additional pathology that arises when an organization simultaneously engages two or more different performance assessment criteria. For instance, at the time of the Columbia disaster, NASA had two performance assessment criteria in play. One assessment criterion had to do with a culture of production (Vaughan 1996) that related directly to meeting predetermined flight schedules. A second assessment criterion had to do with ensuring the continuing safety of the crew. As the Columbia incident unfolded, different action nets emerged around these two performance assessment criteria, pulling together overlapping sources of distributed knowledge. The simultaneous presence of two action nets generated interpretive indeterminacy within the organization and, ultimately, led to no action being taken at all. Based on these observations, we suggest that sensemaking around a potentially dangerous situation may not be able to converge in organizations that operate with multiple and potentially conflicting performance assessment criteria.

## Methods

How is one able to study processes dealing with distributed knowledge as they unfold in real time? In his study of the distributed cognition of a crew navigating a ship's passage into a harbor, Hutchins (1995) placed recording devices everywhere crewmembers worked in order to generate a record of everything that happened in response to both expected and unexpected events.<sup>3</sup> His technology enabled a recording of how the members of the crew, who had access to different technical resources to carry out their different responsibilities and were distributed around the ship, carried out and coordinated their different assignments. With these recordings, Hutchins could identify crewmember interdependencies at different times during the ship's trip into the harbor. He could also examine what happened when errors were made in implementing navigation routines, how these errors were corrected, and how correct procedures were reestablished so that normal crewmember functioning could continue.

Through the many technologies that NASA uses to monitor, generate, and automatically record what occurs during a space flight, members of the Columbia Accident Investigation Board (2003) also had access to data on the distributed

processes that unfolded during the Columbia flight that were similar to the data that Hutchins (1995) generated.<sup>4</sup> These records included data monitoring of the condition of the shuttle's various technical systems before and during the flight, email records of communications between the different units managing the flight, and the communications between the ground control centers and the astronauts during the flight. These records generated a 'techno-ethnography' similar to the data recordings preserved in the 'black box' of a plane. The investigative board further supplemented this data with interviews with many NASA personnel after the tragedy, and then they released their very complete investigation records (<http://www.nasa.gov/columbia/foia/index.html>). Such extensive data provide a comprehensive record of what occurred. In addition, the records of voice and email communications enable us to see how, in real time, different groups perceived and interpreted emerging events and how they and others responded to these interpretations.

The two of us examined the data, first individually and then jointly, to identify the distributed elements of knowledge that were activated over time. Following Hutchins (1995), we plotted these elements over time (Table 1) to gain an overall perspective of the challenges that NASA confronted as the incident unfolded. As a part of this process, we identified the specific occasions when the debris issue was discussed during the flight. As even real-time conversations and emails are now a part of the public record under the Freedom of Information Act, we were able to see the different positions of the people involved in real time. We provide a flavor of this in the form of two sample conversations in Table 2.

Based on this analysis, we generated a case description of what had happened (Dunbar and Garud 2005), which we presented to a group of 12 NASA middle managers participating in a conference held to explore NASA's organization design and other issues that were raised by the Columbia flight experience (Farjoun and Starbuck 2005). Recorders attended the discussion sessions that followed, and noted how our ideas generated many reactions among NASA personnel, who found fresh insights into the issues that NASA had confronted, when a distributed lens was applied to examine the situation.

### **The Institutionalization of Two Performance Criteria at NASA**

We briefly revisit NASA's history in order to appreciate how dual performance assessment criteria — one around meeting safety and the other around maintaining schedules — became institutionalized at NASA. We begin with when President Kennedy articulated NASA's mission in 1962, when he said that the USA would establish technical superiority over the Soviet Union in space and that this achievement would be symbolized with the landing of the first man on the moon and returning him safely to earth by the end of the decade. At the time, NASA's engineers worked in different facilities on separate projects to make a safe space vehicle. The emphasis on engineering reliability required NASA engineers to conduct many experiments that continually uncovered new problems and further experimentation needs. Budget overruns were common and progress was slow. It became clear that NASA would not be able to put a man on the moon by the end of the decade.



Table 1. (Continued)

|   | 1/16   | 1/17   | 1/18, 19   | 1/20                                   | 1/21  | 1/22   | 1/23  | 1/24  | 2/01   |
|---|--|--|--|--|---|--|---|-------|--|
| Prior to incident                                       |  |  |  |  |   |  |   |       |  |
| Program Requirements Board                              | Declared bipod foam loss an 'action', not an 'inflight anomaly' on previous flight   |  |  |  |   |  |   |       | Lowered urgency of action in response to foam-shedding event   |
| Rodney Rocha, Chief Engineer, Thermal Protection System | Coordinates NASA engineering resources and works with contract engineers at United Space Alliance (USA)  | Coordinator of DAT with Pam Madera of USA                                | Made Mission Action Request that Columbia crew inspect left wing |  | Requests JSC Engineering for imagery of vehicle on-orbit    | Believes request for imagery has been denied. Unsent email expresses deep concerns | Disagrees with Schomberg that foam impact is in experience base                 |       | Routing request via JSC Eng. reduces its salience<br><br>Rocha's concerns remain unresolved                          |
| <b>METRICS</b>  |  |  |  |  |   |  |   |       |  |
| Cameras   | Foam shedding assessed after flights. No metrics to assess it during flights<br>On earth, satellites, planes as well as shuttle, but abilities have atrophied due to budget cuts | Picture unclear or missed event  | Need to get supplementary images                                 |  |   |  |   |       | Never knew if there was a flight safety issue or not<br>Cameras unreliable and provide unclear pictures for analysis |
| Crater Model  | Assumes small-sized debris, model gives quick fix on TPS penetration depth   |  | First use of model for ongoing mission                           | Use of model confirms need for imagery |   |  |   |       | Results from use of tool are inconclusive  |
| Int'l Space Station Schedule                            | Importance of core complete date 19 Feb. 2004 linked to Sean O'Keefe   |  |  |  |   |  |   |       | Scheduled launches, already behind, will be backed further   |
| <b>ROUTINES</b>   |  |  |  |  |   |  |   |       |  |
| Flight Readiness Review                                 | Debug through categorization waivers allows adherence to schedule. Delays only permitted by convincing and objective data  | Analysis team needs 'Tiger' status to get Mission Management's attention |  |  | Request for imagery not done through correct formal channel |  | Email directs that future DoD request should go through correct formal channels |       | Routing of image requests outside regular chain of command leads to unclear importance                               |
| Tiger Team Process                                      | Foam shedding is made an accepted risk, not a safety-of-flight issue<br>Detailed procedures and check lists to be explored given out-of-family event                             | Not designated   |  |  |   |  |   |       | Never activated  |
| Prior to incident                                       | Day 1  | Days 2 & 3   | Day 4  | Day 5                                  | Day 6   | Day 7  | Day 8   | Day 9 | Day 17   |

Table 2.  
Examples of Real-time Exchanges between People within Different Action Nets during the Flight

| A verbal exchange about the implications of debris during a Mission Management Team meeting, 24 January 2003 (Day 9 of flight)  | An email exchange about debris among engineers with continuing concerns about safety issues, 30–31 January, 2003 (Day 15–16 of flight)  |
|---|---|
| <p>MER/Don McCormack: Yeah, Linda, on Friday I mentioned the thermal analysis that we're looking at and I had stated that we had looked at five of six areas. Just wanted to let you know that we looked at the sixth location which was an area on the main landing gear door. The Integration folks think this is a low probability area as far as, you know, maybe sustaining a hit there but we went ahead and looked at it. We looked at ...</p> | <p>Hi David,<br/>... One of my personal theories is that you should seriously consider the possibility of the gear not deploying at all if there is a substantial breach of the wheel well ...<br/>The following are scenarios that might be possible ...</p>   |
| <p>Ham: Are you talking debris?</p>   | <ol style="list-style-type: none"> <li>1. If both tires blew up in the wheel well (not talking thermal fuse and venting but explosive decomp due to tire and/or wheel failure) the over pressure in the wheel well will be in the 40+ psi range. The resulting loads on the gear door (a quarter million lbs) would almost certainly blow the door off the hinges or at least send it out into the slip stream ... catastrophic. Even if you could survive the heating, would the gear now deploy? And/or also, could you even reach the runway with this kind of drag?</li> <li>2. The explosive bungies ... what might be the possibility of these firing due to excessive heating? If they fired, would they send the gear door and/or the gear into the slipstream?</li> <li>3. What might excessive heating do to all kinds of other hardware in the wheel well ... the hydraulic fluid, uplocks, etc? Are these vulnerable hardware items that might prevent deployment?</li> </ol> |
| <p>MER: Yeah. Debris.</p>   |   |
| <p>Ham: Okay.</p>   |   |
| <p>MER: We looked at an area about the size of 30 inches by 7 inches, and, of course, you know, sloped, cratered out area, and our results there were similar to what we got elsewhere and that is, although local degradation of the door structure is likely if we were to have sustained a hit there, there is no predicted burn-through and no safety-of-flight issue.</p>  |   |
| <p>Ham: A turn-around issue?</p>  |   |
| <p>MER: Yeah, possibly.</p>   |   |
| <p>Ham: If it were hit there ...</p>  |   |
| <p>MER: If it were hit there, it's a critical area there on the door, but also the Integration guys had indicated that they thought it was a low probability location but it was still one that we went off and looked at.</p>  | <p>Bob,<br/>... As always your points have generated extremely valuable discussion in our group. Thank you. We have been discussing and continue to discuss all possible scenarios, signatures and decisions. Your input is beneficial. Like everyone, we hope that the debris impact analysis is correct and all this discussion is mute.</p>  |

In 1963, George Mueller joined NASA as director of the Office of Manned Space Flight (OMSF) and set about integrating ongoing efforts to speeding development. To integrate efforts, he introduced 'systems engineering,' a set of project management techniques to codify engineering and management practices and so facilitate control over the various projects at different NASA centers. This data could also be used to develop an overall picture of mission progress that top management could track (Johnson 2002).

To speed development, Mueller imposed 'all-up testing' processes on NASA rather than the learning-by-failing process that NASA had been using. In the learning-by-failing process, engineers would keep on testing and modifying a part until it eventually worked satisfactorily. They would then combine parts into components and go through the same test–modify–test cycle once again. This was clearly a time-consuming process and the 'all-up testing' was introduced to hasten the process. If the design and fabrication were to be done correctly, it was argued, the component would work in the first instance. Consequently, rather than testing each component separately, they could all be tested altogether (Murray and Cox 1989).

This new process not only speeded progress and saved costs, but it also introduced unknown risks due to the unknown interactions that would occur between the untested, newly combined components. Implicitly, by pursuing developmental speed as well as engineering reliability, NASA was accepting the risk that a space flight could end up as a disaster. In order to learn about the problems generated by 'all-up' processes, NASA introduced procedures to document all in-flight anomalies in Mission Evaluation Reports (MERs). Over time, the numbers of identified anomalies grew into the thousands even as NASA policy required that, before each new flight, a Flight Readiness Review (FRR) should confirm that all previously identified anomalies had been resolved. Vaughan (1996: 209) describes how a 'can-do' attitude emerged at NASA. There was:

'a commitment to research, testing and verification; to in-house technical capability; to hands-on activity; to the acceptance of risk and failure; to open communications; to a belief that NASA was staffed with exceptional people; to attention to detail; and to a 'frontiers of flight' mentality.'

After a man had been put on the moon and returned safely to earth, securing space flight superiority over the Soviet Union, it became increasingly difficult for NASA to obtain resources from Congress (CAIB 2003). To ensure continued funding, NASA presented itself as an organization that had so much national prestige and accomplishment that Congress could not afford not to provide it with funding. To emphasize this claim, NASA's rhetoric ignored the uncertainties implicit in development work and suggested, instead, that the research needed for its proposed projects had already been done and that the projects themselves would be easily accomplished. Congress responded with funding, but at a reduced level. As Vaughan (1996) reported, by the 1980s, NASA's 'can do' culture had given way to a 'culture of production' where a 'must do' attitude focused on accomplishing more, on time, with less.

In fact, a business ideology emerged infusing the culture with an agenda that emphasized repeated production cycles, the importance of meeting deadlines, and cost and performance efficiency as primary assessment criteria, almost as if NASA were a corporate profit seeker emphasizing objective data and predictable task-performance (Vaughan 1996: 210). For instance:

'The emphasis was on science-based technology. But science, in FRR [flight readiness reviews] presentations required numbers. Data analysis that met the strictest standards of scientific positivism was required. Observational data, backed by an intuitive argument, were unacceptable in NASA's science-based, positivistic, rule-bound system. Arguments that could not be supported by data did not meet engineering standards and would not pass the adversarial challenges of the FRR process.' (Vaughan 1996: 221)

It was against this background that the Challenger disaster occurred in early 1986. One of the seven individuals on board, Christa McAuliffe, a schoolteacher, was to 'teach school children from space'. The mission was intended to celebrate the normality of predictable task-performance in space but, tragically, it turned into a mission that reminded everyone of the terrors of exploring space.

Vaughan (1996) noted that, after the Challenger accident, the Shuttle was no longer considered 'operational' in the same sense as a commercial aircraft. Yet, NASA continued to operate around a 'culture of production'. In 1992, for example, Daniel Goldin, the incoming NASA Administrator, insisted that a reorganized NASA would do things faster, better, and cheaper without sacrificing safety. Goldin's approach implies that, at the highest levels of NASA, a lot of emphasis was placed on increasing efficiency and ensuring predictable task-performance (CAIB 2003: 103). Similarly, in 2001, Goldin's successor, Sean O'Keefe, tied future Congressional funding to NASA's delivery of reliable and predictable shuttle flight performance in support of the International Space Station. Such promises implied a high ability to maintain predictable task-performance — similar to what one might achieve, for example, in managing assembly-line production.

Vaughan's (1996) rich analysis of the Challenger incident offers several alternative explanations to the tragedy. One draws on Perrow's (1984) theory of 'normal accidents' and suggests that when operating systems have interactively complex and tightly coupled elements, accidents are inevitable. The space shuttle in 2003 was clearly a complex technology in that it included 5,396 individual 'shuttle hazards', of which 4,222 were categorized as 'Criticality 1/1R'.<sup>5</sup> The complexity of the interactions that could occur between these identified hazards and some of their interdependent couplings could only increase in a crisis, making gruesome consequences increasingly likely.

Vaughan persuasively argues that organizational issues add to the complexity inherent in technological systems (see also Starbuck and Milliken, 1998). Focusing on the 'production of culture' that supported a 'culture of production', she noted:

'The explanation of the Challenger launch is a story of how people who worked together developed patterns that blinded them to the consequence of their actions. It is not only about the development of norms but about the incremental expansion of normative boundaries: how small changes — new behaviors that were slight deviations from the normal course of events — gradually became the norm, providing the basis for accepting additional deviance.' (Vaughan 1996: 409)

Like Vaughan (1996), we too want to generate a deeper understanding as to why accidents occur. But, rather than highlighting how accidents may occur because of normalization of deviance that allows situational dangers to be overlooked, we want to show how accidents may also occur despite and even because of organizational actors' active participation with emergent situations. The problem emerges, we suggest, from the fact that NASA simultaneously embraced multiple criteria for making performance assessments. This was well summarized by Ron Dittmore, the Space Shuttle project manager, who testified to Congress after the Columbia tragedy on March 6 2003:

'I think we're in a mixture of R&D and operations. We like to say that we're operating the fleet of Shuttles. In a sense we are, because we have a process that turns the crank and

we're able to design missions, load payloads into a cargo bay, conduct missions in an operating sense with crew members who are trained, flight controllers who monitor people in the ground processing arena who process. In that sense we can call that operations because it is repeatable and it's fairly structured and its function is well known.

The R&D side of this is that we're flying vehicles — we're blazing a new trail because we're flying vehicles that are, I would say, getting more experienced. They're getting a number of flights on them, and they're being reused. Hardware is being subjected over and over again to the similar environments. So you have to be very careful to understand whether or not there are effects from reusing these vehicles — back to materials, back to structure, back to subsystems.' (CAIB 2003: 20)

## **Foam Shedding during the Columbia Flight**

Strapped for resources, committed to a demanding launch schedule in support of the International Space Station that could not be met, and operating with a technology with many identified hazards, NASA confronted the series of events that emerged over the 16-day flight period of Flight STS-107 and culminated in the destruction of the shuttle and its crew. Table 1 charts how, for the first nine days of the 16-day flight, events unfolded and interactions occurred between different NASA groups, artifacts, metrics, and routines that comprised the elements of NASA's distributed mission control and response knowledge system. Table 1 is not intended to depict a complete set of the events and responses that occurred over this period. Rather, it is a set that is chosen to illustrate and summarize the sequence of events mentioned in our narrative and also to highlight how indeterminacy came to dominate NASA's distributed response knowledge system.

### **The Foam-shedding Event**

Around 82 seconds into the launch of the STS-107 shuttle, we now know that a large object and two smaller objects lifted off the left bipod area of the external fuel tank and the large object then struck the underside of the orbiter's left wing.<sup>6</sup> Although, in real time, both videos and high-speed cameras captured the foam lifting off the bipod area, they did not capture what followed, and this initial photo image resolution was also fuzzy. When images with better resolution became available on the second day of the flight, people at NASA's Intercenter Photo Working group began wondering if it was a significant event. They were uncertain because the images did not show what parts of the orbiter the bipod foam had actually struck.

### **Foam Shedding and its Historical Categorization**

While the original shuttle design was supposed to preclude foam shedding from the external fuel tank, various amounts of foam have fallen from the tank on almost every flight since the beginning of the shuttle program. NASA had documented how such debris could be large enough to hit the orbiter's left wing and damage parts of the thermal protection system (TPS). At first, NASA categorized foam shedding and other debris events as 'in-flight anomalies' that had not only to be resolved but also the cause of which had to be understood before the next shuttle flight could be permitted to launch.

Over the years, however, NASA has also been subject to increasing pressures to launch more shuttle flights (Vaughan 1996). At the time of the Columbia light, for example, scheduling was so tight that NASA was actively tracking the 'schedule reserve' remaining for each shuttle flight and managers were keenly aware that the scheduling time available was not adequate to meet NASA's goal of completing 'Node 2' of the International Space Station by 19 February 2004. Nevertheless, they wanted to make as much progress as they could and overshoot this target date by as little as possible (CAIB 2003: 131–139). While this pressure to launch flights was in potential conflict with the NASA rule that a shuttle launch could not occur until all in-flight anomalies on previous flights had been resolved, it was consistent with NASA's emphasis on 'faster, better, cheaper' performance (Ocasio 2005). As far as foam shedding was concerned, although the underlying reason for foam shedding was still not understood, NASA had concluded over time that it was something to be expected and that any damage could be repaired after the shuttle flight returned to earth.

In other words, and as the investigatory report documents, a 'normalization of deviance' (Vaughan 1996) had occurred over time with respect to foam shedding, particularly with respect to the external tank's forward bipod attachment that was the source of the largest chunks of foam-shedding debris. Initially, such foam-shedding events had been categorized in shuttle flight assessment reports as 'in-flight anomalies'. Later, however, they were categorized as 'accepted risks'. Following successful repairs in 1992, foam loss was recategorized as being 'not a safety of flight issue'.

After this 1992 recategorization, it was no longer necessary to record foam loss events as they occurred. In fact, significant foam-shedding events occurred on two later flights but they were not noticed until after the Board launched its investigation of the Columbia flight (CAIB 2003: 121–124). On the STS-112 shuttle, launched in October 2002 before the Columbia flight, for example, post-mission inspections found that foam shedding had caused significant damage to the orbiter even though the mission management logs did not mention this. At the Program Requirements Control Board review meeting after STS-112, which was attended by many who would be involved in the Columbia flight, this foam-shedding event was discussed and 'the Intercenter Photo Working Group recommended that the loss of bipod foam be classified as an In-Flight anomaly' (CAIB 2003: 125).

The Program Requirements Control Board decided, however, not to categorize the loss of bipod foam as an In-Flight anomaly. Instead, it assigned 'an 'action' to the External Tank Project to determine the root cause of the foam loss and to propose corrective action'. At the Flight Readiness Review for the next scheduled flight, STS-113, again attended by many involved in the next and upcoming Columbia flight, bipod foam shedding was discussed further. Although the bipod attachment design had been changed from earlier flights, the slides presented during the review stated that there had been no change and, at the meeting, 'managers formally accepted a flight rationale that stated [that] it was safe to fly with foam losses'. The meeting also concluded that bipod foam loss would be more appropriately categorized as an 'accepted risk' rather than 'not a safety-of-flight' issue (CAIB 2003: 125–126). The records show, then, that over a series of shuttle flight review meetings, the categorization of foam-shedding events was a resurfacing and unresolved issue subject to the normalization of deviance process

that Vaughan (1996) identified as characteristic of the way NASA made decisions in the face of performance pressures.

### **Categorizing Foam Shedding on the Columbia Flight**

The initial liftoff imagery obtained from the Columbia flight launch did not clearly show foam loss. But clearer imagery from tracking cameras available the next day showed that a large piece of foam debris had lifted off from the bipod area. Although they could not see how it had impacted the orbiter, members of the Intercenter Photo Working Group were concerned about the size and velocity of the impact, for the debris observed was the largest ever seen so late in an ascent. Consequently, despite the normalization of previous foam-shedding events, the Intercenter Photo Working Group decided to categorize the event as an 'out-of-family event'. To sort out what had happened, they asked for additional imagery from the Shuttle Program Manager for Launch Integration. They also distributed digitized clips throughout NASA and to the shuttle contractor communities, showing the pictures they had of the foam debris strike.

In particular, the Intercenter Photo Working Group reported to the Mission Evaluation Room, the central coordinating unit that monitors shuttle missions in progress and supplies engineering expertise to the shuttle, that: 'The launch video review teams at Kennedy Space Center think that the vehicle may have been damaged by the impact.' They also informed members of the Mission Management Team that Boeing and United Space Alliance engineers were analyzing 'trajectories, velocities and angles, and energies for the debris impact' and that photo analysis work would continue through the holiday weekend along with the analytic work of a newly formed Debris Assessment Team (DAT) to be co-chaired by Rodney Rocha, the chief engineer for the Thermal Protection System, and Pam Madera of the United Space Alliance (CAIB 2003: 141–142). Boeing engineers said later that the incident was 'something the size of a large cooler [that] had hit the Orbiter at 500 miles per hour [800 km/h]' (CAIB 2003: 160). The Intercenter Photo Working Group also requested and was sent the records of all the foam loss events on earlier shuttle flights in order to reanalyze this data to see if there might be any hidden or overlooked patterns.

Even though no analyses had yet taken place, high-level Shuttle Program managers communicated their belief to the Mission Evaluation Room that there were probably no safety implications associated with the foam debris incident and so no one needed to work on debris analysis over the weekend. In fact, Ocasio (2005: 100) concluded that the general role of safety categorizations, particularly at the level of the Mission Management Team, was directed more towards absorbing any emerging uncertainty rather than at improving safety. This was also consistent with the language used on previous flights and Flight Readiness Reviews, which described foam loss events as 'in-family events' that created a 'turnaround' issue that should be dealt with when the shuttle returned to earth. The Management Evaluation Room representative adhered to this position, too, and, when asked, consistently relayed this view back to the Mission Management Team (see Figure 2). Table 1 summarizes the groups involved, and the technologies, operational routines, and metrics being pulled together to establish alternative action nets to make sense of the foam loss event (Milliken et al. 2005).

### Responses to Foam-shedding Categorizations

At NASA, the categorization of an event as being 'out-of-family' during a shuttle flight is supposed to activate a 'Tiger Team' made up of appropriate experts with wide and extensive authority. A Tiger Team has the highest status and authority and can ask questions, make requests, and direct whatever activities necessary in order to find out and report immediately on what has happened on a shuttle flight. As based on past history and current reports, Mission Management categorized whatever might have happened on the Columbia as being 'in-family' and an 'acceptable risk'. However, the possibility that they might move to appoint an investigatory Tiger Team never arose. Instead, Mission Management checked and confirmed its 'in-family' position by contacting several other Thermal Protection System experts, all of whom agreed that the foam-shedding event should not cause any problems for the orbiter.

The investigatory DAT group was appointed by the Intercenter Photo Working Group and not by the Mission Management Team. While Mission Management regarded the event as an in-family event, the Intercenter Photo Working Group considered it to be an out-of-family event. Yet, given this source of the DAT group's appointment, it was unclear what independent status, power or authority, if any, it might actually have as an investigatory group:

'This left the Debris Assessment Team in a kind of organizational limbo, with no guidance except the date by which Program managers expected to hear their results: January 24th.' (CAIB 2003: 142)

### Categorizations and Actions

The DAT was co-chaired by Rodney Rocha, the Chief Engineer of Thermal Protection System (TPS). The shuttle's TPS was the component that a concerned group of NASA engineers believed might have been compromised by the foam strike. Soon after he was appointed, Rocha explained to the leader of the Mission Management Team what he had checked and found to be in order, and what areas he was still investigating. He mentioned in an email, however, that he was not sure that the Mission Management Team leader actually understood the potentially important significance of what was still to be investigated.

To help in the investigation, the members of DAT requested on-orbit photographs, using Rocha's personal contacts at an Engineering Directorate at Johnson Space Center. The Columbia shuttle flight controller observed that this request had been made and that it was not from Mission Management's Flight Dynamics Officer, as Mission Management's protocol required for all mission-relevant requests. Mission Management then interpreted all of the requests from various engineering units for on-orbit photos that did not follow Mission management protocol as being noncritical engineering desires rather than urgent operational needs, and so they canceled them, effectively terminating all of the requests for on-orbit photos that had been made by several different engineering units. Although checks were made with members of Mission Management before making this decision, there were no checks made with anyone on the DAT team (CAIB 2003: 153).

Mission Management had consistently categorized the foam strike as an 'in-family' event, a category sufficient in itself to nullify emergency requests for

on-orbit photos. Rocha wrote an email indicating how DAT's low status within NASA was affecting his freedom to investigate. He did not send his message, however, because, as he said later, he 'did not want to jump the chain of command':

'In my humble technical opinion, this is the wrong (and bordering on irresponsible) answer from the SSP and Orbiter not to request additional imaging help from any outside source ... The engineering team will admit it might not achieve definitive high confidence answers without additional images, but, without action to request help to clarify the damage visually, we will guarantee it will not.' (CAIB 2003: 157)

Once the requests for on-orbit photos had been canceled, DAT and other concerned groups had no access to current data on the shuttle's condition. In this situation, the DAT members resorted to the modeling and estimation techniques they had begun to use earlier in their investigatory process. Specifically, they used a mathematical modeling tool called 'Crater' to assess what the damage to the shuttle wing might have been. This tool was calibrated to assess damage caused by debris of a much smaller size, i.e. 1 cu. inch (16.4 cm<sup>3</sup>) vs the much larger block of foam that they knew had fallen on the shuttle. The use of this model was, therefore, technically inappropriate, but it was also one of the few available tools that might produce relevant analyses and so DAT used it to explore what insights it might suggest (CAIB 2003: 143–145).

DAT's analysis using the Crater model predicted that the falling debris might well have compromised the underside of the wing, generating an 'out-of-family' event that on reentry could expose the shuttle's interior to extremely high temperatures. Crater model analyses are conservative, however, with testing structures designed to minimize the likelihood of failing to identify a 'safety-in-flight' problem, i.e. the probability of a false negative. In the context of dealing with Mission Management, DAT members believed that they had to provide positive proof that there was, in fact, a 'safety-in-flight' problem on this particular shuttle flight. Given the way that the Crater model was designed and calibrated, it could well have identified a false-positive result. Having used a Crater model analysis to determine that a safety-in-flight problem might exist, therefore, the DAT team then sought to discount these initial findings in order to make sure that they were not identifying a false-positive safety-of-flight issue.

They reasoned, for example, that their analysis with the Crater model did not factor in the additional padding that the Columbia had packed on the underside of its wing. To explore the protective effectiveness of this additional padding, the engineers had to determine the location and angle of the foam strike impact. An analysis suggested that, most likely, the foam strike hit the shuttle at an angle of 21°. The question was whether such an angled strike would compromise the reinforced-carbon-carbon (RCC) coating of the padded wing. To answer this question, DAT resorted to yet another mathematical model, calibrated to assess the impact of falling ice. It predicted that strike angles greater than 15° would result in RCC penetration and portend disaster. However, as the foam on the shuttle is not as dense as ice, DAT decided that, again, it needed to make adjustments in order to avoid identifying a false-positive safety-of-flight issue. Together, these various adjustments led them to conclude that, as they could not be certain that a foam strike impact angle of up to the suspected 21° would have penetrated the RCC, they could not positively prove a safety-of-flight issue. The CAIB report states:

Table 3. Action Nets around Scheduling and Safety Issues

|                          | Scheduling issues   | Safety issues   |
|--------------------------|---|---|
| <b>Artifacts</b>         | <ul style="list-style-type: none"> <li>• Video clips and incomplete photographic images of what had happened to the orbiter</li> <li>• NASA’s Flight Readiness Reports</li> <li>• Program Requirements Board Reports</li> <li>• In-Flight Anomaly reports and analyses from all previous shuttle flights</li> </ul>   | <ul style="list-style-type: none"> <li>• Video clips and incomplete photographic images of what had happened and how it had affected the orbiter</li> <li>• NASA’s Flight Readiness Reports</li> <li>• Flight Review Reports</li> <li>• Program Requirements Board Reports</li> <li>• In-Flight Anomaly reports</li> <li>• Analyses from all previous shuttle flights</li> <li>• Cameras not correctly sighted or focused.</li> <li>• Crater Model and other analytic models</li> </ul> |
| <b>People and Groups</b> | <ul style="list-style-type: none"> <li>• Mission Management Team</li> <li>• Mission Evaluation Room</li> <li>• Thermal Protection System experts</li> <li>• Department of Defense resources</li> <li>• United Space Alliance, Boeing</li> </ul>   | <ul style="list-style-type: none"> <li>• The Intercenter Photo Working Group</li> <li>• United Space Alliance</li> <li>• Boeing</li> <li>• DAT with analytical expertise to adjust Crater Model findings</li> <li>• Mission Evaluation Room</li> </ul>  |
| <b>Metrics</b>           | <ul style="list-style-type: none"> <li>• Driven by scheduling concerns based on the continuing ‘normalization of deviance’ of foam-shedding events</li> </ul>   | <ul style="list-style-type: none"> <li>• Safety driven based on problematization of deviance implicit in the foam-shedding event</li> </ul>   |
| <b>Routines</b>          | <ul style="list-style-type: none"> <li>• Given ‘normalization’ routines, a lack of evidence</li> <li>• ‘In-family’ categorizations of events precludes consideration of whether a Tiger Team should be activated</li> <li>• Low status DAT appointment affects how on-orbit photo requests are made and processed, how the DAT analysis is assessed, etc.</li> <li>• Charts assessing ‘time schedule reserves’ relative to ‘Node 2 of the International Space Station’</li> <li>• Meetings to monitor flight progress and developments</li> </ul> | <ul style="list-style-type: none"> <li>• Intercenter Photo Working Group appoints DAT team to manage an investigation of the foam-shedding event</li> <li>• DAT is heuristic driven, using team members’ analytical skills to use the Crater model beyond its normal use</li> <li>• Regular DAT meetings explore findings</li> <li>• Idea exchanges among safety experts</li> </ul>   |

‘Although some engineers were uncomfortable with this extrapolation, no other analyses were performed to assess RCC damage.’ (CAIB 2003: 145)

DAT’s abilities were limited in important ways because it had no authority to make direct requests to the Department of Defense, for example, for on-orbit photos. These conditions created a catch-22 situation: in order to get Mission Management to request the needed photos, DAT first had to present objective evidence to Mission Management to establish the need for the photos, something it could not do until it actually had the photographs (CAIB 2003: 157).<sup>7</sup> Yet, fears of what might have occurred to the shuttle flight were nevertheless widespread in NASA. One engineer wrote: ‘There is lots of speculation as to the extent of the damage, and we could get a burn through into the wheel well upon entry.’ Scenarios developed and exchanged within NASA over the remainder of the flight speculated on what might have happened, and foretold what the consequences would be (for another example, see Table 3).

On the other hand, based on continually revised ways of categorization implemented over a 20-year period and based on the records of around 100 space flights, Mission Management Team members believed that foam loss events on shuttle flights were well documented and well understood and, based on careful analysis and historical precedence, managers and engineers who were responsible for shuttle flights had agreed to recategorize foam-shedding events as either in-family events or acceptable risks. As they acted in ways that were consistent with this established categorization, and as they also believed they had not been presented with information that directly contradicted this view, Mission Management believed they acted appropriately. In fact, after the request for imagery to the Department of Defense was canceled, a liaison to USSTRATCOM was so certain of the situation, that he sent the following email reemphasizing the need to use approved reporting channels in all communications with the Mission Management Team:

'Let me assure you that, as of yesterday afternoon, the Shuttle was in excellent shape, mission objectives were being performed, and that there were no major debris system problems identified. The request that you received was based on a piece of debris, most likely ice or insulation from the ET, that came off shortly after launch and hit the underside of the vehicle. Even though this is not a common occurrence it is something that has happened before and is not considered to be a major problem. The one problem that this has identified is the need for some additional coordination within NASA to assure that when a request is made it is done through the official channels ... Procedures have been long established that identify the Flight Dynamics Officer (for the Shuttle) and the Trajectory Operations Officer (for the International Space Station) as the POCs to work these issues with the personnel in Cheyenne Mountain. One of the primary purposes for this chain is to make sure that requests like this one do not slip through the system and spin the community up about potential problems that have not been fully vetted through the proper channels.' (CAIB 2003: 159)

On Day 9, watched by a standing-room-only audience of NASA engineers, DAT made a formal presentation to the Mission Evaluation Room representatives, setting out its findings and also the many uncertainties that had plagued its analyses. Ultimately, DAT said they could not claim beyond a reasonable doubt that there was a safety-of-flight issue aboard the Columbia shuttle. While their analyses were ultimately inconclusive rather than a clean bill of health, the Mission Evaluation Room representatives interpreted this report as confirmation of their view, held all along, that a foam strike would not have generated a safety-of-flight issue. According to the CAIB report (2003: 160), 'engineers who attended this briefing indicated a belief that management focused on the answer — that analysis proved there was no safety-of-flight issue — rather than concerns about the large uncertainties that may have undermined the analysis that provided that answer'.

In sum, after a formal presentation by the DAT group of investigating engineers to the Mission Evaluation Room, an event initially categorized as 'out-of-family' by the Intercenter Photo Working Group was recategorized as an 'in-family event' by the Mission Evaluation Room with the formal consent of the DAT. Organizationally, it was no longer a 'safety-of-flight' issue although what had actually happened was still not determined. Nevertheless, nothing further was done. A week later, the shuttle reentered the earth's atmosphere, hot plasma breached the RCC panels, and the shuttle disintegrated.

## Discussion

What can we make of these events? It is all too easy to think of NASA simply as an information-processing organization and then attribute blame to specific people involved. But when we apply a distributed knowledge perspective to the analysis of the incident, we see additional contributing factors. As we explain in greater detail below, the presence of two criteria for assessing performance — one around safety and the other around schedules — and the action nets associated with these alternative criteria generated quite different views concerning what might have been occurring in real time.

Indeed, we found that, faced with an unexpected and potentially worrying event, there were intensive efforts by many NASA personnel to identify an appropriate course of action. During this time, conflicting hypotheses were considered by the Mission Management Team and also by other groups. People chose to make sense of the unfolding events, however, based on their own frames of reference, using the artifacts, metrics, routines, and social cues — the knowledge underlying the different action nets — that they had access to and within which they were embedded (Garud and Rappa 1994; Callon 1998; Beunza and Stark 2004; Boltanski and Thévenot 2006). It is not surprising, therefore, that people framed the same situation in different ways for themselves and for others. Given their different perspectives, it is the only reasonable course of action to expect from highly engaged, professional people.

Kim and King (2000) have documented such a process of engaged involvement in their in-depth description of an interconnection wire event in a DRAM chip production facility.<sup>8</sup> In contrast to the situation confronted during the Columbia shuttle, there was consensus that the wire event signaled trouble amongst those involved in the DRAM chip facility. But, as the engineers at the facility focused, respectively, on chip design operations, materials, or process integration issues, the responses that they proposed were all different from one another. Kim and King (2000: 79–98) explained the process:

‘Trouble management in DRAM production is plagued by ambiguity and social contention in the determination of what the trouble is — a process of “problematization” in which problems and the teams which will take charge of them are simultaneously determined (Callon 1981). Trouble management is a process of matching ambiguous problem situations to potentially relevant solution strategies, in which the classification of the problem is itself a significant social action in the articulated work process (Strauss 1988).’

Kim and King’s (2000) study highlights why it is difficult to ‘defer to expertise’ even in relatively clear situations where it is agreed that an event is indeed a signal of trouble. Specifically, deference to expertise begs the question concerning expertise: for what? A situation framed one way (around scheduling, for instance) could identify person A, who is highly aware of the data analyses related to scheduling issues, as the appropriate expert. Framed in a different way (around safety, for instance), it could identify person B, who is highly aware of what real-time signals may indicate about threats to shuttle safety, as the appropriate expert. Each of these individuals will frame the situation in a way that takes their expertise into account, and there is every reason to think that this is exactly what happened at NASA during the Columbia disaster, a case where, in real time, there was no organizational agreement concerning whether or not the incident represented imminent danger.

The processes that unfolded and the indeterminacy that persisted also have some similarities to the situations Reeves and Turner (1972) described in two batch production firms. According to Reeves and Turner, these batch production facilities confronted an 'ill-structured' problem (Tonge 1961). This was indicated by the fact that people in different parts of the factories possessed different pieces of information about what was going on and held differing theories about the production systems' capabilities, and so the meaning of information exchanged continually varied — a state that Reeves and Turner called 'variable disjunction of information'. Employees could not estimate, for example, the precise loads that would be placed on any particular production station, and they also did not know the sequence in which production stations would be required. According to Reeves and Turner, employees dealt with these complexities by using heuristic procedures to devise problem solutions on an ad hoc basis.

As a comparison, Reeves and Turner (1972) reported on how a 'well structured' problem was addressed in a mass-production facility. There were no scheduling problems to be dealt with, as workers on the shop floor followed simple decision rules. Information on the state of work progress in the production system was centrally available and there was also consensus on the capabilities of the production system. As a result, operations in this mass-production facility were able to be driven by centralized information-processing approaches and predetermined production plans.

Reeves and Turner's (1972) study sheds additional light on the challenges that NASA confronted when it discovered that insulation foam had lifted off the external tank's left, forward bipod attachment during launch. Having encountered this problem before, and being simultaneously driven by performance assessment criteria concerned with both shuttle safety and schedule adherence, it was not clear in real time whether this event should be categorized as an ill-structured problem (similar to batch production situations) concerned with the safety implications of the foam-shedding incident (requiring the deployment of NASA's legendary 'can-do' attitude, where people use heuristics to develop solutions on an ad hoc basis) or as a well-structured problem (similar to mass-production situations) concerned with shuttle scheduling issues (requiring the deployment of a 'must-do' attitude and so adherence to predetermined schedule plans). Moreover, in contrast to Reeves and Turner's observation, that variable disjunction of information usually occurs across different organizational units, and Weick et al's (1999) mention of this as a possible boundary condition, everyone in the present case was a member of the same organization, sharing the same role of supporting the Columbia flight.

With hindsight, the investigators could also criticize Columbia flight managers for not having been more aggressive in taking the steps required to mount a rescue operation. But the two different performance criteria emphasizing a concern for safety and a concern for meeting schedules placed contradictory demands on the organization in real time. In the case of STS-107, elements of the organization were pulled together around different action nets with different performance criteria, and so they functioned to generate organizational indeterminacy that could not be resolved within the time frame that NASA had available to mount a rescue operation.

In trying to sort things out, an organization deploys its resources and takes actions to develop an appropriate response. Given constraints on time and resources,

however, an organization as a whole necessarily starts moving in one direction or another. Soon after the foam-shedding event was noticed, for example, there were possibilities for the event to have been categorized as being either 'in-family' or 'out-of-family'. But as specific actions were then taken — the activation of a DAT rather than a Tiger team done by the Intercenter Photo Working Group rather than Mission Management Team, for example — an unfolding sequence of events began generating a developmental direction along with associated constraints on what different people and groups then thought it would be possible for the organization to do. These views on emerging constraints then spread rapidly through the different action nets. Beyond a critical threshold, such processes start to tip a system of distributed elements towards a particular path and an overall pattern of responses. This is what seems to have occurred at NASA despite its access to vast resources and widespread goodwill.

### **Possible Approaches to Addressing the Problem**

Is there a way for organizations to address this problem? Clearly, it may serve an organization such as NASA well to have safety be the predominant performance criterion that drives operations and to actively resist pressures driven by schedules. Ocasio's (2005) observation that NASA developed a 'vocabulary of organizing' that obscured the risks involved suggests a further cultural issue. The implication is that NASA ought to examine its 'vocabulary of organizing' to ensure that the labels available to deal with emergent situations do not privilege schedules at the cost of safety, irrespective of any normalization that may have occurred in the past (Vaughan 1996). In addition, Weick and his colleagues (Weick et al. 1999; Weick and Sutcliffe 2001) have suggested the importance of fostering a culture that values plausibility rather than accuracy, and active listening rather than advocacy, so that, in a case where an organization encounters a situation such as the foam-shedding incident during the Columbia flight, then, in real time, it is able to take advantage of the distributed knowledge resources it possesses in order to address the situation.

However, the reality is that complex organizations such as NASA typically operate in environments that impose conflicting demands on their operations, and so they often find themselves dealing with conflicting performance assessment criteria. Consequently, it may be prudent to consider additional structural solutions such as those proposed by Adler et al. (1999) to complement cultural approaches to address this challenge. Specifically, Adler et al. looked at how NUMMI, operating with two performance assessment criteria — efficiency and flexibility — managed an automobile line changeover process. A successful changeover depends on different departments in the same plant working effectively together. As many differences are expected as a result of the different sources of expertise, and also due to unexpected events, management routinely assigns people who represent the knowledge available in the different groups within the plant to a pilot team. This team is charged with monitoring and directing the changeover process and recognizing and resolving any differences that arise.

The pilot team is appointed before the changeover process begins and it remains in place until after the changeover is complete. In the changeover context, unexpected events are recurring and expected, and so the pilot team puts a

structure in place to recognize, discuss, and categorize whatever comes up, while having access to all of the knowledge in the plant and being subject to all of the performance assessment criteria that are applied in the plant. The pilot team's continuing role is to facilitate negotiation between concerned parties, resolve emerging events and differences as they develop, and so fine-tune and also implement the changeover. Through the pilot team, discrepancies reflecting different perspectives are continually surfaced, all available data and resources are routinely available to everyone, and resolutions reflecting mutual adjustments of perspectives are continually found.

The appointment of an equivalent Tiger Team, in contrast, was contingent on confirmation by Mission Management of the categorization of an 'out-of-family' event. Although Mission Management is concerned about both safety and schedules, given the normalization of foam-shedding events in the past, it transpired that the decision rights to trigger such an investigative team for STS-107 overlapped with the action net that focused primarily on scheduling concerns that also shaped Mission Management's situational understanding. The situation was different from the NUMMI plant, then, where management appointed the pilot team to represent all different views in the plant and the appointment is made before the changeover begins and it continues through to the end of the changeover. As we saw in the shuttle flight, to the extent that one has first to activate such a special team based on a categorization of emergent events, the presence of alternative performance assessment criteria makes agreement on the appropriate categorization difficult, if not impossible, and indeterminacy is the most likely outcome. In addition, and when safety issues are possible, any overall team needs a clear mandate that directs that action nets emphasizing safety concerns and safety-relevant responses must always have priority. The implication is that action nets emphasizing scheduling concerns must be required to demonstrate why continuing to pursue a routinized response is the appropriate choice. To be sure, such a conservative approach may result in actions that in hindsight represent 'Type II errors' (errors of commission from a safety perspective) rather than 'Type I errors' (errors of omission from a safety perspective). But, without such a clear mandate to a pilot team that draws its members from across the organization and has ongoing authority over all of mission operations during flights, a group such as the Mission Management Team will always be subject to the possibility and consequences of data indeterminacy, due to the use of two assessment criteria simultaneously within the organization.

## Conclusion

Our study has implications for how organizing processes are conceptualized, how organizational actions are agreed upon, and how organizational sensemaking and decision making are assessed. The CAIB report's overall conclusion suggests a view of organization from an information-processing perspective with upper and middle managers making critical decisions. From an 'organization as information processing' perspective, managers ought to gather the relevant information, calculate risks, and take responsible actions. From this perspective, NASA managers didn't obtain all of the relevant information in the Columbia case and they relied

on authority and formal reporting procedures to understand what had occurred. Moreover, as responsible decision makers, they also did not pursue informal discussions to reach a consensus agreement about how this particular foam-shedding event should be categorized, and so, ultimately, they were to be blamed when the mission failed.

If investigators are to understand and learn from processes that lead to disasters around emergent situations, they cannot continue to rely on a conceptualization of organizations as information-processing systems that are somehow subject to the objective control and direction of responsible individual decision makers. At a minimum, they must conceptualize organizations as systems where knowledge is distributed across artifacts, people, metrics, and routines. If an organization is conceptualized in this manner, then it becomes clear that top and middle managers cannot know all of the relevant information that is required to categorize an event in real time and, consequently, investigations will be forced to consider a wider range of explanatory factors. As Tsoukas (1996: 22) observed:

'The key to achieving coordinated action does not so much depend on those "higher ups" collecting more and more knowledge, as on those "lower down" finding more and more ways of getting connected and interrelating the knowledge each one has.'

Our analysis of communication during the Columbia shuttle flight shows that interpretive indeterminacy emerged for reasons that go beyond variable disjunction of information as articulated by Reeves and Turner (1972). Although the batch production plants in Reeves and Turner's study were characterized by a state of variable disjunction of information, the people in the plants knew they were operating in this state and they developed ready-at-hand heuristics to address the issues that arose. In contrast, and after identifying the foam-shedding event, NASA did not know what the situation was that it confronted, what it should be doing, or how it should be responding. In order to find out, it organized itself so that it first had to categorize the emergent situation as requiring either a routinized response focused around scheduling concerns (based on an 'in-family' assessment of the event), or an improvisational response focused around safety concerns (based on an 'out-of-family' assessment of the event), and this categorizing process activated distributed and overlapping action nets with different perspectives on what was happening and what was required. Consequently, rather than triggering a convergence of views, the event triggered ongoing categorization efforts that ultimately simply reinforced indeterminacy.

What are the implications of these findings for other organizations? NASA is an elite organization with vast experience and knowledge, highly motivated employees, and a record of great achievement. Might other organizations with multiple assessment criteria also confront situations that are similar to the one NASA confronted with the Columbia disaster? We suspect they might, given the tensions that have been noted between organizational criteria such as exploration and exploitation (March 1991), flexibility and efficiency (Adler et al. 1999), value maximization and risk abatement (Beunza and Stark 2005), and continuity and change (Jelinek and Schoonhoven 1990). Future research must look into how interpretive indeterminacy plays out in these organizations operating with multiple performance criteria. For instance, what roles do time pressure and resource constraints play in such processes? To what extent may conflicting assessment processes be triggered even

more strongly in organizations representing high stakes and visibility? As a sequence of events unfolds, what triggering events might potentially tip an organization in one direction or another? A deeper understanding of these issues can help us better understand how other prominent organizations may deal with and respond to unexpected events similar to the one that NASA confronted with the Columbia disaster.

## Notes

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- 1 Vaughan (1996: 65) calls this 'normalization of deviance', by which she means that behavior first identified as a technical deviation is subsequently reinterpreted as being within the norm for acceptable performance and, eventually, is officially labeled as an acceptable risk.
- 2 Variable disjunction refers to 'a complex situation in which a number of parties handling a problem are unable to obtain precisely the same information about the problem so that many different interpretations of the problem exist' (Turner 1978: 50).
- 3 Hutchins (1995) studied how a ship navigates its way into harbor. The captain and his team are clearly important. But equally important are the midshipmen carrying out navigating routines, including those making sightings, those recording bearings, and those timing the readings, etc. In turn, the actions and judgments of these people are profoundly shaped by the knowledge implicit in the designs of the instruments they use and in the evaluation metrics that they employ to assess the readings their routines generate. The rules for taking a bearing at regularly scheduled intervals ensure that these distributed elements taking action in a temporally ordered manner continually ascertain the position of the ship.
- 4 The report that the accident board put together is 248 pages in length. The investigatory board was made up of independent and knowledgeable authorities and the work in the report itself was carried out by an army of investigators and researchers with complete access to NASA's vast historical archives of flight and maintenance data and routine and investigatory reports. All this material is now available on the Internet: <http://spaceflight.nasa.gov/shuttle/archives/sts-107/investigation/index.html>. The board's report was also read, discussed with, and elaborated upon by leading outside consultants and academics. We believe the report is exemplary in terms of its data detail and its effort to provide a transparent explanation for what happened to the Columbia (CAIB 2003).
- 5 CRIT 1/IR component failures are defined as those that, if they occur, will result in loss of the Orbiter and its crew.
- 6 Foam shedding and potential tile damage was just one of over 5,396 known and documented hazards associated with the shuttle and, among these, NASA informants told us it was certainly not the problem being accorded the highest concern.
- 7 This is a problem similar to the one reported by Reeves and Turner (1972: 90) of 'convincing others of the status of their own set of information and thus of the validity of their analysis of the situation and their suggestions for action'.
- 8 The manufacturing process was divided into engineering teams, each with specialized technical expertise: design of circuits, the use and management of process equipment, and the design and management of process integration. In terms of metrics, the primary objective of the designers was to design chips to run at the highest possible speed. Process engineers were mainly interested in stabilizing the steps in the management process and making them as predictable as possible. The primary objective of the process integration engineers was to take the initial circuit design and create a working electronic device able to be fabricated through management process steps.

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