Managing Abnormal Situations in the Process Industries I: Automation, People, Culture

Edward L. Cochran
Honeywell Technology Center

Consider the following incidents, all of them missed opportunities to demonstrate excellence in the management of complex systems:

- The left engine on a British Midlands 737 fails catastrophically. The flight crew mistakenly shuts down the *right* engine, and the aircraft ultimately crashes short of the runway while attempting an emergency landing.
- An air traffic controller clears a 737 to land on a runway at LAX, forgetting that she had cleared a commuter aircraft to hold for take off on the same runway. The 737 collides with the smaller aircraft with horrific results.
- The U.S.S. Vincennes, a guided missile cruiser engaged in combat operations, detects an aircraft leaving a commercial airport in an uninvolved country. The crew concludes the target is a threat and ultimately shoots down a commercial airliner, killing 290.
- The navigation of the lead ship in a squadron of destroyers on a night sortie breaks down, and the bridge crew, misperceiving lights on shore and believing they have passed a dangerous shoal, turn the ship directly into the hazard. It runs aground, as do most of the ships following behind.
- A process operator begins to start up equipment on the Piper Alpha production platform following a shutdown for maintenance. Unfortunately, the maintenance crew has not yet finished reconnecting the pipes, and escaping vapors explode, leveling the platform and killing 167 workers and rescue personnel.
- The operator of a chemical plant disbelieves a level reading that has led to the activation of safety interlocks and prevented the initiation of a batch process. He overrides the interlock and the reactor explodes.
- An operator sent to open a valve on one of four identical process units opens the valve on the wrong unit, leading to a catastrophic fire.

Acknowledgments. The author gratefully acknowledges the contributions made by Peter Bullemer, Richard Lewis, and Ian Nimmo to the ideas presented in this paper.

Preparation of this paper was in part supported by a grant from the National Institute of Standards and Technology's Advanced Technology Program to the Abnormal Situation Management Joint Research and Development Consortium.

These incidents all have one thing in common: The people involved weren't really at fault, and the causes of the incidents should not be listed as human error. Instead, these incidents are just a few examples from a long and tragic list of cases in which the complexity of the systems involved combined with the communications requirements of the specific situations led to performance demands that individual humans are fundamentally not capable of sustaining.

In all of these cases the result was an accident, and therefore newsworthy. However, it is likely that, although not newsworthy, nonoptimal management of complex systems is ubiquitous, and has enormous financial impact in terms of waste and inefficiency. We are only beginning to understand the magnitude of the problem, and the true nature of its cause.

System complexity is a function of the number of components, the number of changes that can occur, the interactions among those changes, and the speed with which those interactions propagate. In practice, the number of components and relations is less important than the possibilities for change in the behavior of those components: People can often learn to deal with static complexity given sufficient training, but once the possibility of change is introduced, difficulty increases exponentially.

When systems become too complex for one person to manage, the management task is divided among members of a team of people. This works for a while, but the advantages of having more people to think about the problem is offset by the need for communication among those people, and by the introduction of new kinds of problems resulting from various kinds of communication lapses. People not only must be capable of understanding the situation and developing a successful response, but they must rely on each other in developing their understanding and determining the best course of action. There is a delicate balance to strike here, lest the communication demands consume all of the attention of the people who were added to the system to help manage it.

As systems become more complex , their human supervisors need to be more capable.

As the numbers of people involved increases, the amount of communication required increases.

Eventually, too much is required of the individuals charged with supervising the system, and breakdowns occur. To blame these breakdowns on human error is akin to criticizing a novice juggler for her inability to juggle 15 balls at once. While standing on someone's shoulders. On a unicycle.

Since the capabilities of individual humans are limited and change too slowly for us to rely on evolution as a solution, there are only two options:

- Reduce the apparent complexity of the system, or
- Reduce the need for, or increase the efficiency of, communication.

The remainder of this paper describes a number of ways of achieving these goals. I begin with an overview of some of the problems experienced by individuals and teams in dealing with complex systems, which will inform our concluding discussion on promising solution approaches.

The Role of Individual Humans in Complex Systems

Many current views of human action in complex systems use a model similar to that in Figure 1. The model in Figure 1 is a variation of a decision-making model adopted by the Chemical Manufacturers Association.

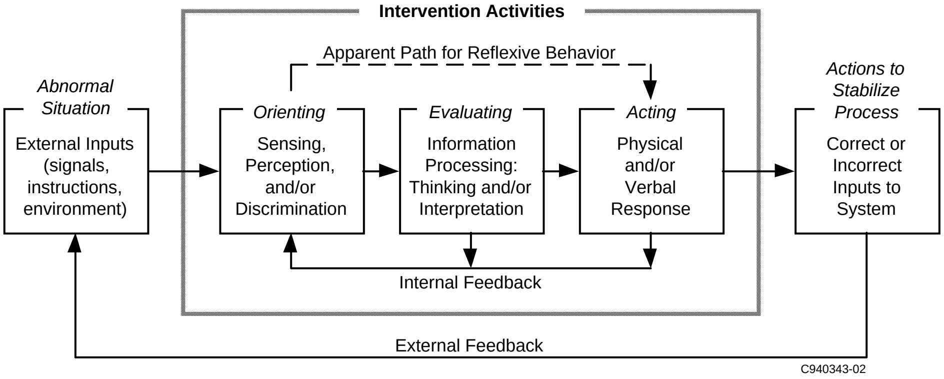
Intervention Activities
Apparent Path for Reflexive Behavior
Abnormal Situation
External Inputs (signals, instructions, environment)
Orienting
Sensing, Perception, and/or Discrimination
Evaluating
Information Processing: Thinking and/or Interpretation
Acting
Physical and/or Verbal Response
Actions to Stabilize Process
Correct or Incorrect Inputs to System
Internal Feedback
External Feedback
C940343-02

Figure 1: Standard model of human interaction with complex systems.

In this model, there is an outside world which generates events, some of which are perceived by humans, processed internally, and ultimately generative of responses—actions which initiate new cycles of activity.

This model is often used to explain and categorize the kinds of errors that can arise during different stages of the Orient-Evaluate-Act cycle. For example, operators may fail to notice key information that is present on their displays, leading to inadequate orientation and inaccurate evaluation. Such errors can be minimized by increasing the conspicuity of the information or reducing the workload of the operator. There has been increasing emphasis on the rigorous application of human factors principles to the user interfaces to complex systems to identify and minimize such problems.

However, those who apply this model in that traditional way often make two assumptions which are only approximately true. Worse, these assumptions break down precisely in the same way and for the same reasons that management of complex systems often breaks down. The result is that our traditional approaches to developing better ways to manage complex systems have a large blind spot.

The first assumption is that, in describing the activities of the operator, the outside world is the standard reference. Thus, we tend to think that if turning on a pump lowers the level in a tank, and the operator needs to lower the level in a tank, the operator should turn on the pump. If that act is not carried out, a mistake is declared. Most of the time this way of thinking is perfectly adequate.

However, the world that *really* matters is the one in the head of the observer. If the operator does not know that turning on a pump lowers the level of a tank, or does not know that the particular tank with the problem has a pump that can be turned on, then it is pointless to expect the operator to turn on the pump. The “mistake” is not the operator’s—the operator is after all acting perfectly consistently with respect to the world as they know it. Instead, the problem is with the way the operator learned about the system. That process is not represented in the model at all.

Abnormal situations frequently arise because the physical world is not congruent with the world in the head of the operator [Indeed, all of the examples at the beginning of this paper such examples].

The second assumption that users of the Orient-Evaluate-Act model often make is related to the first. We assume that there is a single set of “facts” to be had, which should, ideally, serve as a reference for evaluating the performance of operators and the system itself. This assumption serves us well most of the time, especially when the facts in question concern physical things that can be observed and discussed and agreed upon. The assumption that facts are facts is clearly not true in the realm of political opinion, religion, and other cultural matters, and in fact there is a long tradition in Western philosophy to distinguish between “facts” and “beliefs” and to develop a method (the “scientific method”) of extending the realm of fact.

The problem is that individuals rarely distinguish between the two, and therefore it is wrong for us to assume that individuals will be orienting, evaluating, and acting solely with respect to “the facts.” Consider the operator of a process unit faced with an unexpected and severe upset. The plant manager has stated in writing that the policy in such instances is to shut the unit down to prevent damage and to permit an orderly recovery. All operators have read and signed this policy. The operator in this instance attempts to ride the disturbance out, and, after some drastic control moves, ultimately succeeds. The “facts” would indicate that the operator in this case made a mistake by persisting, in direct opposition to standing policy, with the attempt to recover from the upset without shutting down. However, what if the last four times this event has occurred, operators who have kept the plant running have been rewarded, and those that have followed established policy have been ostracized?

When conflicts such as this exist, people do the best they can, forming beliefs about what the facts are based on their own observations, knowledge, and experience[1]. When the need to act in accordance with the “facts” arises, the results can be unpredictable.

A different example of a problem with the use of “facts” arises in complex systems due to the relative rarity of the kinds of problems that people have been tasked to prevent. In essence, the issue is that humans are not very good at understanding and explaining events with which they have little experience. College-educated adults may believe that objects that are dropped from a moving car fall straight down, or that objects swung around on a string and released will spiral away. Humans are also fundamentally flawed statisticians, and fall prey to all manner of inaccurate assessments of low probability events, which causes problems when those assessments are acted upon as “fact.”

[1] The contributions of culture to experience can significantly affect the results, as we will see later in this paper.

The problem for us as designers of complex systems is that we tend to design them as if the users will understand the facts and determine the true state of the world and act accordingly. As we have seen, the facts are quite malleable and the perceived state of the world may be inaccurate. Abnormal situations frequently arise for this reason. [Indeed, all of the examples at the beginning of this paper such examples].

Richard Feynman makes a similar point in a discussion of the Challenger accident:

> "Let us make recommendations to ensure that NASA officials deal in a world of reality in understanding technological weaknesses and imperfections well enough to be actively trying to eliminate them.... And they must be realistic in making contracts, in estimating costs, and the difficulty of the projects. Only realistic flight schedules should be proposed, schedules that have a reasonable chance of being met. If in this way the government would not support them, then so be it. NASA owes it to the citizens from whom it asks support to be frank, honest, and informative, so that these citizens can make the wisest decisions for the use of their limited resources.
>
> "For a successful technology, reality must take precedence over public relations, for nature cannot be fooled."

The simple orient-evaluate-act model needs to be viewed as a more complex system of interactions between perceivable events and the knowledge and beliefs of an individual, leading to the construction of an understanding of the situation upon which responses are based. This expanded model is depicted in Figure 2.

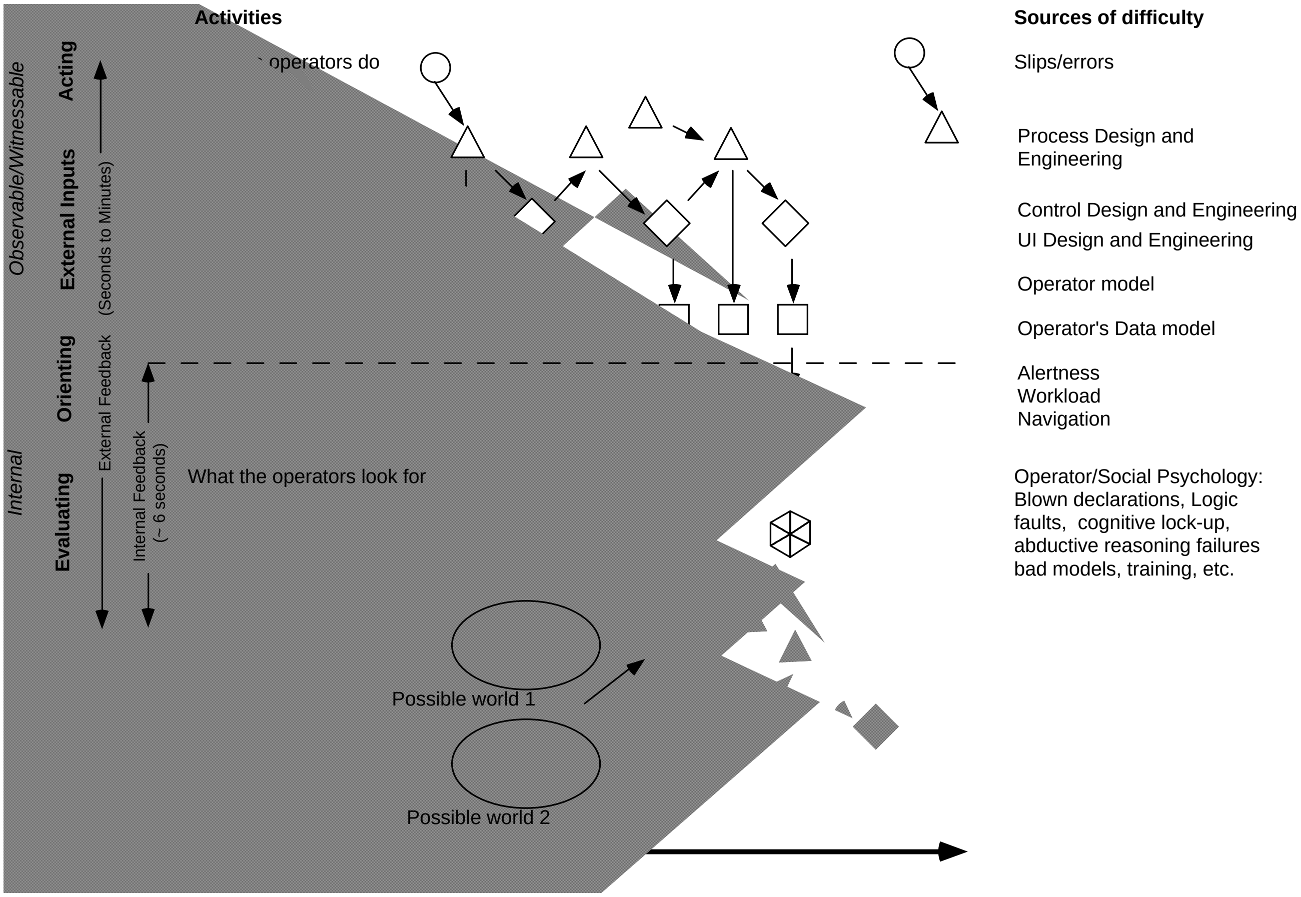

Figure 2: Elaborated model of human interaction with complex systems.

Operations Teams and Complex Systems

Complex systems are usually managed by *teams* of individuals. As a result, all of the issues discussed above are present for each individual member of the operations team. In addition, a number of new issues emerge as a consequence of the need to solve problems collaboratively.

Shared understanding of how the world works.

As important as it is for the lone system operator to have thorough and accurate knowledge of their system, it is even more so for members of operations teams, for two reasons. First, teams are responsible for larger, more complex systems, and no single person may be capable of understanding the whole system. Instead, all of the members of the operations team depend on each other's understanding of parts of the system, and gaps in that understanding are both more likely, and more likely to have greater consequences.

The second reason that thorough and accurate knowledge of the system is critical for members of operations teams is related to the first: The team member with inaccurate knowledge is likely to lead the rest of the team down the wrong path *even when they presumably know better*.

There are many reasons for this. The more knowledgeable team member(s) may incorrectly yield to the authority, experience, or position of the other, or be overly influenced by irrelevant social factors such as friendship (or lack thereof) or be shaken by stress, excitement, fear, or other emotional reaction to the situation.

In the British Midlands incident described at the beginning of this paper, at least one of the pilots may have acted on the "knowledge" that fresh air to the cockpit is provided by the right engine. The smell of smoke may have led to the assumption that the right engine was the one that had failed—an assumption that was not challenged by the other pilot nor shaken by the evidence of the instruments.

Shared understanding of the desired state of the world

It is critical that the members of the operations team develop a consistent understanding of their short- and long-term goals—the formal and informal rules and guidelines for the operation of the system they are responsible for. We have already seen that the "facts" about the desired response to an incident may be not be the same for operators and plant managers, and indeed this is an example in which the lack of shared vision within an operations team can lead to nonoptimal results.

The same sort of problem (albeit on a much shorter time scale) happens hundreds of times a day in the U.S. when team members miscommunicate—when one or more members of the team fail, for whatever reason, to receive the message that another member intends to send. From that point forward, the team members are operating with respect to different views of the world. As a result, the wrong valves get opened, airplanes land on the wrong runway, ships run aground, and plants run short of raw materials.

Shared understanding of the current state of the world

It is critical that the members of the operations team not only develop an accurate model of the state of the system they are responsible for, and its desired state, but the state that the system is actually in. When a members of an operations team believe different things about the state of a plant, trouble often results. [Note that post incident review teams typically label the beliefs of the team member(s) who is determined to have been incorrect as "beliefs" or "assumptions" (often described as "unfounded"). In fact, the team member(s) who are determined to have been *correct* often were working with beliefs or assumptions as well—they just happened to be accurate. All of the team members—correct as well as incorrect—act consistently with the world inside their own heads.]

When an operator believes that maintenance is complete on equipment at a plant at the same time that a maintenance worker believes that the equipment is still out of service for maintenance, an incident is likely. Whether the operator or the maintenance worker is "correct"—that is, has a set of assumptions more consistent with the "true" state of the plant—is irrelevant, as this changes only the nature of the incident, not the likelihood that an incident will occur. Some of the most horrific incidents in the history of technology (including the loss of Piper Alpha oil rig with most of those on board and the $1.6 billion fatal explosion and fire at the Phillips plant in Texas City in 1989) can be traced to this precise problem.

The problem worsens when the state of the plant is unfamiliar (as it is during upsets), when the understanding has to be developed rapidly (as it is during upsets), when the team is inexperienced in working together on the particular problem involved problem (as it is during upsets), and when accurate understanding is important to the selection of an appropriate response and ultimately to the outcome of the event (also as it is during upsets). Reviewers of the Vincennes incident describing the chaotic environment on the bridge and in the ships combat information center —the ship had been maneuvering violently, and firing weapons at surface targets—concluded that it played a significant role in the incident.

Shared understanding of the plan to reduce the discrepancy between actual and desired states of the world.

Even when the operations team has a shared vision, an understanding of the how the process works, and an accurate diagnosis, they may fail to develop a shared understanding of the recovery plan. This is relatively rare, and usually happens in combination with one of the previous problems described above. Nevertheless, since most processes are complex enough that several options are available to recover from any undesirable state, it is important that the operations team agree on and operate consistently with respect to a single recovery plan.

Opportunities for error arising from the need for communication

Given the need for every person on the operations team to act consistently and accurately with respect to the state of their process, it is not surprising that errors occur. In fact, the relatively low rate of incidents stands as testament to the effort that has been devoted to creating just this kind of shared vision across process teams.

Many good analyses of the causes of individual human errors exist, and need not be summarized here. In an ideal culture of team operations, most errors of this type would be quickly detected and corrected, given the interlocking responsibilities and oversights of the members of the operations team.[2]

Since most operations teams do not yet operate with respect to completely consistent perspectives, they are subject to several kinds of errors which are unique to team settings and which are extremely difficult to overcome. Awareness of these team-induced errors has been growing, and attempts are being made to address the problem (e.g., Cockpit Resource Management training initiatives in aviation), but the study of this area is still in its infancy.

[2] An exception occurs when the team structure is designed to depend on the complete trust of members of the team in an experienced team leader, who must make accurate decisions in isolation. The need for this team structure is rare—formation acrobatics is one example—and when the leader of the team does make a mistake, the cost can be high: There have been instances in which entire formations of planes followed the leader into the ground.

Several examples of these errors are described below.

Inadequately qualified assertions

Assertions are statements about our observations. While we may believe these statements are descriptions of the way things “really” are, in fact all we know is how we ourselves observe them. An assertion is “true” if we could provide a witness who would concur with our observation, and it is “false” if a witness would dispute it. The act of making an assertion commits us to truthfulness, but assertions may be qualified and thus relieve us of the need for absolute precision (this paper is a fine example).

However, accurate communication requires that we be able to assess the need for such qualifications in our sharing of observations, facts, urgency, and so on, with other members of our team. This requires either significant knowledge of the other people on the team (as is the case in close-knit teams of long standing), or absolute adherence to procedure (is as the case in naval carrier operations or air traffic control.) Most process plants—indeed most civilian operations of all kinds) operate as if the team has the requisite self-knowledge to accurately communicate in the absence of rigorous procedures. This is risky, as demonstrated by the large number of audio recordings of incident communications in which amplifications and clarifications of observations are required in order to get an appropriate response.

Inaccurate declaration of knowledge

Declarations are decrees—impositions of aspects of our own world, such as our beliefs, on others. They can be loosely described as determining a view of the world that those subject to the decree will abide by, “accurate” or not. Because declarations represent the views of at least one person, but not others (else imposition would not be necessary), they are usefully described as valid or invalid, according to the power of the person making the declaration, as well as accurate or inaccurate.

The power we grant to some people to make valid declarations is called authority. Thus valid declarations (whether accurate or not) are made by those with authority, and invalid declarations (whether accurate or not) are made by those without authority. It is easy to understand how valid but inaccurate declarations can be a source of problems, as when a flotilla of destroyers follows the admiral’s ship into the shoals.

Inaccurate declarations are in fact a major cause of the progression of abnormal situations to accidents, because they are relatively frequent, and because they create a world—a set of shared beliefs—in the operations team, whether it is accurate or not. For example, in the presence of conflicting temperature readings and no other witness, a declaration is required to determine which reading is “correct”—and that declaration will be used to coordinate subsequent action. The declaration may be valid—the shift supervisor may have the authority to make it—but it may not be accurate. This is a critical point in any situation, because from then on the operations personnel will act in accordance with the world they have created, until it becomes so obviously inconsistent with further events that the declarations are retracted. Unfortunately, humans are very good at weaving consistency out of noisy or incomplete observations— “obvious inconsistency” must be very obvious indeed.

Ineffective culture of authority

A more insidious kind of problem arises when the exercise of authority is ill-defined, as when incident command functions are not specified, or those with authority do not exercise it appropriately. Authority is important, because it enables declarations to be valid. Declarations are one of only two ways of defining shared knowledge, and by far the most efficient in terms of time.[3]

Hierarchies often exist primarily to permit declarations to be made in the presence of unresolved questions. In the absence of authority, decision making can become a social process, and anyone on the team becomes capable of making a de facto declaration on the basis of field knowledge, social influence, bravado, self-certainty, or other factors, whether appropriate or not. There is no time for an effective inquiry process, and a consensus "state of the world" is thus reached in an ad hoc way.

Many incidents attributed to so-called "garden path thinking" or "cognitive lock-up" can be viewed in these terms. A human declares that a radar blip represents an attacking fighter, or that safety interlocks have inappropriately engaged. The declaration is not questioned, even though authority structures are supposedly in place to ensure that it is. Subsequent actions, consistent with the inaccurate declaration, lead to incidents.

Throughout the Piper Alpha oil platform fire, a neighboring production platform pumped product to Piper Alpha (literally adding fuel to the fire) because the supporting platform manager assumed that he had no authority to do otherwise in the absence of an order from Piper Alpha to stop production. [Piper Alpha's control room and communication capability was destroyed in the initial explosion].

Confusion between requests, promises, offers, and assertions

We should not expect operations teams to be students of discourse and rhetoric, but in fact in the absence of clear procedures or team with enormous experience working together, the opportunity for confusion is rampant. Consider the opportunities for problems inherent in the confusion between requests, promises, offers, and assertions:

- *Promises* are the linguistic acts that allow us to coordinate action with others (both implicitly and explicitly). Four fundamental elements are involved in a promise: A speaker, a listener, a condition of satisfaction, and a completion time. The act of making a promise commits the promiser in three domains: sincerity, competence, and reliability.
- *Requests* are solicitations of promises from someone else. They can be thought of as a promise of the form "I [perhaps conditionally] promise X if you promise Y." X can stand for tangible and intangible conditions of satisfaction, e.g., "I will be pleased," "I will be better able to make a diagnosis," "I will get you safely out of this." Y carries the form of the promise in return, e.g., "[Listener] will fetch a reading from the gauge;" "[Listener] will close valve 17 and open valve 18." A request, when answered with a declaration of

[3] The other way to define shared knowledge is through a process of inquiry—questioning the sources of differences in assertions until they are explained through more comprehensive sharing of context.

acceptance, creates a promise. If a request is declined no promise has been made. [A request which cannot be declined is not a request, it is a declaration.] The act of making a request implies that we can competently assess our knowledge of the system, and it commits us to acting consistently with an implicit assertion we thereby make, that the *other* person is sincere, competent, and reliable.

- *Offers* are a request for a promise of the form “If I promise Y, will you promise X?” where X and Y are defined as above. Thus a simple “May I help you?” if it is sincere, carries a social meaning such as “I will help you [the promise] if you would be pleased for me to do so [promise as condition of satisfaction].” The commitments, structure, and implications of making offers are very similar to those involved with making requests; only the agent of conditionality is reversed.

This is obviously a brief and highly simplified treatment of an extremely rigorous and extensive domain of study. Successfully transferring information from one person to another requires the successful application of myriad knowledge about ourselves and our colleagues, otherwise confusion results: We make requests of people who are not able to carry them out, raising doubts about our own competence and the validity of further requests. We unknowingly accept a request that we are unable to fulfill, calling into question our competence and/or sincerity. Ultimately, we may not know what is being asked of us, or why, or what the consequences will be for failing to meet the request.

If that were not challenging enough, the linguistic domain of *pragmatics* enables every one of the above distinctions to be rendered false; for example, an assertion (“It is cold in here!”) can be a request (“Please close the window!”). An offer (“May I review your monthly report”) can be a declaration (“Give me your monthly report”)—especially if the speaker has authority over the listener. And so on. Pragmatics requires a further layer of social knowledge to be negotiated, one that focuses on the implicit or implied motivations, values, and characteristics of the people with whom we interact. Pragmaticians study linguistic acts from both sides—the intent of the speaker and the interpretation of the listener—and the social mediations can be complex indeed. The fact that humans communicate so well is testimony to how finely-tuned and sophisticated are our abilities to act within a social environment.

Summary: Teams and culture in complex systems

We have argued that all of these linguistic acts imply social commitment; they can only function from the background of shared social practices and a shared ability to recognize and act in accordance with those practices. An operations team in a complex process, then, must understand how the process works, and their goals for the process, and the state of the process, and the actions to required to close any gap between the state of the process and their desired state. But they need to know more.

They need to understand themselves, their team members, and their culture.

As a rule, those charged with designing, implementing, operating, and maintaining complex processed pay little if any attention to these issues, if they are aware of them at all. The result is that we handle the requirements imposed by the need to collaborate with others in process operations in the same informal way that we handle the need to collaborate with others in planning a PTA fund-raiser, remodeling a kitchen, raising a family, and every other endeavor typical of life.

As a rule, people are intuitively very good at this, as the continued existence of PTAs and remodeling contractors, to say nothing of civilization itself, amply demonstrates. Nevertheless, mistakes are made; misunderstandings occur; backtracking is necessary; failure is a possibility.

There are two primary reasons why this situation is not tolerable in complex systems:

- The complexity of the systems and the speed with which events propagate make our intuitive methods of gaining alignment very inefficient and error-prone.
- The consequences of error are too high.

Lessons for managing automation in complex processes

Given the forgoing discussion, we are left with two primary issues that need to be addressed if we are to progress further to successfully manage systems of higher complexity, with larger operations teams.

First, we need to find better ways to manage the apparent complexity—to assure that team members have consistent views of all the things that we have argued they must.

Second, we must find better ways to support real time collaboration and the exchange of information as accurately, quickly, and richly as the operations teams of complex systems will require.

Consistency

There are a number of ways to ensure consistency in the understanding of systems.

Training

Rigorous, high quality training is mandatory, especially including training for the rare events that test the operations team the hardest. As technology improves, the extension of simulation-based training from domains such as aviation is becoming more economical. But good training need not be expensive: “What if?” training, role playing, and scenario development are all very effective in building shared views and expectations.

Reporting

Incident tracking and reporting is critical to the deliberate and disciplined sharing of insights and experience gained from unusual events with everyone who might benefit from them.

Communications

A formal communications policy must be in place that ensures that consistent messages are sent from the top to the bottom and from one end of the plant to the other.

Authority

An incident command structure must describe the authority of those involved—and those involved must live up to that authority.

Procedures

Most important of all, consistency requires that the operations culture make a disciplined practice out of creating, evolving, and following *procedures*. Procedures incorporate knowledge compiled when there is time to think so as to benefit those in situations in which there isn't. Procedures clarify ahead of time the goals, expectations, and information requirements of unusual situations. Communications procedures ensure that the appropriate information is available to the appropriate people at the appropriate time. [Good radio procedures alone can reduce uncertainty in message content by a factor of two, and perhaps even more in an industry that often refers to equipment entirely in easily confused alphanumerics, such as J-159A].

The U.S. Navy, over the past thirty years, reduced the rate of mishaps by a factor of six, from 19.3/100,000 hours of flying time in the early 1960s to under 3.0 in the early 1990s through a comprehensive effort to develop best practices and instill absolute procedural discipline in using those practices.

Collaboration Support

Once we have achieved some measure of consistency within the operations team—and only then— we can begin to develop ways for the members of the team to collaborate quickly and accurately. [The introduction of collaboration support technology before consistency is achieved is not helpful and may in fact be harmful in that it might permit the more rapid exchange of inaccurate information.]

The goal will be to ensure that each member of the operations team has access to the right information, at the right time, for the right reasons. The next paper describes an ambitious approach in this area.

Conclusion

We have seen that the use of operations teams to the management of complex systems introduces a number of extremely challenging issues that must be solved if progress is to be made. Most of these issues result from the fact that our normal approaches to human interaction, and our skills in communicating with others, are simply not adequate to keep up with the rapid changes that occur in processes. Even if we could keep up with these systems as well as we do in our other daily activities, the consequences of the occasional mistakes are too great for us to tolerate.

To make further progress, effort needs to be devoted to the development of deliberate, principled approaches to the establishment of rigorous and consistent operations cultures. Only then will further advances in automation technology be likely to succeed.