



Organizing Work by Adaptation

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ORGANIZING WORK BY ADAPTATION*

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Common sense suggests that work is organized in accordance with plans that are created by designers who reflect on the work setting and manipulate representations of the work process in order to determine new and efficient organizational structures. Or, even if "outside" designers are not involved, the reorganization of work is normally attributed to the conscious reflection by members of the work group itself. A detailed examination of the response of a real-world group to a sudden and unexpected change in its informational environment shows that these common sense assumptions may be quite misleading.

While entering a harbor, a large ship suffered an engineering breakdown that disabled an important piece of navigational equipment. This paper considers the response of the ship's navigation team to the changed task demands imposed by the loss of this equipment. Following a rather chaotic search of the space of computational and social organizational alternatives, the team arrived at a new stable work configuration.

In retrospect, this solution appears to be just the sort of solution we would hope designers could produce. However, while some aspects of the response appear to be the products of conscious reflection, others, particularly those concerning the division of cognitive labor, are shown to arise without reflection from adaptations by individuals to what appear to them as local task demands. It is argued that while the participants may have represented and thus learned the solution after it came into being, the solution was clearly discovered by the organization itself before it was discovered by any of the participants.

(NAVIGATION; ORGANIZATIONAL DESIGN; SOCIAL INTERACTION; MENTAL ARITHMETIC)

Introduction

This paper attempts to raise some questions about the processes by which the organization of work arises. Common sense suggests that work is organized in accordance with plans that are created by designers who reflect on the work setting and manipulate representations of the work process in order to determine new and efficient organizational structures. Or, even if "outside" designers are not involved, the reorganization of work is attributed to the conscious reflection by members of the work group itself. Here I examine the response of a work group to a change in its informational environment. I will argue that several important aspects of a new organization are achieved not by conscious reflection but by local adaptations. The solution reached is one that we recognize in retrospect as being just the sort of solution we would hope designers could produce, yet it is a product of adaptation rather than of design.

The setting is the pilothouse or navigation of a large navy ship. The bridge is the "brain" of the ship. It is where the captain sits, where the helmsman stands and steers, and where the navigation team works to ensure that the ship knows where it is located and where it is going at all times. Several years ago, while I was recording both video and audio data of the performance of an actual navigation team bringing a real ship into a narrow harbor, the ship's propulsion system failed unexpectedly. This was a bit of bad luck for the ship, simultaneously robbing it of its ability to maneuver and interrupting all electrical production. The loss of electrical power caused a cascade of failures of electrical devices including one that is literally and figuratively

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instrumental to navigation. This incident provided an opportunity to witness and record the response of a complex organizational system to a very real crisis situation. In this paper I will describe the way a navigation team adapted to the loss of an important piece of navigational equipment while the ship was entering a harbor. Before doing so, it is necessary to provide some background on the nature of navigation work and the navigation team.

Navigating Large Ships

Guiding a large ship into or out of a harbor is a difficult task. Ships are massive objects: their inertia makes them slow to respond to changes in propeller speed or rudder position. Because of this response lag, changes in direction or speed must be anticipated and planned well in advance. Depending on the characteristics of the ship and its velocity, the actions that will bring it to a stop or turn it around, for example, may need to be taken tens of seconds, or even minutes, before the ship arrives at the desired turning or stopping point. Aboard naval vessels, a continuous plot of the position of the ship is maintained to support decisions concerning its motion.¹ The *conning officer* is nominally responsible for the decisions about the motion of the ship, but usually, such decisions are actually made by the navigation team and passed to the conning officer as recommendations, such as, "Recommend coming right to zero one seven at this time." The conning officer considers the recommendation in the light of the ship's overall situation, and if the recommendation is appropriate, he acts upon it by giving orders to the *helmsman*, who steers the ship, or to the *leehelmsman*, who controls the ship's engines.

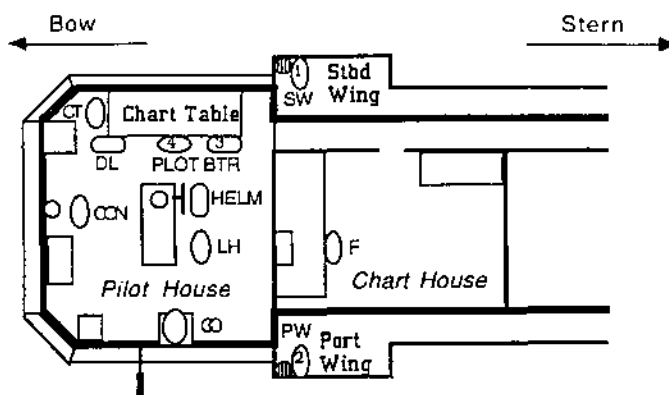
The navigation activity is event-driven in the sense that the navigation team must keep pace with the movements of the ship. Unlike many decision-making settings, when something goes wrong aboard ship, quitting the task or starting over from scratch are not available options. The work must go on. In fact, the conditions under which the task is most difficult are usually the conditions under which its correct and timely performance is most important.

Position Fixing by Visual Bearings

In order to plan the motions of the ship, the navigation team must establish the position of the ship and compute its future positions. The most important piece of technology in this task is the navigation chart, a specially constructed model of a real geographical space. The ship is somewhere in space, and to determine or "fix" the position of the ship is to find the location on the appropriate chart that corresponds to the position of the ship in the world.

The simplest form of position fixing, and the one that concerns us here, is position fixing by visual bearings. For this, one needs a chart of the region around the ship, and a way to measure the direction, conventionally with respect to north, of the line of sight connecting the ship and some landmark on the shore. The direction of a landmark from the ship is called the landmark's *bearing*. A line drawn on the chart starting at the location of the symbol for the landmark and extending past the assumed location of the ship is called a *line of position*. The ship must have been somewhere on that line when the bearing was observed. If we have another line of

¹Such complete records are not always kept aboard merchant vessels and are not absolutely essential to the task of navigating the ship in restricted waters. It is possible for an experienced pilot to "eyeball" the passage and make judgments concerning control of the ship without the support of the computations that are carried out on the chart. Aboard naval vessels, however, such records are always kept for reasons of safety primarily, but also for purposes of accountability so that, should there be a problem, the ship will be able to show exactly what it was doing and where it was at the time of the mishap.



Watchstander Positions for Sea and Anchor Detail

FIGURE 1. Plan View of the Navigation Bridge Showing the Location of the Chart Table and the Main Navigation Duty Stations. Position 1, starboard wing bearing taker; Position 2, port wing bearing taker; Position 3, bearing timer; Position 4, plotter.

position, constructed on the basis of the direction of the line of sight to another known landmark, then we know that the ship is also on that line. If the ship was on both of these lines at the same time, the only place it can have been is where the lines intersect. In practice, a third line of position with respect to another landmark is constructed. The three lines of position form a triangle, and the size of the triangle formed is an indication of the quality of the position fix. It is sometimes said that the anxiety of the navigator is proportional to the size of the fix triangle.

The Fix

The necessity for continuously plotting the ship's position, projecting the future track, and preparing to plot the next position is satisfied by a cycle of activity called the fix cycle. When the ship is operating near land, the work of the fix cycle is distributed across a team of six people.² The duty stations of the members of the team in the configuration called Sea and Anchor Detail are shown in Figure 1 as elliptical shapes. We can follow the fix cycle by following the trajectory of information through the system.

New information about the location of the ship comes from the bearing takers on the wings of the ship (Position 1 and 2 in Figure 1). They find landmarks on the shore in the vicinity of the ship and measure the bearings of the landmarks (direction with respect to north) with a special telescopic sighting device called an *alidade*. The true north directional reference is provided by a gyrocompass repeater that is mounted under the alidade. A prism in the alidade permits the image of the gyrocompass scale to be superimposed on the view of the landmark. (An illustration depicting the view through such a sight is shown in Figure 2.) The bearing takers read the measured bearings and then report them over a telephone circuit to the bearing timer.

The bearing timer (Position 3 in Figure 1) stands at the chart table inside the pilothouse. He talks to the bearing takers out on the wings and writes the reported bearings in a book called the bearing log which he keeps on the chart table in front of him.

The plotter (Position 4 in Figure 1) plots the reported bearings. He normally has no direct communication with the bearing takers, but either is told the bearings by the

²On other ships, and on this ship in different circumstances, the team may be somewhat larger or smaller depending on the availability of qualified personnel.

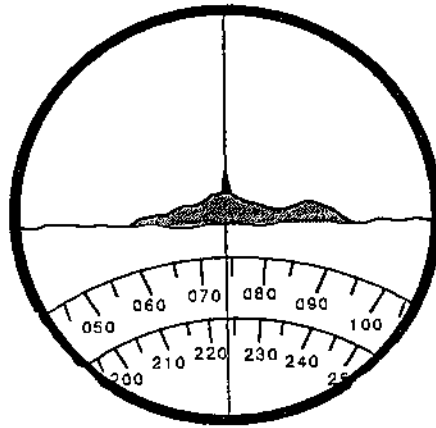


FIGURE 2. The View through the Alidade. The upper scale shows bearings relative to the ship's head, the lower scale swings with the gyrocompass and shows true bearings.

bearing timer, or reads them out of the bearing log. From the perspective of the plotter, the bearing timer is an information buffer. In order to make a high-quality fix, the bearings should be observed as quickly and as nearly simultaneously as possible. Since it takes much longer to plot a line of position than it does to make the observation of the bearing, the activities of the plotter and the bearing takers have different distributions in time. The activities of the bearing timer not only provide a permanent record of the observations made, but also permit the bearing takers and the plotter to work, each at his most productive rate, without having to coordinate their activities in time.

Once he has plotted the ship's position, the plotter also projects where the ship will be at the time of the next few fix observations. To do this he needs to know the heading and speed of the ship. The plotter normally reads these from the deck log, which lies on the chart table near his left hand.

When the projected position of the ship has been plotted, the bearing timer consults with the plotter to decide which landmarks will be appropriately situated for the next position fix, and assigns the chosen landmarks to the bearing takers by talking to them on the phone circuit. The bearing timer times the fix intervals, and about 10 seconds before the next fix time, he says "Stand by to mark." This alerts the bearing takers that they should find their landmarks and aim their telescopic sights at them.

At the time chosen for the fix observations, the bearing timer says "Mark," and the bearing takers observe and report the bearings of the landmarks they have been assigned. Thus the cycle begins again.

The Casualty

Crisis

After several days at sea, the USS Palau³ was returning to port, making approximately 10 knots in the narrow channel between Ballast Point and North Island at the entrance to San Diego harbor. A junior officer had the con under the supervision of the navigator and the captain was on the bridge. Morale in the pilothouse had sagged during two frustrating hours of engineering drills conducted just outside the mouth of the harbor, but was on the rise now that the ship was headed toward the pier. Some of the crew talked about where they should go for dinner ashore and joked about going all the way to the pier at 15 knots, so they could get off the ship before nightfall.

³All of the names appearing in this document are pseudonyms, including that of the ship itself.

The bearing timer had just given the command, "Standby to mark time three eight"⁴ and the fathometer operator was reporting the depth of water under the ship, when the intercom erupted with the voice of the engineer of the watch, "Bridge, Main Control. I am losing steam drum pressure. No apparent cause. I'm shutting my throttles." Moving quickly to the intercom, the conning officer acknowledged, "Shutting throttles, aye." The navigator moved to the captain's chair repeating, "Captain, the engineer is losing ah steam on the boiler for no apparent cause." Possibly because he realized that the loss of steam might affect the steering of the ship, the conning officer ordered the rudder amidships. As the helmsman spun the wheel to bring the rudder angle indicator to the centerline, he answered the conning officer, "Rudder amidships, aye sir." The captain began to speak, saying, "Notify . . .", but the engineer was back on the intercom, alarm in his voice this time, speaking rapidly, almost shouting, "Bridge, Main Control, I'm going to secure number two boiler at this time. Recommend you drop the anchor!" The captain had been stopped in mid-sentence by the blaring intercom, but before the engineer could finish speaking, the captain restarted in a loud, but cool, voice, "Notify the bosun." It is standard procedure on large ships to have an anchor prepared to drop in case the ship loses its ability to maneuver while in restricted waters. With the propulsion plant out, the bosun, who was standing by with a crew forward, ready to drop the anchor, was notified that he might be called into action. The falling intonation of the Captain's command gave it a cast of resignation, or perhaps boredom, and made it sound entirely routine.

In fact, the situation was anything but routine. The occasional cracking voice, a muttered curse, the removal of a jacket that revealed a perspiration soaked shirt on this cool spring afternoon, told the real story: the Palau was not fully under control, and careers, and possibly lives, were in jeopardy.

The heart of the propulsion plant had stopped. The immediate consequences of this event were potentially grave. Despite the crew's correct responses, the loss of main steam put the ship in danger. Without steam, it could not reverse its propeller, which is the only way to slow a large ship efficiently. The friction of the water on the ship's hull will eventually reduce its speed, but the Palau would coast for several miles before coming to a stop. The engineering officer's recommendation that the anchor be dropped was not appropriate. Since the ship was still travelling at a high rate of speed, the only viable option was to attempt to keep the ship in the deep water of the channel and coast until it had lost enough speed to safely drop an anchor.

Within 40 seconds of the report of loss of steam pressure, the steam drum was exhausted and all steam turbine operated machinery came to a halt. This machinery includes the turbine generators which generate the ship's electrical power. All electrical power was lost throughout the ship and all electrical devices without emergency power backup ceased to operate. In the pilothouse a high pitched alarm sounded for a few seconds, signaling an under-voltage condition for one of the pieces of equipment. Then the pilothouse fell eerily silent as the electric motors in the radars and other devices spun down and stopped. The port wing bearing taker called in to the bearing timer, "John, this gyro just went nuts."

"Yah, I know, I know, we're havin' a casualty."

Because the main steering gear is operated with electric motors, the ship now not only had no way to arrest its still considerable forward motion, it also had no way to quickly change the angle of its rudder. The helm does have a manual backup system located in a compartment called *after-steering* in the stern of the ship, a worm gear mechanism powered by two men. However, even strong men working hard with this mechanism can change the angle of the massive rudder only very slowly.

Shortly after the loss of power, the captain said to the navigator, who is the most experienced conning officer on board, "O.K., ah, Gator, I'd like you to take the con." The navigator answered "Aye, sir." and turning away from the captain announced to the pilothouse, "Attention in the pilothouse. This is the navigator. I have the con." As required, the quartermaster of the watch acknowledged, "Quartermaster, aye." and the helmsman reported, "Sir, my rudder is amidships." The navigator had been looking over the bow of the ship trying to detect any turning motion. He answered the helmsman, "Very well. Right five degrees rudder." Before the helmsman could reply, the navigator increased the ordered angle, "Increase your rudder right ten degrees." The rudder angle indicator on the helm station has two parts, one shows the rudder angle that is ordered, and the other the actual angle of the rudder. The helmsman spun the wheel causing the desired rudder angle indicator to move to right ten degrees, but the actual rudder angle indicator seemed not to move at all. "Sir, I have no helm sir!" he reported.

⁴All of the discourse reported in this passage is direct transcription from the audio record of actual events. Rather than presenting the transcript itself with annotation, I have combined the transcript and annotation into a single narrative structure. The purpose of this passage is to convey a sense of the drama of the situation and to set the scene for subsequent events that will be analyzed in detail.

Meanwhile, the men on the worm gear were straining to move the rudder to the desired angle. Without direct helm control, the conning officer acknowledged the helmsman's report and sought to make contact with after-steering by way of one of the bridge phone talkers. "Very well. After-steering, Bridge." The navigator then turned to the helmsman, "Let me know if you get it back." And before he could finish his sentence, the helmsman responded, "I have it back, sir." When the navigator acknowledged the report, the ship was on the right side of the channel, but heading far to the left of track. Very well, increase your rudder to right fifteen." "Aye, sir. My rudder is right fifteen degrees. No new course given." The navigator acknowledged, "Very well," and then looking out over the bow of the ship itself whispered, "Come on, damn it, swing!" Just then, the starboard wing bearing taker spoke on the phone circuit, "John, it looks like we're gonna hit this buoy over here." The bearing timer had been concentrating on the chart and hadn't heard. "Say again," he said. The starboard wing bearing taker leaned over the railing of his platform to watch the buoy pass beneath him. It moved quickly down the side of the ship staying just a few feet from the hull. When it appeared that it would not hit the ship, he said, "Nuthin," and that ended the conversation. Inside, they never knew how close they had come. Several subsequent helm commands were answered, "Sir, I have no helm." When asked by the captain how he was doing, the navigator, referring to their common background as helicopter pilots, quipped, "First time I ever dead-sticked⁵ a ship, captain." Steering a ship requires fine judgments about the angular velocity of the ship. Even if helm response were instantaneous, there would still be a considerable lag between the time a helm command was given and the time the ship's response to the changed rudder angle was first detectable as the movement of the bow with respect to objects in the distance. Operating with this manual system, the conning officer did not always know what the actual rudder angle was, and could not know how long to expect to wait to see if the ordered command was having the desired effect. Because of the slowed response time of the rudder, the conning officer ordered more extreme rudder angles than usual, causing the Palau to weave erratically from one side of the channel to the other.

Within three minutes, the emergency diesel electric generators were brought on the line and electrical power was restored to vital systems throughout the ship. Control of the rudder was partially restored, but remained intermittent for an additional four minutes. Although the ship still could not control its speed, it could at least now keep itself in the dredged portion of the narrow channel. Based on the slowing down over the first fifteen minutes following the casualty, it became possible to estimate when and where the ship would be moving slowly enough to drop the anchor. The navigator conned the ship toward the chosen spot.

About five hundred yards short of the intended anchorage, a sailboat took a course that would lead it to cross in front of the Palau. The Palau's enormous horn is steam driven and could not sound. The keeper of the deck log was ordered outside with a small manually pumped horn. Men on the flight deck ran to the bow to watch the impending collision. Five feeble blasts were sounded from the middle of the flight deck, two stories below. There is no way to know whether or not the signal was heard by the sailboat—by then it was directly ahead of the ship, and so close that only the tip of its mast was visible from the pilothouse. A few seconds later, the sailboat emerged, still sailing, from under the starboard bow and the keeper of the deck log continued to the bow to take up a position there in case other horn blasts were required.

The Consequences for the Navigation Team

The immediate response of the navigation team to the loss of steam and electrical power was simply to continue with the fix they were in the midst of taking. However, one of the pieces of electrical equipment that was subjected to loss of power was the Mark-19 gyrocompass. There are two layers of redundant protection for the gyrocompass function—*independent emergency electrical power and a backup gyrocompass.* Unfortunately, the emergency power supply for the gyrocompass failed, and the backup gyrocompass had been taken out of service earlier, due to a maintenance problem. So when the power failed, the Mark-19 lost power. The gyrocompass did not fail completely when the lights went out, but it did appear to be mortally wounded. Sixteen minutes after the loss of power, the Palau's speed had dropped to less than 4 knots and the ship was less than half a mile from its intended temporary anchorage, when word was passed to the bridge from the forward IC room that the gyrocompass had ceased operation. This was an especially critical period for the navigation team.

⁵To "dead stick" an aircraft is to fly it after the engine has died.

The chosen anchorage location was out of the navigation channel, and near an area where the water shoaled rapidly. Dropping the anchor too soon would leave the ship obstructing traffic in the channel, while dropping too late would risk the ship swinging over and grounding upon a shoal. Simply restoring the power to a gyrocompass is not sufficient to bring it to a usable state; several hours are usually required for the gyro to “settle-in” and provide reliable readings.

As we saw in the description of the normal activities of the navigation team provided earlier, the gyrocompass provides input to the determination of true bearings of landmarks for position fixing. For the navigation team, then, the primary consequence of the power outage was the loss of the only remaining functioning gyrocompass on the ship.

Computational Structure of the Task

Figure 3 shows the relationships among the various terms of the computation. With the gyrocompass working, the alidade (telescopic sight) mounted on the pelorus permits the direct measurement of the direction of the bearing of the landmark with respect to true north (TB in Figure 3). When the gyrocompass failed, all that could be measured by the bearing takers with the pelorus was the direction of the landmark with respect to the ship’s head (RB in Figure 3). In order to compute the true bearing of the landmark, once the relative bearing has been determined, it is necessary to determine the direction of the ship’s head with respect to true north. The compass measures the direction of the ship’s head with respect to magnetic north (C in Figure 3). But the compass reading must first be corrected for errors, called deviation, that are specific to the compass and dependent upon heading (D in Figure 3). Cartographers measure the difference between true north and magnetic north for all mapped regions of the world. This is called the variation (V in Figure 3). The sum of these terms is the true bearing of the landmark, that which was directly measured when the gyrocompass was working.

There is a mnemonic in the culture of navigation that summarizes the relations among the terms that make up the ship’s true heading. It is “Can Dead Men Vote Twice?” and it stands for the expression “ $C + D = M$, $M + V = T$ ” or “compass heading plus deviation equals magnetic heading, magnetic heading plus variation equals true heading.” This specifies a meaningful order for the addition of the terms in which every sum is a culturally meaningful object in the world of navigation. Every competent navigation practitioner can recite this mnemonic, and most can give an accurate account of what it means. The knowledge that is embodied in this formula will be an important component of the solution discovered by the navigation team. Notice, however, that this mnemonic says nothing about relative bearings.

The computational structure of the task is well known. As described above, computing true bearings for landmarks from relative bearings involves adding together the ship’s compass heading, the compass deviation for that heading, the magnetic variation appropriate for the geographic location, and the bearing of the landmark relative to the ship’s head. The procedure for a single line of position, therefore, requires three addition operations. If one used this procedure for each line of position, the set of three lines of position that make up a position fix would require nine addition operations. There is a substantial savings of computational effort to be had, however, by modularizing the computation in a particular way. Since all three lines of position in any given fix are observed as nearly simultaneously as is possible, the ship’s head for all of them must be the same. Thus, one can compute the ship’s true heading (sum of compass heading, deviation and variation) just once, and then add each of the three relative bearings to that intermediate sum. This procedure requires only five addition operations for the entire fix, two for the ship’s true heading

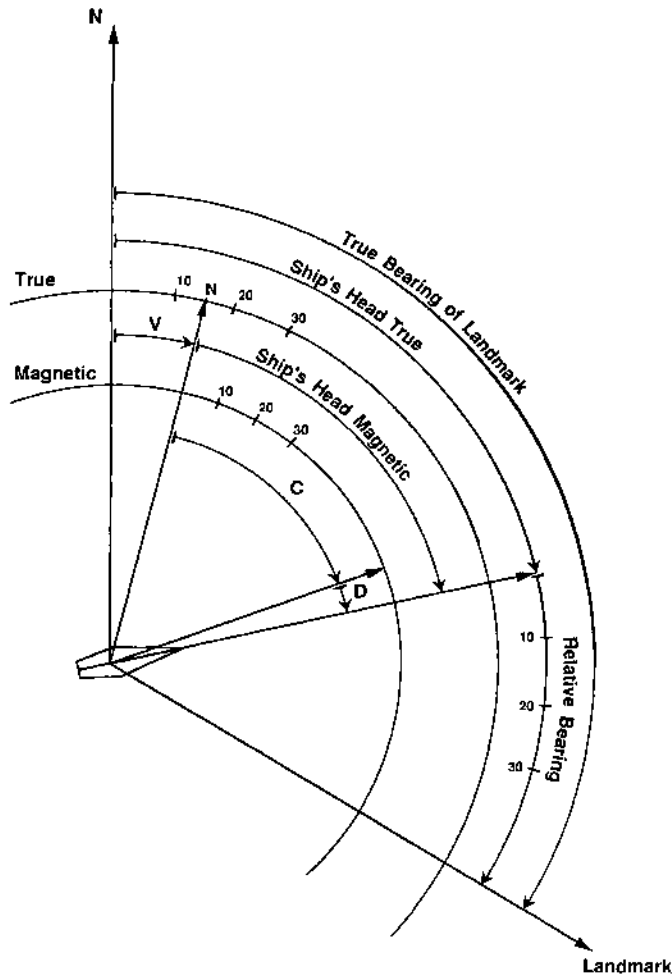


FIGURE 3. The Relationships among the Terms of the Bearing Correction Computation. True bearing of landmark from ship equals compass heading (C), plus deviation (D), plus magnetic variation (V), plus relative bearing (RB).

and one for each of the relative bearings, while nine addition operations are required by the nonmodularized procedure. As we shall see when we consider the details of the actual performance of the team, even a small savings of computational effort can be very helpful in this high workload environment.

The Problem of Organization

A search of ship's operations and training materials revealed many documents that describe in detail the nominal division of labor among the members of the navigation team in the normal crew configurations, and many that describe the computational requirements for deriving a single line of position from compass heading, deviation, variation, and relative bearing. There was, however, no evidence of a procedure that describes how the computational work involved in doing position fixing by visual observations of relative bearings should be distributed among the members of the navigation team when the gyrocompass has failed. The absence of such a procedure is not surprising. After all, if the ship had a procedure for this situation, it should have one for hundreds of other situations that are more likely to occur, and it is simply

impossible to train a large number of procedures in an organization characterized by high rates of personnel turnover.

Even though no such procedure exists, since this event did occur, we may ask what a procedure for dealing with it should be like. Clearly, the design of a procedure for this situation should take advantage of the benefits of modularizing the computation. Perhaps one would design a procedure that calls for the initial computation of ship's true head followed by the computation of each of the true bearings in turn. That much seems straightforward, but how should one organize the activities of the separate team members so that they can each do what is necessary and also get the new job done in an efficient way? This is a non-trivial problem because there are so many possibilities for permutations and combinations of distributions of human effort across the many components of the computational task. The design should spread the workload across the members of the team to avoid overloading any individual. It should incorporate sequence control measures of some kind to avoid dis-coordinations, in which crew members undo each other's work; collisions, in which two or more team members attempt to use a single resource at the same time; and conflicts in which members of the team are working at cross purposes. It should exploit the potential of temporally parallel activity among the members of the team and, where possible, avoid bottlenecks in the computation.

As specified, it is quite a complicated design problem, and it looks even more difficult when we examine the relationships between the members of the navigation team and their computational environment. Given the nature of the task they were performing, the navigation team did not have the luxury of engaging in such design activities. They had to keep doing their jobs, and in the minutes between the loss of the gyrocompass and the arrival of the ship at anchor, the requirements of the job itself far exceeded the available resources.

The Adaptive Response

Viewing the navigation team as the cognitive system leads us to ask where in the navigation team this additional computational load was taken up and how the new tasks were accomplished. To summarize before examining the performance of the team in detail, the additional computation originally fell to the quartermaster chief who was acting as plotter. To correct the relative bearings passed to him, he attempted to do the added computations using mental arithmetic, but it was more than he could do within the severe time constraints imposed by the need for fixes on one-minute intervals. By trading some accuracy for computational speed, he was able to determine when the ship had arrived at its intended anchorage. After the Palau came to anchor, the plotter introduced a hand-held calculator to relieve the burden of mental arithmetic under stress, and recruited the assistance of the bearing timer in the performance of the computation. There was no explicit plan for the division of the labor involved in this added task between the plotter and bearing timer. Each had other duties that were related to this problem that had to be attended to as well.

Since this correction computation has well defined sub-parts, we may ask how the sub-parts of the task were distributed among the participants. But here we find that at the outset there was no consistent pattern. The order in which the various correction terms were added, and who did the adding, varied from one line of position to the next, and even the number of correction terms applied changed over the course of the 66 LOP's that were shot, corrected, and plotted between the loss of the gyrocompasses and the arrival of the Palau at its berth. Gradually, an organized structure emerged out of the initial chaos. The sequence of computational and social organizational configurations through which the team passed is shown in Figure 4.

Region 1:																
LOP#	1	2	3	4		5	6	7	8	9	10	11	12	13	14	15
				a	b											
1. (C+RB)+V	P	P								P	P	P				
2. (RB+V)+C			SP													
3. (RB+C)+V				SP	SP	P	P	P		SP			SP			
4. (C+RB)+V															P	SP SP

Region 2:																
LOP#	16	17	18				19	20	21	22	23	24				
			a	b	c	d	e	f	a	b		a	b			
1. (C+RB)+V																
2. (RB+V)+C																
3. (RB+C)+V																
4. (C+RB)+V																
5. (C+V)+RB	PS				P	SP				P		SP				
6. (RB+C)+V		S	S	S	S					S	S			S	S	SP
7. (C+V)+RB							P	P								

Regions 3 & 4:																			
LOP#	25	26	27		28	29	30	31	32	33	34	35	36	37	38	39	40	41...	
			a	b															
8. [(V+D)+C]+RB	P				P														
9. (RB+C+D)+V			S																
10. RB+((V+D)+C)					S	PS													
11. (C+D)+V+RB							S			P	S								
12. [C+D]+RB+V								S	S										
13. [C+D+V]+RB										P	PS	PS	S	S	PS	S	P	S	S

FIGURE 4. Line of Position Computations. The structure of the computation performed is given in the left hand column. Lines of position are numbered across the top of each section of the table. "P" indicates an LOP computation performed entirely by the plotter. "S" indicates an LOP computation performed entirely by S. "SP" indicates an LOP computation begun by or structured by S and completed by P. "PS" indicates a computation begun by or structured by P and completed by S.

After correcting and plotting about 30 LOP's, a consistent pattern of action appeared in which the order of application of the correction terms and the division of labor between plotter and bearing timer stabilized. While the computational structure of this stable configuration seems to have been, at least in part, intended by the plotter, the social structure (division of labor) seems to have emerged from the interactions among the participants without any explicit planning.

Analysis

The bearing takers out on the wings of the ship were only slightly affected by the loss of the gyrocompass. For them, it meant only that they had to remember to shoot the bearings relative to ship's head, the outer rather than the inner of the two azimuth circles in the alluded view-finder (See Figure 2). The analysis will therefore focus on the activities of the plotter, a quartermaster chief (designated "P" in the analysis), and the bearing timer, a quartermaster second class (designated "S" in the analysis).

We can consider the behavior of the plotter and the bearing timer to be a search in a very complex space for a computational structure and a social structure that fit each other and that get the job done. As Figure 4 shows, on their way to a stable configuration, these two explored 13 different computational structures and many social configurations.

How can we account for this seemingly bizarre search of computational and social space? I will claim that there are four main principles of the organization of

computation involved. They are:

- (1) computational structure driven by the availability of data
- (2) the use of a normative description to organize computation
- (3) the computational advantages of modularizing the addition task
- (4) the fit between computational and social organization.

The events between the failure of the gyrocompass and the end of the task can be partitioned into four regions based on these principles. In the first region, Lines of Position (LOP's) 1-15, P does all the computation himself and the computational structure is driven primarily by the availability of data. The end of this region is marked by the introduction of an electronic calculator. In the second region, LOP's 16-24, P begins to push some of the computational load onto the bearing timer, S, and while providing the bearing timer instruction on how to do the computation, begins to use a normative description to organize the computation. In the third region, LOP's 25-33, the modularity of the computation becomes a shared resource for the two workers through their joint performance of the modular procedure. In the fourth and final region, LOP's 34-66, they discover a division of labor that fits the computation, and they coin a lexical term for the modular sum, thus crystalizing the conceptual discovery in a shared artifact. Let's look now at the details of the work at the chart table, considering the lines of position plotted from the time the gyrocompass failed until the system had settled into its new stable configuration (refer to Figure 4).

Region 1: Computational Structure Driven by Data Availability

The first 12 lines of position are computed by P, using what would normally be called mental arithmetic. In some cases, this arithmetic is aided by artifacts in the environment. In the very first LOP, for example, he uses the scale of the hoey (chart plotting tool) as a medium for addition, lining up the scale index with 29 (the compass course), sliding it 52 gradations upward (the relative bearing), etc., and in LOP 2 he uses the bearing log itself as a memory during the computation, tracing out the addition columns with his fingers. LOP's 8 and 9 were computed using paper and pencil in the margins of the chart. P had a good deal of trouble keeping up with the demands of the task, as shown by the fact that the first fix has only two LOP's in it, the second fix has but one LOP and the third fix has two LOP's. The anchor was dropped at 17:06 in the afternoon just before the fifth line of position was plotted. Once the anchor was down, the team went from one-minute-fix intervals to six-minute-fix intervals, but P was still having trouble keeping up while doing mental arithmetic.

P's behavior in this region can be described as opportunistic. He used three different computational orderings and several different media in computing the first twelve lines of position. While at first glance this behavior looks unsystematic, there is a simple but powerful regularity in it. The order in which P took the terms for addition depends upon where the terms were in his environment, and on when and with how much effort he could get access to them. For example, in LOP 8, P returned to the chart table verbally rehearsing the ship's magnetic heading. He began his computation with that term. In LOP 9, where P had to consult S in order to establish the identity of the next relative bearing to add, he began his computation with relative bearing. In LOP 10, P was again doing the calculation on his own and again he began with ship's magnetic head. These patterns are hints to a more general organizing principle that we will see throughout this event. An examination of Figure 4 shows that in the first two regions, twelve out of fifteen LOP's for which the computation is initiated by P begin with the ship's magnetic head, and thirteen out of eighteen computations initiated by S begin with the relative bearing of the landmark.

This regularity appears to be a consequence of local strategies for individual cognitive economy. From the perspective of a person trying to do the addition, if one of the terms is already in working memory when it is time to begin the computation, then it is most efficient to start with that term.

Consider the situation of the bearing timer. When the computations are done on-line, the bearing timer is in interaction with the bearing takers. He has listened to, written down and verbally acknowledged relative bearings. These activities, although not part of the addition procedure itself, influence the course of the addition procedure because they put the RB term into the working memory of the bearing taker. With RB already in working memory, in order to do the computation in the order that supports modularization, $(C + V + RB)$, S must either somehow keep RB active in working memory, or he must overwrite RB in working memory and read it again later when it is needed. If he chooses to maintain RB in working memory, then it must remain unaltered (and must not alter the other number representations present) during the reading of C, the recall of V and the addition of C and V. This may require him to maintain up to 11 digits in working memory (eight for the addition of $V + C$, plus up to three for RB.) If the memory load of that task is too great, S may choose to let RB be overwritten in working memory and read it in again later. Of course, doing that involves wasted effort overwriting and rereading RB.

In contrast to the costs of this "preferred" order, taking the terms in the order $(RB + C + V)$ or $(RB + V + C)$ involves lighter loads on working memory and no wasted effort. Thus, from the bearing taker's local perspective, it was simply easier and more efficient to begin each computation with the relative bearing.

P was in a different position. In most cases, he went to the helm station to get the ship's compass head while the relative bearings were being reported. This puts the C term into P's working memory at the beginning of the fix. Notice in Figure 4 that except for LOP's 5-7, every LOP initiated by P himself begins with C as the first term. But interaction with S or with other representational systems can change P's position in the computation. In each case where P began by asking S for a term to add, that term was the relative bearing and the relative bearing was taken as the first item in the addition. On closer inspection, the apparent exceptions to the rule in LOP's 5-7 are not exceptions at all. These computations were not done while the data were coming in. The observations of the three relative bearings were made while P worked to determine the location of the anchor. Then he set out to compute the LOP's with all of the data in the book in front of him—relative bearings in the left hand columns of the bearing book page and the ship's magnetic head in the rightmost column. This interaction with the bearing book changed the temporal pattern of availability of data, which in turn changed the organization of the most efficient ordering of terms for the performance of mental arithmetic.

It is unlikely that either man was ever aware of having made a decision concerning the order in which to add the terms. Rather, each was simply trying to do the additions as correctly and as efficiently as possible. Since the two participants at the chart table experienced different patterns of availability of data, this principle produced characteristically different results for each of them.

The principle at work so far can be summarized as follows: individual actors can locally minimize their work load by allowing the sequence of terms in the sum to be driven by the availability of data in the environment. But, since data become available primarily via social interactions, the computational structure is largely an unplanned side effect of this interactional structure. The interactional structure itself is chaotic because it is shaped by interference from other tasks and social interactions with other members of the navigation team and members of other work teams on the bridge.

After LOP 12, S initiated a round of bearings on a two-minute interval. P instructed him to take the fix on six-minute intervals, and complained about trying to keep up doing mental arithmetic. When asked if he had been able to keep up with the work he said,

- P: No, I was running it through my head and it wouldn't add. It wouldn't make numbers, so I was making making right right angles in my head to see where the hell it was at.
 S: You take the variation out of it.
 P: Yes, you add the, you add the magnetic head, then you add the variation.

This conversation is the first evidence of reflection on the structure of the computation. P explicitly names the variables, saying, "...you add the magnetic head, then you add the variation." After this, P remarked that the only way to keep up with the work would be to use a calculator. Shortly after this conversation, P went to the chart house and returned with a navigation calculator.⁶

The use of the calculator eliminated the need for the intermediate sums that P computed when doing mental arithmetic. In LOP's 13-15, P keyed in the data. He started each LOP computation by keying in $C +$, then he looked for RB in the bearing book, keyed $RB +$, then keyed $V =$. Here the calculator was not only a computational device; P also used it as a temporary external memory for the C term while he looked for the RB term. The immediate consequences of the introduction of the calculator were that it eliminated that production of intermediate sums (this will be important in the development of the modular solution below), and it changed the memory requirements for P by serving as an external memory. It did not change the fact that the order in which the terms were added was dependent on the pattern of availability of data in the task environment.

The dependence of the computational sequence on the availability of data is the main characteristic of events in the first region. It will survive into later regions in the behavior of the bearing timer, but the introduction of the calculator marks the beginning of the end of this sort of data-driven task organization for P. Up until and including the first calculator round, S has sometimes fed values of RB to P, but has done no arithmetic, mental or otherwise. That is about to change.

Region 2: The Emergence of Mediating Structure

The most important consequence of the introduction of the calculator was that it created a new context of interaction between P and S, in which P gave S instruction in the procedure. For example, in LOP 16, P returned from the helm station where he had read the compass heading and keyed in the value of C.

LOP 16: (C + V + RB)

P returns from helm.

P: 2 3 1. What have we got? {231 + }

(Then slides the calculator to S.)

P: Here, add these things.

P: You want ... You want the head. You want the head

|which is

2 3 1.

S:

|and add

variation.

P: Plus variation.

S: Oh, 231 is the head?

P: 2 3 1. Here {Clear 2 3 1}

⁶The calculator was capable of computing a number of specialized navigation functions, but only addition and subtraction were used in what follows.

S: I got it. (*puts his hands on the keys.*) (clear, 2 3 1)
 P: Plus 14.
 S: {+14} Okay.
 P: Okay. (*intermediate sum not computed*)
 S: {+0 0 7 =} is 252 on Silvergate.
 P: 2 5 2 Silvergate.

P controlled the order of the arguments in this LOP. S seemed surprised that he started with the ship's head.

In LOP's 17 and 18a, P was busy plotting a previous bearing. S initiated the computation himself by reading the RB from the book and beginning with it. In LOP 18a, the result was in error because the bearing that was reported was misread by the bearing taker. But the context of the error provided an opportunity to restructure the work. S slid the calculator over in front of P and began to dictate values starting with what was, for him, the most salient term, RB. P, however, ignored S and began keying in the data in the sequence C + V. P made an error and cleared the calculator. S, having seen the sequence in which P wanted to add the terms, dictated the terms in the order C + V + RB as seen in LOP 18c.

LOP 18c: (C + V + RB)

S: 2 3 1, Chief, plus 14, plus |
 P: (2 3 1 + 1 4 +) |Okay, what was ah,
 S: The bearing was 1 5 7. (3 sec) |Okay
 P: (1 5 7 =) |4 0 2
 S: Minus 3 60 |is
 P: (- |3 60 =) is 0 4 2. No it ain't. It isn't no 0 4 2. It's just not working. Look where 0 4 2 goes. (*P points to the chart.*) If it's 0 4 2, we're sitting over on Shelter Island!

There were three more attempts to compute this LOP. In LOP 18d, S made a data entry error and passed the calculator to P in frustration. In LOP 18e, P made a data entry error, cleared the calculator and began again.

We might have thought that the importance of the introduction of the calculator would be its power as a computational device. In fact we see that using the calculator, the team was neither faster nor more accurate than they were without it! The important contribution of the calculator was that it changed the relation of the workers to the task. When P pushed the calculator over to S and told him to add the terms, he engaged in a new task, that of instructing S in the computation, and he organized his instructional efforts in terms of the normative computational structure, "C + D = M + V = T." This was evident in LOP 16 where P named the variables, "You want the head, which is 2 3 1 . . . plus variation." Note that S did not seem to learn from the explicit statements of P. He returned to taking the RB first in LOP's 17, 18a and b. However, once P had articulated this structure, it became a resource he could use to organize his own performance of the task. In LOP 18b, in spite of S having dictated the RB to him first, he keyed in C + V. There, S verbally shadowed P's keystrokes. This joint performance was the first time S had taken ship's head as the first term. Once P began behaving this way, S was able to internalize that which appeared in interpersonal work and under certain social conditions, could use it to organize his own behavior. Thus, in LOP 18c where S took the role of dictating the values to P who was keying them in, S said, "2 3 1, Chief, plus 14, plus . . ." But the structure was not yet well established for S. In the next attempt, LOP 18d, a new RB was observed and, driven by the data, S began the computation with it.

The introduction of the calculator and the errors that were committed with it provided a context for instruction in which the sequence of terms could be explicitly discussed. The errors they were responding to were not sequence errors, but simple

key pressing errors, yet they still served as contexts for sequence specification. P appeared to learn from his own instructional statements (intended for S) and changed his own behavior. Until he tried to instruct S on what to do, he took the terms in the order in which they were presented by the environment. S appeared to change his own behavior to fit with what P *did*, not what he *said*. This newly emergent normative structure dominated P's instructional efforts and came to dominate the organization of his task performance as well.

In LOP 21a, S made a key pressing error while adding the terms in the order (RB + C + V). The error drew P's attention and he turned to watch S.

LOP 21b: (C + RB + V) & ((C + V) + RB) = ((C + V) + RB + V)

S: {clear 2 2 1 | + 14}

P: | plus 14 is 2 3 5. (C + V. P does it in his head.)

S: 2 3 5?

P: Yah, its 2 3 5 plus 1 1 8. ((C + V) + RB)

S: Oh. {clear} (S doesn't realize that hitting = would have produced 235.)

P: 2 3 5 is |3 3 5, 3 4 5, how about 3 5 3. Right?

S: {235 | + 1 1 8 + 14 =} How about 0 0 7.

((C + V) + RB + V)

P: 0 0 7.

S: Chief, the computer just beat you. (Chief glares at S)

Just kidding. (all laugh 4 sec) The modern technology.

P: I'll modern technology you.

Here, in LOP 21b, two important things happened. First, S demonstrated that he could produce the normative sequence when trying to show P he could do the addition correctly. Second, this was the first time P had organized a properly modular computation. Unfortunately, it is also clear that S did not yet understand the meaning of the intermediate sum (C + V), which is the key to the modularization. He mistook it for C alone, and added in RB and V, generating an error. P seemed intimidated by the calculator and did not challenge the result. It led to a poor fix, but he had been getting really poor fixes all along. Fortunately, the anchor was holding and they were in no danger, but at this point if they had had to rely on the quality of the fixes, they would have been in trouble.

P performed LOP 23 with the non-standard sequence (C + RB + V). However, this is not a violation of the principles described above. P did not get C from the helm at the beginning of the fix as he usually did. Instead, he was busy asking whether the anchor was being hoisted at this time. S announced C when P returned to the table. P looked in the bearing book for C. He read it aloud, and while still leaning over the book he added in the RB nearest him in the book, pointing to the place digits in it with the butt of his pencil as he added the numbers. Once again, the availability of data in the environment drove the organization of the computation.

LOP 24a: (RB + C + V)

S: 1 1 2 plus 2 2 6 plus 14, 3 5 2 on ship's head. (means Hamm's light)

P: Which tower is he shooting for North Island Tower? (P leaves table for wing)

P: Hey, which tower are you shooting for North Island Tower? (PW points to tower) You are?

Okay.

PW: Is that the right one?

P: Yep.

(P returns to table)

LOP 24b: (C + V + RB)

S: Which tower |wa—

P: |And ah, what was Hamm's?

S: And Hamm's was {2 2 6 + 1 4 + 1 1 2 =} 3 5 2. (5 sec) Time 56 Chief.

In LOP 24a S, working on his own, took the terms in the order (RB + C + V). A few moments later when P asked S what the bearing was to Hamm's, instead of remembering it, S re-computed it. This time, LOP 24b, he did it in the prescribed order, (C + V + RB). This is evidence that he knew the sequence preferred by P, but he seemed to produce it only in interactions with P.

This is the end of the second region. In this region we have seen that a mediating structure is being remembered by P, but S's organization of the computation is still driven largely by the pattern of availability of data. The clear boundary between this region and the first one is not marked by the introduction of the calculator, but by P's order "Here, add these things." The change in computational structure follows from a social innovation that was made possible by a technological change rather than from the technological innovation itself.

Region 3: Partial Modularization

In the description of the computational structure of the task given above, we noted that the true bearing is the sum of four terms: ship's magnetic head, C; deviation, D; variation, V; and relative bearing, RB. By now the team had computed and plotted 24 lines of position and the deviation term was not included in any of them. This seems surprising, since we have ample evidence that both of them knew well what deviation is and how to use it. One can only surmise that they were so busy trying to do the job that they forgot this term. The absence of the deviation term had no effect on the quality of the fixes plotted until LOP 22, because until then the ship was on a heading for which the deviation was near zero. Just before LOP 22, however, the ship's head swung southwest, and on that heading there was a three-degree deviation. The fix triangles started opening up, and it became clear to P that something was wrong. He lay the hoey on the chart from various landmarks and moved it slightly, seeing what sort of different bearings would make the triangle smaller. LOP's 25-27 are a re-working of LOP's 22-24, this time taking deviation into account.

1. P: I keep getting these monstrous goddamn, these monstrous frigging goddamn triangles. I'm trying to figure out which one is fucking off.
2. S: You need another round?
3. P: No, no no, uhuh. 1 2 0 I know what he's doing. Let me try, let me try, (*turns and moves to helm station*) let me try, with my new ones, say three. (*reads deviation card posted on compass stand*). Say three, add three to everything.
4. S: Add three?
5. P: Yah.
6. S: 'Cause he's using magnetic? (*S does not get it yet.*)

LOP 25: ((V + D) + C) + RB)

7. P: On a southwest heading add three. So its (14 + 3 =) 17 plus 2 2, 17 plus 2 2 6 is ah, 2 3 ah
8. S: Plus 2 2 6 is 3 4 is 2 4 3 (*S working on paper with pencil*)
(V + D) + C)
9. P: Okay, 2 4 3 and 0 1 3 is 2 5 6. 2|5 6
((V + D) + C) + RB)
10. S: |2 5 9 (*this is an error*)
11. P: 2 5 nuhuh?
12. S: 2 5 9, plus 0 1 3? It's 2 5 9.
13. P: 2 5 9 that's right. Okay. And plus 1 1 2 was what?

LOP 26a

14. S: 1 1 2 plus 2 2 6. (*Here is clear evidence that S doesn't understand the attempt to modularize. (RB + C)*)

LOP 26b: $((V + D) + C) + RB$ & $RB + ((V + D) + C)$

15. P: Plus 2 4 3, 2 4 3 plus 1 1 2.

$((V + D) + C) + RB$

16. S: 1 1 2 plus 2 4 3 is 5 5, 3 5 5, (*still working on paper*) $RB + ((V + D) + C)$

In P's moment of discovery, line 3, where he said "I know what he's doing," he noticed that the geometry of the triangle was such that a small clockwise rotation of each of the lines of the previous fix would make the triangle smaller. Any small error that belongs to all the LOP's suggests deviation. He went to the helm station and consulted the deviation card to determine the deviation for this heading. Although he describes the results as "much better," with deviation included, the two errors introduced by S still result in a poor fix.

The computation of 243 as the ship's true head, and its use in LOP 26b is the very first full modularization of the computation. P has control of the computations in all three LOP's, although in LOP 26b he has to fight S's strong propensity to put the RB first. S clearly does not yet understand either the benefits of modularization or the necessity to add the RB last in the modular form. The structure of LOP 27 was modular too, but the value of ship's true head, while properly computed, was not correctly remembered.

P seems to have taken the discovery of deviation and the recomputation of the bearings as an opportunity to think about the structure of the computation itself. The reflection that came in the wake of the introduction of the calculator led him to organize the computation in accordance with the normative form. The reflection that came with the addition of the deviation term led him to the modular structure. He never explicitly mentioned the advantages of modularization, but if he was not aware of the advantages when he organized the computation, he must certainly have been aware of them once the computation had been performed.

S computed LOP 28 while P explained to the keeper of the deck log why the gyrocompass could not be restarted in time to help, and why they will therefore make the remainder of the trip using magnetic bearings. P's conversation was interrupted by S who checked on the procedure for using the deviation table.

LOP 28: $((C + D) + V + RB)$

S: Charles? (2 sec) Head?

H: 2 2 6.

S: 2 2 6.

S: So it's 2 2 6. You wanna add 3, right? On a southerly course? (3 sec) Chief?

P: Say again.

S: You wanna add 3 to that /? / southerly course? (*pointing at the entry on the deviation table.*)

(2 sec) It's 2 2 6. The magnetic head is 2 2 6.

P: Yah.

S: 2 2 6 plus |3, okay, so that makes 2 2 9. {2 2 9 + 14}

P: |right.

S: {+1 1 5 =} (3 sec) 3 5 8 on Hamm's light.

$((C + D) + V + RB)$

Thus, S took the arguments in the right order in LOP 28, but did only a partial modularization. He computed $(C + D) = 229$ as a modular sum. Then he added V and added RB without producing ship's true head as an intermediate sum. In LOP's 29 and 30, S started with the partially modular sum, and added the terms in the order $\{C + D\} + RB + V$. Even this partial modularization is an important step forward

for S. It appears to be due to two factors. First, including deviation in the computation may have made the C term more salient. Second, S's location in the computation had changed. He recorded the relative bearings as usual, but he had to go to the helm station himself to get the compass heading because P was otherwise occupied. At that point he had the C term in working memory and it was time to begin the computation. This change in position meant that what was best for the computation was also easiest for S. This is not the best division of labor, but it is one for which there is a momentary local fit between social and computational structure. The pattern of availability of data was not running counter to the computational structure. Paradoxically, then, the extra work that took P away from the chart table (a burden on the system) may have been a factor that permitted the system to improve.

Weighed Anchor

LOP's 32-33 are a turning point in the procedure. In LOP 32 there is a clear conflict of understanding between P and S. In LOP 33 they perform what will be the stable configuration for the first time.

LOP 32: $((C + D) + V) + RB$

1. S: You want the aero beacon?
2. P: Yah, I want the aero beacon now, yah. It's just.. 1 8 7, 8 8, 8 7, 8 8.
3. S: 0 2 0, what's the ship's head?
4. P: Huh? 0 8 7. 8 7, It's| 1 west
5. S: |0 87 it's 1 west, 7
6. P: its 8 6 (C + D)
7. S: {8 6.}
8. P: And 14| is 1 0 0 ((C + D) + V)
9. S: |(+ 14)
10. S: {+1 0 0}, hold it
11. P: No, it's 1 0 0 plus whatever. $((C + D) + V) + RB$
12. S: 1 0, where are you getting?..
13. P: 1 0 0 is the heading, the whole thing, |plus relative.
14. S: |Oh, the whole thing, plus relative, {+ 20 =}.
1 20.
15. P: Okay
16. S: 1 20 |is for North Island Tower.

LOP 33: $((C + D) + V) + RB$

17. P: |and Hamm's? (2 sec) 1 0|0 plus whatever for Hamm's.
18. S: |Hamm's
19. Okay, {100 + 2 2 4 =}. 3 2 4 on|Hamm's
20. P: |3 2 4. That's all three of 'em. I got 'em all.
21. S: Okay
22. P: Looks good. Right on. Perfect. Pinpoint fix.
23. S: Alright!

In LOP 32, P works with S to recompute the ship's true heading. This joint work in lines 4-16 provides the opportunity for S to understand that the "whole thing" is the modular sum to which the RB can be added. The order in which S added the terms still followed the pattern of data availability, but P actively constructed the pattern of data availability such that the sequence produced by S was the desired one. That is, P acted as a mediator between the pattern of data availability in the task environment and the addition activities of S.

The most salient features of this region were the emergence of the partial modularization of the computation and the conflicts between P's newly solidified conceptual schema, and S's practices. In this region, P began to provide mediating structure that changed the pattern of data availability experienced by S. In LOP 33, S

showed signs of using this mediating structure himself. For S, the addition activity was no longer on the surface being applied opportunistically. It now lay behind a conceptual and social organization that fed it the terms of the expression in a particular order.

Region 4: The New, Stable Solution

In the previous section, we saw how the behavior of one individual can act as a mediating device that controls the pattern of availability of data for the other. In this, the last region, the team discovered a division of labor in which each of them could use a computational sequence that followed the availability of data in the task environment (thus minimizing memory load and wasted effort) while each simultaneously produced for the other patterns of data availability that supported the modular form of the computation. In this region the computational structure was still driven primarily by the pattern of availability of data, but the availability of data itself was determined by the social organization of the actions of the members of the team. Thus, the issue here is the fit between the constraints of cognitive processing (memory limitations, e.g.) and the social organization of work (distribution of cognitive labor), as mediated by the structure of the computational task (modularity of addition).

In LOP's 34-36 they tuned their division of labor, jointly computing the modular sum in LOP 34, and S remembering it in LOP's 35 and 36.

LOP 34: $((C + D) + V) + RB$

P: Okay, what's he on? (to helm) What are ya on right

now? 8, 8 5. 8 5, 0 8 5, 0 8 4 plus 14 0 9 8. $((C + D) + V)$

S: |0 8 5 is/ 0 8 4 plus 14, {8 4 + 14 =} that's

P: Okay

S: 98

P: 9 8 and 2 6

S: 9 8 {+2 6 =} 1 2 4. $((C + D) + V) + RB$

P: |1 2 4

S: |1 2 4 North Island Tower

P: Okay

LOP 35:

S: (9 6 + 2 1 2 =) 3 0 8 on Hamm's light. $((C + D) + V) + RB$

(S has mis-remembered the true head. Should be 98, not 96)

P: Okay

LOP 36:

S: (98 + 3 5 7)

P: Damn near reciprocals.

S: (-3 6 0 =)

P: 3 60 is|0 9 5

S: ah|0 9 5 $((C + D) + V) + RB$

This is essentially the pattern of work they would maintain all the way to the dock. By LOP 38 the final pattern was achieved. In this, P computed the modular sum alone, finding C and D at the helm station and recalling V from long term memory. Meanwhile, S recorded the relative bearings. P then added the first relative bearing to the modular sum, usually while S was recording the last of the relative bearings. P announced the modular sum to S, and S then added each of the other relative bearings to the modular sum. The only important event not included in these first 38 LOP's was the advent of a linguistic label for the ship's true head. They called it "total" in LOP 42 at 18:42. Once they had a name for it, they could pass it around

among themselves more easily. The “publication” of the modular sum is essential to the final solution, since it acts as the bridge between the portion of the computation done by P and that done by S.

Discussion

It appears that four forces control the navigation team's bizarre search of the space of computational and social structures. They are (1) the advantages of operating first on the contents of working memory which leads computational sequence to be entrained by the pattern of availability of data, (2) the use of normative computational structure, which permitted the discovery of (3) the advantages of modularization of computation, and (4) the fit of social to computational structure. Each region of the adaptation process is dominated by one of these forces. In fact, all of them, except the advantages of modularization, are present to some extent in all regions of the adaptation history.

Memory Limitations and the Availability of Data

In the beginning, the structure of the computation seems to be driven exclusively by an interaction of limitations of the human cognitive system, specifically memory limitations, and the availability of data in the environment (Newell and Simon 1972, Anderson 1983). Memory limitations make it advantageous to add the terms of the correction in the order they become available. The availability of data depends on the pattern of social interactions. This seems to characterize P's behavior until he assumes a different relation to the computation at LOP 16. It describes S's behavior at least until LOP 32, and possibly to the end of the task.

At LOP 16, the introduction of the calculator gave rise to a new social arrangement (S punching keys while P told him which keys to press) that gave P a new relation to the computational task, that led, in turn, to the introduction of the normative computational structure. What P remembered was acted out in interaction with S. When S took dictation from P while keying in values, P was mediating the task for him. P was changing S's relation to the task such that what was convenient for S was also what was effective for the computation.

The Normative Computational Sequence, $C + D = M$, $M + V = T$, $T + RB = TB$

There is no doubt that P's computations were shaped by variants of the normative structure from LOP 16 on. There was only one exception to this (LOP 19), and in that case the RB had a value that was particularly easy to handle: 0 0 7. P maintained this structure even when it ran counter to the pattern of availability of data as in LOP 18b.

S appeared to be capable of producing the normative sequence when in interaction with P (LOP's 24b, 27); but when on his own, he seemed clearly driven by the availability of data. Thus, when computing the true bearings on-line as he recorded the values of relative bearings, he always took the RB as the first term. Before the discovery of the deviation term he used the sequence (RB + C + V) and after the inclusion of deviation, (RB + C + D + V). In one instance, however, P was removed from the table by another task, and S computed the true bearings alone. After having recorded the relative bearings and having obtained the ship's magnetic head from the helmsman (C term in working memory), he began with the C term.

The computational importance of the normative sequence is that it makes the modularization possible. Since addition is a commutative operation, there is no difference in the sum achieved by adding the terms in any of the 24 possible sequences. But if the addition is to take advantage of the modularity of ship's true

head, the terms C, D, and V will have to be added together before any of them is added to a relative bearing. The normative structure provides a rationale for doing this, and it provides culturally meaningful interpretations of the intermediate sums that are lacking from such non-normative additions as $(RB + V)$ or $(V + D)$ (see Figure 3).

The Modular Computation

The modular organization of the computation emerges haltingly from P's attempts to apply the normative form, but it seems unlikely that P took up the normative form for its links to modularized form of the computation. It is more likely that it gave him a better understanding of what was going on by providing intermediate sums that have meaningful interpretations in the world of the ship. For an experienced navigator, a bearing is not simply a number, it is a body-centered feeling about a direction in space. Taking the terms in non-normative sequence results in intermediate sums that are just numbers. Taking them in normative sequence results in intermediate sums that are meaningful directions in the world of the navigator. In this form they become directions that make sense (or don't), and this gives the navigator another opportunity to detect error or to sense that the computation is going well or badly even before it is completed.

There was a hint of modularity in LOP's 18e and f where P computed $C + V$ and then asked for the RB. Similarly in LOP 21b he said, "... it's 2 3 5 (C + V) plus 1 1 8 (RB)." In each of these cases, there was only one LOP involved, so it was not possible to exploit the advantages of modularization. The first unambiguous case of modular computation was in the LOP's 25-27, that introduced the deviation term. These were performed in the non-standard sequence $((V + D) + C) + RB$. It is probably significant that P chose to perform these calculations with paper and pencil rather than with the calculator. The paper and pencil computation produced, as a natural side effect, a written record of the sum $\{(V + D) + C\}$ which was then easily at hand for addition to each of the relative bearings. The written record of the modular sum in this instance was functionally similar to the verbal "publishing" of the labeled modular sum in the later fixes.

The Fit of Social and Computational

The modular form of the computation only became stable when a new division of cognitive labor was established in LOP 32 and 33. The pattern of availability of data produced by the division of labor in this stable configuration fit the computational structure of the problem. P obtained C from the helmsman and D from the deviation table, added them and then added the variation (easily available in memory). At the same time, S recorded the relative bearings of the landmarks. P told S the modular sum, which S recorded, and S provided P with the first relative bearing. P added this relative bearing to the remembered modular sum. While P plotted the first LOP, S then added each of the other recorded relative bearings to the modular sum. Thus, the team arrived at a division of cognitive labor in which the behavior of each of the participants provided the necessary elements of the information environment of the other, just when they were needed. Each could behave as though driven by the availability of data in the world; and at the same time, as a team, they performed the additions in the sequence that provided the benefits of modularization.

Adaptation by Design?

Since the work of Cyert and March (1963), organization theory has viewed routines as fundamental building blocks. Thus the processes that change routines are very important to study. The description of the behavior of the four factors shows how a

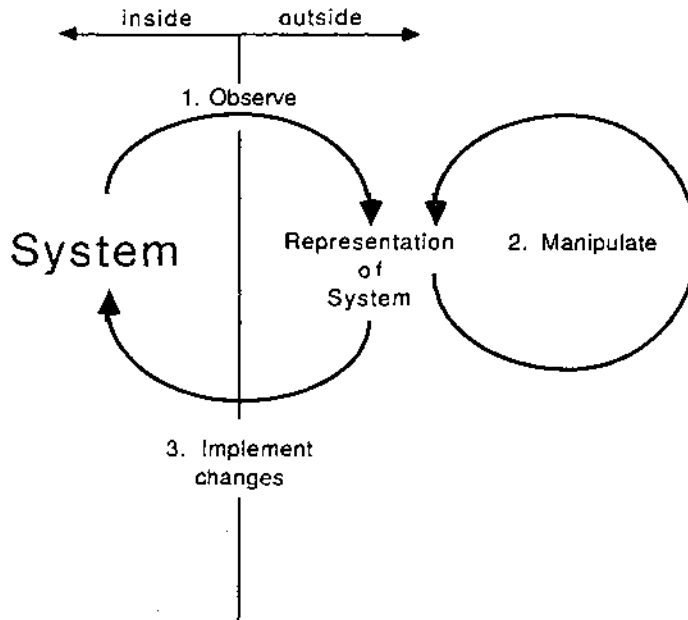


FIGURE 5. The Basic Design Process. A representation that is “about” the entire system is created from observations of the system. This representation is manipulated in order to plan an intervention in the system.

variety of solutions may be explored, but it does not in itself answer the question of how better solutions may become the routine operations of the system.

A classical view of organizational change (a folk view?) is that an analyst looks at the behavior of the system, represents it explicitly and plans a better solution (e.g., Chandler’s (1966) well-known account of the reorganization of Dupont). The better solution is expressed as an explicit description of system operation that is subsequently implemented in the real system by somehow altering the behavior of the participants to bring it into line with the designed solution. We often think of the organization of a system as a consequence of this sort of planning or design. We imagine an “outside” observer who observes the system’s performance, represents it, operates on the representation to determine how to change the system, and then uses a channel of communication from outside the system to effect the changes (see Figure 5).

In her work on energy policy analysts, Feldman (1989, p. 136) adds some complexity. She describes organizational routines as “complex sets of interlocking behaviors held in place through common agreement on the relevant roles and expectations.” She says, “Any particular set of agreements about rules and roles is a sort of equilibrium satisfying the demands of many different parties” (p. 136). A similar view is expressed by Nelson and Winter (1982) when they characterize routines as memory, truce, and target. This is a more subtle and interactive sense of the nature of the solutions to the problem of organization. An organization has many parts, and the operation of the whole emerges from the interactions of those parts. Each part may simultaneously provide constraints on the behavior of other parts and be constrained by the behavior of other parts. Elsewhere (Hutchins, in press), I have referred to this sort of system of mutually adaptive computational sub-parts as a “cognitive ecology.” This describes the sort of solution discovered by the navigation team. The parties to the computation are the plotter and the bearing recorder, and the demands on them are constructed in the interactions among their cognitive processing capabilities, the

structure of the computation, the availability of data, and the fit between computational and social organization. They settled into a solution that simultaneously satisfied all these constraints. Feldman continues in the same vein:

Many organizations or parts of organizations must coordinate their behavior in such a way that each can cope adequately with the pressures and constraints it has to satisfy. While there may be many possible solutions to such a problem, they are not necessarily easy to find (1989, p. 136).

The question is now posed. Given that organizations are the kinds of systems that consist of many interlocking, interacting, and mutually dependent parts, how can solutions to the organization problem be discovered? Feldman provides one answer as follows:

Even if one of the participants finds a new solution that will satisfy the constraints of all parties, the problems of persuading everyone else that this would be a beneficial change may still be considerable (1989, pp. 136-137).

Clearly the process described in this passage must happen frequently. Parts of the behavior of the navigation team fit this description nicely. P's use of the normative computation scheme and his attempts to make that scheme explicit for S are examples. But this answer is a retreat to the classical view. It posits a designer, albeit "one of the participants" who "finds a new solution," and then must "persuade everyone else" that it is a good solution. And there remain aspects of the adaptive responses of the members of the navigation team, particularly those involving the changing division of labor, that are simply not captured by *any* description which relies on explicit representation of the shape of the solution.

Adaptation and Local Design

In the analysis presented above, there are no instances of anyone reflecting on the whole process. P seems occasionally to represent the entire computation, but there is no evidence he ever imagined the structure of the division of labor. The adaptation process seemed to take place by way of local interactions, mostly of two types. First, team members put constraints on each other by presenting each other with partial computational products. When there is no previously worked out division of labor and assignments of responsibility for various parts of the computation, team members negotiate the division of labor by doing some (what they can, or what is convenient) and hoping that others can do whatever else is required. These are changes that result from the interactions among the behaviors of the subparts of the system as they adapt to the information environment and to each other's behaviors. There is no need to invoke any representation of the behavior of any part of the system to account for these adaptations. The way the computation was driven by the availability of data is an example of this kind of unreflective adaptation process. Even though they are not planned, these changes are not necessarily chaotic. If one part of the system behaves in a systematic way, another part may come to behave in a systematic way by adapting to the behavior of the first. In the interaction between P and S we saw that the behavior of one subsystem can be entrained by that of another.

A second adaptive process involves local design. When implicit negotiations of the division of labor fail, an actor may become aware of his own inability to keep up with the computation and attempt to recruit others to take on parts of it. Thus, the most striking thing P said during the search for a new configuration was something he said to S while falling behind in his attempts to compute bearing corrections with a pocket calculator. He pushed the calculator at the timer and said, "Here, add these things."

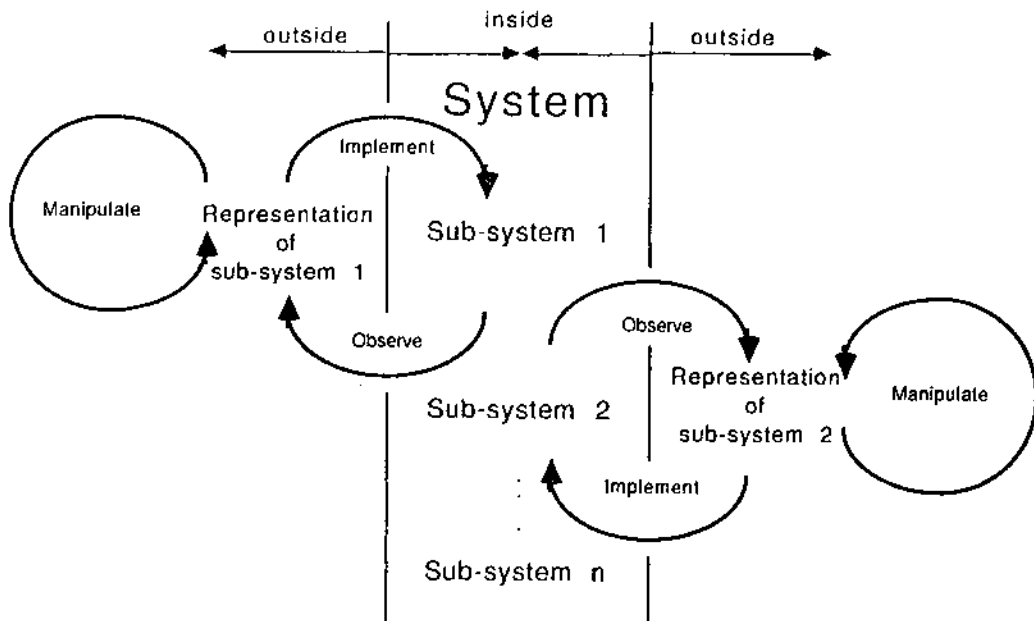


FIGURE 6. Local Design Activity. Subsystems interact with each other and adapt to each other's behaviors. Representations of local subsystem behavior are created and manipulated in order to plan changes to sub-system operation. These changes may trigger adaptive responses in other subsystems.

There is no need to attribute a global awareness of the process to P to account for this. He doesn't have enough time to do his own work, much less reflect on the overall division of labor. He is just acutely aware that he is falling behind and that he needs help to catch up. This is a case of local design. As shown in Figure 6, design processes may be local to subsystems. Figure 6 depicts an overall system that can change in three modes:

- (1) Without any design activity at all, through the adaptive interactions among the subsystems.
- (2) Through local design activities in which manipulations are performed on representations of local subsystems in order to discover more adaptive relationships with the sub-system's environment. These changes may, in turn, lead to adaptive changes, either designed or not, by the other subsystems.
- (3) Through classical global activities in which the representation is of the entire system of interest.

The response of the system to the change in its environment was eventually successful, but it was the consequence of a large number of local interactions and adjustments, some of which led the system away from the eventual solution. Many of these adjustments appear to have been local design decisions by the participants. Prior to its discovery by the system as a whole, however, the final configuration appears not to have been represented or understood by any of the participants. To the extent that the acquisition of a useful adaptation to a changing environment counts as learning, we must say that this is a case of organizational learning.

Evolution and Design

It seems to me that there is an important difference between the process of change by supervisory reflection and intervention imagined in the classical view, and the

process of change by local adjustment described above. It strongly resembles the difference between design and evolution (Alexander 1964).

Both evolution and design can be characterized as searches. The evolutionary search is conducted by the system itself in terms of itself, while the design search is conducted by an "outsider" on representations of the system. The evolutionary search is the process of adaptation (cf. Weick's view of enactment, 1979), while the design search precedes and guides an implementation of the, hopefully adaptive, design. Pure evolution is, in fact, a process without design (cf. Dawkins 1986). What we see in the case of the adaptation by the navigation team is an organizational change that is produced in part by an evolutionary process (adaptive search without representation of the search space), and in part by a process that is something that lies between evolution and classical global-perspective design.

From this perspective, human institutions can be quite complex because they are composed of sub-systems (people) that are "aware" in the sense of having representations of themselves and their relationships with their surroundings. Whether we consider a particular change at the upper system level to be the result of evolution or the result of design depends on what we believe about the scope of the awareness of the subsystems. If we think that some of the subsystems have global awareness, and can represent and anticipate the consequences of possible changes, then we may view an organizational change as a result of design. If we believe that the subsystems do not form and manipulate representations of system operation, then we must view organizational change as evolutionary. What do we say when the individual sub-systems only engage in local design activity—say, crying out for help when one is overworked? In that case, design is clearly involved, and the change in the local environment of the individual that adapts this way is a *designed* change. Now, that local designed change may have undesigned and unanticipated consequences for other parts of the system. It may thus provoke local adaptations by other parts of the system as all of the parts seek (either by design or not) to satisfy the new environment of constraints produced by the changes in the behaviors of other parts. Ultimately, this process may produce a change in the behavior of the system as a whole. Even when many local design decisions are involved, such an adaptation that occurs at the system level appears to be evolutionary in the sense that the system level change that resulted was never represented. I believe most of the phenomena labeled as social or organizational "evolution" are instances of this kind of change.

Is the navigation task setting primarily the product of evolution or of design? When we consider human systems, we have to acknowledge that every participant in the system can be both inside and outside some systems in this sense. The changes in the organization of the navigation team were brought about by changes in the thinking of the participants of the system, that is, the agreements about rules and roles that constitute the organizational routine. To this extent, the structure of the setting is a product of design. But, since the observed reorganization was never fully represented by any of the participants in the system, the actor's designs alone cannot account for the solution that was achieved. Thus, the organization of the navigation task is also a product of evolution. Finally, while the participants may have represented and thus learned the solution after it came into being, the solution was clearly discovered by the organization itself before it was discovered by any of the participants.

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Appendix. Transcription Conventions

Speakers

- P: Quartermaster Chief, acting as plotter. The Chief is the ranking enlisted man in the navigation department. Also has the title Assistant to the Navigator.
- S: Quartermaster Second Class, acting as bearing timer-recorder. Sometimes referred to by his first name, John.
- H: The helmsman who is steering the ship. First name, Charles.
- PW: Port Wing bearing taker.

Conventions for Transcription

- () Words enclosed in parentheses are comments or annotations of the actions observed in the video record. Never verbatim transcription.
- | Vertical bars are used in adjacent lines of transcription to indicate simultaneity of occurrence.
- /?/ Unintelligible portion of utterance.
- { } Numbers and actions enclosed in curly brackets denote key presses on the calculator.
- {3 + } Numbers and actions in bold font enclosed in curly brackets are key presses on the calculator that are verbally shadowed. This would mean a person pressed the 3 and the + key while saying "Three plus." In addition to numbers, the most frequent key presses are +, -, = and clear.
- 1 20 Spoken numbers have been transcribed mostly as numerals for convenience. If they are separated by spaces, each numeral was pronounced separately. If they are not separated by space, then they are read as conventional numbers. This example could also have been transcribed, "One twenty."

Formulas for the Computation

- C The compass heading of the ship with no corrections.
- D Compass deviation. A function of heading.
- V Magnetic variation. Approximately 14 degrees East in San Diego Harbor.
- RB The relative bearing of a landmark. This is the bearing of the landmark with respect to ship's head.
- TB True bearing (T + RB).
- M Ship's magnetic heading (C + V).
- T Ship's true head (M + V).
- () Terms enclosed in parenthesis were entered into the calculator with only plus or minus operators among them. The = operator closes the parenthesis. Thus (C + V + RB) means the three terms were added together as a group, whereas ((C + V) + RB) means that the = operator was applied to (C + V) which was then added to RB.
- [] Sums in square brackets were spoken as intermediate sums. Thus, +RB) denotes the following actions: key V, key +, key D, key =, key +, key C, key =, read the displayed value aloud, key +, key RB, key =.

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