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Some Remarks on the Improvement of Engineering Education

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This paper combines the quality management principles of Deming with the educational theories of Feuerstein and Bloom in the design of a system of engineering education in which every student, on graduation, will display mastery of the subjects in the curriculum.

KEY WORDS: engineering education; brain theory; managing the learning process; quality in education.

INTRODUCTION

On September 26, 2003, Wm. A. Wulf, President of the National Academy of Engineering gave me the following assignment:

> "Define the bodies-of-knowledge required for professional practice in engineering fields and using study within engineering fields as a basis for non-technical careers"

Dr. Wulf also specifically mentioned two fields he and his advisors felt very strongly should be incorporated in my response: *Quality Management* and *Cognitive Modifiability*.

As I struggled to design a curriculum, which would make these two topics integral parts of an engineering education, I began to realize that it would not be possible to achieve the aims of education by just tinkering with the current design. The demands on the graduates of engineering schools in the coming decades are so different from the demands faced by earlier generations that a thorough overhaul of the system is demanded. I concluded that I should do more than just meet the stated requirements of the NAE. I decided that I should present a system to not only answer the questions raised in the assignment, but also to address the issues out of which the questions arose.

The depth and complexity of this era of change have been described by Drucker in an insightful and thought provoking essay,[2] "The Age of Social Transformation." Drucker argues that we are in the midst of the most extreme societal changes in recorded history. These changes now challenge our abilities to *manage* our institutions and to *learn*, collectively.

As an engineering educator in the 1950s and 1960s I thought I had a pretty good idea of the questions my students would be called upon to answer and I strove to prepare them by exercises which developed skill in answering these questions. Today's educators can no longer be confident they can provide such answers. In fact, they do not know what the questions will be, let alone the answers. At the time of this writing, I see discussions on the Internet on such topics as how to introduce nanotechnology, bionics, and the energetics of living cells to engineers. No one can forecast the topics that engineers will be expected to learn 10 years from now.

The one thing we can say for certain is this: Our students will need to become continuous learners. They will need to be able to adapt themselves to rapidly changing situations. They will need to be able to design and develop new products and new services in areas yet to be invented and for which we can provide no formal studies. They must leave our

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[2] Drucker, Peter F. "The Age of Social Transformation." The Atlantic Monthly, November, 1994, p. 53.

care, ready to become self-supporting citizens, participants in a self-governing society, responsible, caring adults, and, above all, autonomous learners.

I have prepared this report in four parts:

1. Part I describes the nature of Cognitive Modifiability, as defined by Dr. Reuven Feuerstein. I present this material because very few engineering educators (or educators in general) know about Structural Cognitive Modifiability (SCM). SCM provides a method to help people improve their intelligence. Most of us haven't the faintest idea of how our brains work. Feuerstein's methods provide insights and methods to improve the way we think.
2. Part II describes the nature of Quality Management, as defined by Dr. W. Edwards Deming. I present this material because I know that most engineering educators are not familiar with quality management and do not always accept that management is a part of (not apart from) engineering. Also, because people cannot understand what quality management is all about until they experience it, I believe that we cannot simply offer courses in the subject; the students and staff need to experience it. In quality management the workers assume greater responsibility for defining what they do, how well they do it, and for seeking ways to improve. If we are to introduce and sustain innovation in the classroom, the methods of school administration and management need to change. What happens in the classroom affects what can be done in administration and vice-versa.
3. Part III describes Bloom's taxonomy. This material was copied from the Internet, using the materials of Donald Clark.[3] Bloom defined levels of competence in a very general manner. Since I am proposing that we stop using only input measure, such as "seat time" to describe educational attainment and instead describe educational attainment by measuring competencies, Bloom's pioneering work forms the backbone of what is proposed in part IV.
4. Part IV describes how to combine the teachings of Deming and Feuerstein with the taxonomies of Benjamin Bloom to produce a new approach to the education of engineers. In presenting this combination I build upon the contributions of James Hills.

Because the paradigm shifts in both teaching and learning are so great, I have gone into great detail to describe a design in which every student, on graduation, will display *mastery* of the subjects in the curriculum. In this vision of engineering education, students do not get grades and credits for "seat time" in classes, but rather must demonstrate requisite levels of mastery before they may advance. The notion that we can develop the competencies of professional engineers by having them sit in classes, all learning the same material at the same rate is an abomination in education. The current approach should be understood as a method of sorting students; not a method for developing them. By using competency matrices to define and measure progress, the students may take an active part in their own learning and teachers may use their time in individual instruction, not in managing a classroom. Competency matrices also eliminate the need for grades and the attendant evils of the grading system. Competency matrices lead to great savings in both effort and time for students, instructors, and administrators. The key to these savings lies in the combination of Deming, Feuerstein, and Bloom in the new system devised by Dr. James Hills.

SECTION I: THE THEORY AND PRACTICE OF STRUCTURAL COGNITIVE MODIFIABILITY ACCORDING TO THE TEACHINGS OF DR. REUVEN FEUERSTEIN

A Different Approach to Teaching and Learning

Feuerstein's approach to the teaching/learning process involves a profound change in paradigm on the part of teachers and learners. Conventional teaching may be likened to a process of pouring information into a student's head.

The *process* is described more aptly by the following diagram (Fig. 1).

As suggested by Fig. 1, the teacher having something in mind to transfer to the mind of the learner, places a stimulus (**S**) before the learner and then looks at the response (**R**). If the teacher judges from the response that the learner has "gotten it" properly, the teacher then passes on to another stimulus. If not,

[3]Many thanks to Dr. Clark for permission to use his material verbatim. I tried to paraphrase what he had to say but found I could not improve on his presentation.

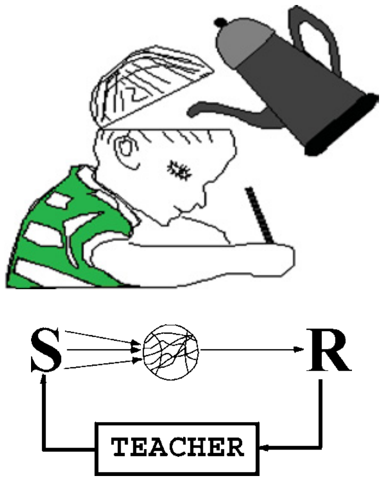


Fig. 1. Conventional teaching.

the teacher may repeat the stimulus or present another related stimulus. The teacher takes the learner around this circuit many times and based on the responses decides if the student is "bright" or "not-so-bright." The result is that the teacher hangs an invisible sign on each student, an "IQ," and adjusts the teaching pace and style accordingly. As Benjamin Bloom pointed out over 70 years ago, applying this process to students in groups of 20 or 30 (or more) tests the *speed* of learning rather than the ability to learn. Teachers will adopt the rate of teaching in such a way as to not lose interest of the fastest students through boredom and at the same time not lose the slower students through frustration. The process then becomes one of *sorting* the students rather than developing them.

The approach promoted by Dr. Reuven Feuerstein is suggested in the following diagram (Fig. 2).

In Fig. 2, the stimulus, **S**, may or may not have been placed before the student by the Mediator, represented by the letter **H** in the diagram. (We use the letter **H** to emphasize that the Mediator is a warm human being.) The Mediator places himself or herself between the learner and the stimulus and helps the learner to interpret the input. Some of the stimulus flows around the mediator directly to the learner. The amount of the input intercepted depends upon

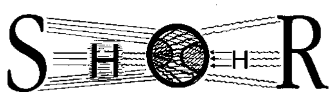


Fig. 2. The Feuerstein approach.

the needs of the learner. The learner and mediator are partners in the interpretation of the input. The Mediator also reflects back to the learner the response, **R**, so that the learner will understand how the response appears to others. The Feuerstein approach adjusts the process to the needs of the learner.

Some people might object to the close involvement of the teacher in the learning, protesting that the teacher is "spoonfeeding" the learner. An essential aspect of the Feuerstein approach is a focus on the *processes* used by the learner. The teacher does not "feed" the information to the learner. The teacher helps the learner improve the *processes of learning*. By helping the student improve the process, it becomes possible for the student to increase the *speed* of learning.

In Section III we shall consider how to take into account the need to work with many students at the same time while still paying attention to those who learn more slowly.

The mediator is guided in the mediation process by knowledge of the underlying processes in the brain. We begin this section, therefore, with a brief review of brain structure and processes involved in learning.

Brain Structures

The brain is made up of hundreds of billions of neurons immersed in an even larger number of glial cells. Since neurons and glial cells are so small and their interconnections so complex, the challenge in trying to understand the structure of the brain is very great. Until recently, it was believed that the glial cells serve as the chemical factories for neurons and that only the neurons carried out the thinking. Now it is believed that the glial cells, in addition to serving as chemical factories, also participate in the thinking process[4] but the mechanisms are still unclear.

Neurons connect to other neurons by means of little tubular extensions, called dendrites. Neurons use dendrites to connect to one another and form structures. Some of these structures are created by experience and are quite stable. This stability accounts for memory, for example. Other stable structures are the result of evolution and are genetically determined. For example, at the back of the eye, nerve cells connect to neurons, which then connect to

[4] R. Douglas Fields, "The Other Half of the Brain" *Scientific American*, Vol. 290, No. 4, April 2004, p. 54,.

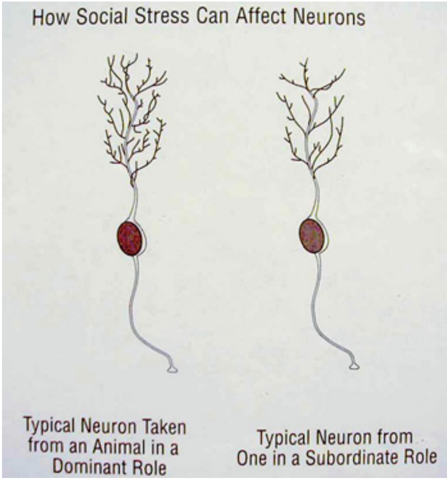


Fig. 3. How social stress can affect neuron development.

other neurons leading to different parts of the brain. The connections at the eye and nearby seem to be the result of evolution and are coded in our genes. Other structures within the brain are developed through life experiences. As a child grows, it develops neuronal structures reflecting its experiences in its environment. As Dr. Feuerstein has remarked, experience shapes the brain and the brain shapes experience.

Recent advances in imaging allow neurologists and other scientists to peer into a living brain and to see the differences in structure resulting from life experiences. They also learn by studying the brain cells of animals. The brain structure in a rat which has lived with other rats in a stimulating environment with running wheels, climbing stairs, etc., differs markedly from the structure of a rat which has lived alone in a cage without any source of stimulation. An animal, which has been subordinated to another, will feel social stress and, as shown below, develop fewer neurons (Fig. 3).

When neurons connect to one another, they require energy and matter to build dendrites. This energy is supplied by an increased flow of blood in the brain. Using positron emission tomography, Dr. Richard Silberstein, director of the Brain Research Institute of Swinburne University in Melbourne, has made movies of this blood flow as it occurs in different regions of the brain. The following frame from one of his movies shows, by means of computer enhancement, the amount of blood flow activity in two patients, working on the same problem. On the left is a "normal" person and on the right is a person diagnosed as having attention deficit syndrome (Fig. 4).

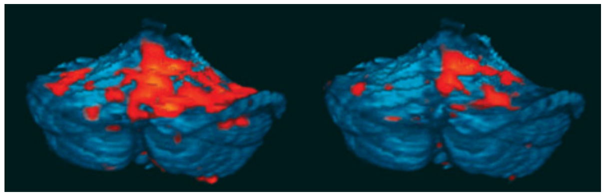


Fig. 4. Brain scan of a normal person (left). Of a person with attention deficit (right).

Dr. Silbertstein's movies show that intense blood flow occurs when a person undertakes a mental task for the first time. From this and similar evidence, we see clearly that learning corresponds to the creation of new brain structures.

An interesting result, easily seen using his techniques, is that if a person learns to solve a particular problem effectively, when asked to do the problem over again, the blood flow is much less intense. Indeed, as we know, when a problem has been solved repeatedly, we solve it without effort. We interpret these results to indicate that once the structures have been formed, more materials and energy are no longer required. Learning ceases. What has been learned is strengthened by repetition.

Sometimes we solve a familiar problem without even realizing we have done so. In these circumstances, our brain seems to have a mind of its own. We drive our automobile from point to point and have difficulty remembering the route we took. We remember a familiar tune but not the words.

We also are aware that we have some bad habits and resolve to change them. Why is it so difficult to change what our brains do effortlessly? It takes a *conscious* effort to make a change in the structure of our brain. Sometimes we find that the effort is so great it seems to be beyond our ability to make the change, as any smoker can attest. We make a conscious effort and fail.

What Do We Mean by the Word *Conscious?*

What do we mean by *conscious?* I decided in 2002 to resolve this question by making a Google search on the Internet for "consciousness." I found about 3.4 million hits. A year later I made another search and Google returned 4.16 million hits, about a million more than I found earlier. I had concluded that with so many papers being written about consciousness, no one really understood the subject. In my search for the meaning of consciousness, I also read a few books. In the book *Consciousness Explained* by Daniel C. Dennett.[5] I read (p. 255): "With so many idiots working on the problem, no wonder consciousness is still a mystery."

Our brains have one important function: To make sense out of what is going on. Human brains constantly monitor the incoming information from the five senses (sight, sound, touch, smell, and taste) plus the information generated internally (regarding the state of readiness of the body and what is stored in memory) At a rate of about 1000 times per second, the brain decides what to do next. Some of our decision making processes come to us genetically, via evolution. As Dennett cleverly put it (p. 188) in order to persist, all creatures must, at every instant in time, decide primarily among the four basic "F's" (Fight, Flee, Feed, or Mate). Every brain must answer the question: "What do I do next?"

The Unique Demands of Mobility

At this point you are probably in the same state as I was when I had read Dennet's book and scanned the 4 million Google "hits." Where is this leading? How do I find useful advice out of all this? Then thanks to a lucky break, my daughter, Kamala Tribus, told me about a paper she had found on the Internet while looking for something else. She directed me to a paper by Dr. Bjorn Merker who takes the view that *mobile* living systems have different needs for decision making than, say, plants, rooted in the soil. Plants need to be able to react to changes in the environment. They have vascular systems, which do this, but the range of circumstances to which they require a response is limited and they make do without a nervous system. But mobile animals have such a large variety of potential choices that they cannot possibly rely on genetic endowment alone; they must have the capacity to learn quickly to deal with the kinds of new situations into which their mobility thrusts them. Merker's main point is that this mobility creates the need to develop a "work space" in the brain for the special kinds of decision making associated with mobility.

> Dennet provides a case in point (p. 177) when he cites the case of the sea squirt: The juvenile sea squirt wanders through the sea searching for a suitable rock or hunk of coral to cling to and make it home for life. For this task, it has a rudimentary nervous system. When it finds its spot and takes root, it doesn't need its brain any more, so it eats it!

Following Dr. Merker, we may construct a list of *fundamental* competencies required in the brain of an intelligent mobile creature:

(1) Orientation in Space relative to self: (up, down, right, left, front, back)
(2) Orientation in Space relative to Earth: (North, South, East, West)
(3) Orientation in Space relative to another: (front of, behind, left side, etc., etc.)
(4) Orientation in Time: (Before, after, now, later, sooner, etc., etc.)
(5) Labeling of objects for recall; (I see a lion, I see a snake)
(6) Constancy of form and shape: (That lion is the same one I just saw.)
(7) Comparison: (Is this a different lion from the one I just encountered?)
(8) Forming Mental Relationships: (Are these lions working together?)
(9) Attention to detail: (Has anything just changed? What's new in this scene?)
(10) Categorization: (Lions, leopards, tigers are one kind of danger while squirrels, chipmunks, beavers are another)
(11) Family Relations: (A special kind of categorization—these are my offspring, these are my parents, here is my family)

Reserving a Space in the Brain for Efficient Decision Making

According to Dr. Merker's view, a *neurological space*, perhaps distributed over the brain, needs to be selected, perhaps temporarily, where various bits and pieces of information, properly decoded, may be the inputs and various potential decisions may be the output. For efficiency, this space excludes the preprocessing required for the various senses. I am going to call this the "Decision Space" without insisting that it be localized or fixed in place. For the moment think of the "Decision Space" as analogous to a subroutine in a computer program. The subroutine does not necessarily exist at any particular place in computer memory and it may be moved around during computation. It serves a function. The decision space also seems to be analogous to the "War Room" where the information required for high level decision making is displayed on the walls of the room while the actual

[5] Daniel C. Dennett, *Consciousness Explained* (Little Brown and Company, 1991).

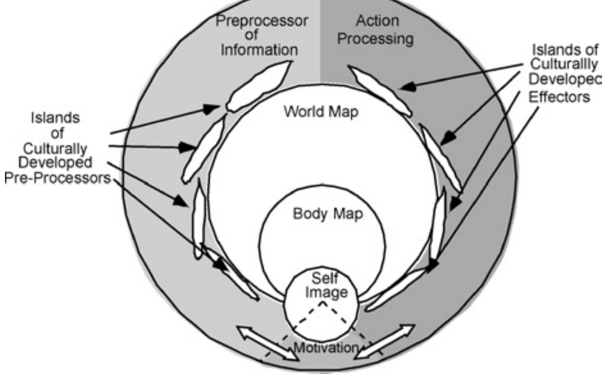


Fig. 5. Defining a decision space (adapted from Merker, by permission).

processing of the field data takes place somewhere else.

Dr. Merker argues strongly for the existence of this space for decision making because of another characteristic of mobile animals. When I walk and move my head, at the back of my eye the image constantly changes, yet the world about me seems to be rock steady. My eyes bob up and down as my legs move. I glance right and left *yet my image of the world remains steady*. If you own a video camera, you know that you must keep it steady while filming.[6] If you move your camera too much, you may induce a kind of seasickness in the audience. Obviously, as I walk, some exceptional compensatory calculations are taking place somewhere in my brain, filtering out the effects of my movements—but I am entirely unaware of these detailed calculations. For the brain to decide what to do next, when the basic information required for the decision is subjected to so much *preprocessing*, some portion of the brain should be dedicated to making the decision, and the preprocessing relegated to another part of the brain. This special space used for decision making, where preprocessing has been excluded, deserves the name "consciousness." The other preprocessing activity may be called "subconscious activity" or "unconscious activity."

Thus, according to Dr. Merker, consciousness derives from the evolutionary pressures created by mobility. I prepared Fig. 5 from Dr. Merker's Fig. 2.

The outer circle of Fig. 5 represents the brain. I do not intend that the reader attach too much significance to the amount of area allocated to various activities, as portrayed in Fig. 5, nor do I intend to "map" the areas in Fig. 5 onto the physical brain. Dr. Merker has already done some of this mapping. It takes an extraordinary knowledge of neurology to do so.[7]

The large white circle in the center represents the map of the external world required if the brain is to make decisions regarding what to do about external events. Of course this map cannot be complete. As Korzybski has told us, "The map is not the territory."[8] However, most people tend to think that the internal map they hold is "reality." The brain also requires a "map" of what lies inside the skin; this part of the brain constantly receives updated information on *some* of the states of internal organs. The third white circle represents the "image of self." Most of us do not like to know that the *map of self* is quite unreliable but we have nothing better.[9]

The large gray area on the left of the diagram represents areas of subconscious preprocessing activity for input information, such as the preprocessing in the optic system providing a stable view of the world during motion of the viewer. Some of these preprocessors are the result of evolution while others are culturally developed. Speaking, for example, involves a great deal of preprocessing before utterances. I have decided to distinguish those preprocessing operations (which I visualize as little white "islands") learned from our culture differently from those preprocessings hard wired from genetics. On the right side of the diagram, the large shaded area represents *action preprocessing*. We digest our food, take a breath or a step without being conscious of how we do it. I have also indicated islands of culturally developed enablers representing competencies, which may be taught, as for example, in sports. I have located these "islands" close to the area we associate with consciousness, to indicate they are often just outside the area of consciousness.

I am not certain how to classify some of the unconscious effectors as resulting from evolution or culture. We can, for example, exert some control over our breathing. While the processes, which lead up to breathing, are mostly unconscious, some aspects are

[6]In more expensive video cameras, computers *preprocess* the image before it goes to the tape to remove shaking motion. The corrections are very small compared to what happens in the human visual system.

[7]Professor Merker cites 148 references in his paper.

[8]Korzybski, Alfred *Science and Sanity*, 5th edn., International Non-Aristotelian Library, Institute of Generas Symantics, Englewood, New Jersey (1994).

[9]If you doubt, try answering the question "Who are you?" and compare it with the answers others give to "Who is she/he?" (Referring to you)

not. Eastern cultures differ from American culture, in putting greater emphasis on being aware of our unconscious activities. I once witnessed a Japanese man who could put thermometers behind his kneecaps, and while sitting motionless on a chair, cause one thermometer to have a different temperature than the other. Experiments with biofeedback, for example, represent attempts to gain control over otherwise unconscious processings.

I follow Dr. Merker in depicting motivations arising from the unconscious activities, as suggested by the arrows, and bringing the results into the *image of self*. More on that later.

The Most Important Part of Any System

I wish I could recall the name of the fellow who about 50 years ago asked me this rhetorical question: "What is the most important part of any system?" Then he answered it himself: "The part that is not working."

Consider, for example, what happens on a wintry day as I move from the cold outdoors into a warm room. My glasses fog over. When I was outdoors, I looked without even being aware that I wore glasses. I saw through them and accepted the various corrections they provided without ever a thought. But when they fogged over, they ceased to work as before. I became conscious of the failure of that part of the system, took off my glasses and wiped off the fog. Then I put them back on and their existence faded from my consciousness.

Fixing Subconscious Processes When They Go Awry

Refer to Fig. 5 above and consider that when something in a subconscious area is not working, we need to move the unconscious activity into the area of consciousness. If we follow Dr. Merker in defining consciousness as that part of the brain where decision making occurs and relegate to *unconsciousness* the activities associated with preprocessing of input information for decision making, then the question arises, how do we become aware which of the unconscious activities may not be working? If a function stops working effectively, it becomes the most important part of the system. We must, therefore, bring this failing process into our conscious considerations and do something about it. How do we know to do so?

In the example of the eyeglasses that fogged over, the answer seems obvious—but it is not. A child with newly acquired eyeglasses will not know what to do when the child's glasses fog over. Deming used to say that a system cannot diagnose itself. An outside force must be brought in—a coach or a consultant.

Let me give a different example—this time swimming. I am a fairly decent swimmer but if I am to improve I need a coach. I think I have a good stroke and consciously work on improving it. However the coach can see that I have not properly synchronized my stroke with my kick. The coach can observe that the way I move my head interferes with my stroke. These are interactions I cannot see for myself; I need a coach. If the cognitive functions supporting the decision space are not working well, we may become aware that we do not like the outcomes of our decision process, but often we cannot identify the cause.

Improving Intelligence

For the purposes of this discussion I define *intelligence* by:

> *Intelligence* is what you use when you do not know what to do.

We judge intelligence by observing what people do when confronted by a problem in a new situation. Do they run around like a chicken with its head chopped off? Do they bury their head in the sand, like the fabled ostrich? Do they wring their hands and say: "I can't do this"? Or do they try to figure out what the problem requires for its solution? It would be better if we were to think of intelligence as a process. If we wish to improve intelligence, i.e. improve the process a learner uses to solve a problem, we need a way for the learner to become conscious of what is wrong in his or her process.

Feuerstein's Intervention Technique

Dr. Merker's theory of consciousness provides an important conceptual basis for the improvement of mental processes, but that theory, alone, is not enough. As the basis for the improvement process we require an additional theory and methods to apply it. Prof. Reuven Feuerstein has provided such a theory and specific methods for applying it.[10] He calls his theory "The Theory of Structural Cognitive Modifiability" (SCM) and his method for applying

[10] Go to http://www.icelp.org for extensive descriptions of the components of SCM.

it is called "Mediated Learning Experience" (MLE). Dr. Feuerstein's theory builds upon our understanding that what we know is represented in the brain by structures of neurons. MLE is a method to alter or create these structures. Here are some of the fundamental tenets of SCM:

1. *The brain is* plastic*, that is, structurally modifiable throughout life*. This premise contradicts many existing beliefs which teach that we are born with a limited number of neurons and after early childhood, begin to lose them until in late life we have about half as many as we started with. Fortunately, this view is changing rapidly. The Internet provides many examples of growing new neurons in the elderly. *There is hope; stupidity is not forever.*
2. *Cultural transmission provides an important method for the creation of cognitive structures.* An adult, either a parent or a caregiver, plays a crucial role in the development of cognitive structure. A child deprived of his or her cultural heritage will not develop cognitive structures required for survival. *Intelligence is culturally transmitted.*
3. *A human mediator may intervene in the mental processes of a learner, at any age, and can cause the learner's brain to either create a missing structure or correct a dysfunctional cognitive structure.* (Through abuse, structures may also be destroyed.) New structural changes persist and, with use, strengthen over time. Such changes may cause a person to begin an entirely new life trajectory. Life is not a deterministic process; the brain influences our life experiences. Life experiences influence the brain. Dr. Feuerstein calls the method of intervention "Mediated Learning Experience" (MLE). *MLE provides a method to put the theory to work.*
4. *The cause of the missing or dysfunctional cognitive structure is irrelevant.* The "rewiring" of the brain may be produced even in the presence of severe physical damage to the brain, as is the case with automobile accidents, blows, or even gunshots to the head. Genetics may determine how the brain starts out but *the chromosomes do not have the last word*.
5. *Successful intervention involves both affect and intellect.* The mediator needs to pay attention to both the intellectual and the emotional processes. Changes in structure always involve emotions; attempts to separate intellect and emotion will fail. *Feelings matter*.

Creating Cognitive Functions Using MLE

How does our brain build these cognitive functions? Feuerstein's theory of Mediated Learning Experience (MLE) provides the answer. All children have experiences. The lessons they take away from these experiences will depend on how they are mediated by a caring adult. Without assistance from an older person, a child will not draw the lessons appropriate to the culture in which the child is raised. The lessons learned are retained in the brain as cognitive structures.

Feuerstein's method for correcting or creating cognitive functions relies upon two stages of interaction with the learner. The first stage involves an evaluation device, which by means of a variety of paper and pencil exercises, allows a trained person to identify the weak or even missing cognitive functions. This device is called the "Learning Propensity Assessment Device" (LPAD). In the second stage his method provides exercises, "Instrumental Enrichment," conducted by the use of Mediated Learning Experience, (MLE), to help the learner to strengthen or develop the needed cognitive functions.

The Feuerstein method of Instrumental Enrichment involves a series of tasks appearing to the learner as simple puzzles. The puzzles are arranged in increasing order of difficulty so that a learner has good chance to solve the easiest puzzles first. The puzzles are also intriguing in and of themselves. Because the tasks are all so simple, when the learner has difficulty, a disequilibrium is established in the brain of the learner. "*I know I can do this, what is wrong?*" When this disequilibrium has been established the brain is open to suggestions.

The genius in the Feuerstein method is this: All of the tasks are "content free," that is, do not seriously depend upon prior knowledge. Thus the cognitive functions are not "attached" (i.e., related) by the brain to any specific subject. At the time the cognitive function is exercised in this content free "context," the competent mediator will "bridge" to a number of specific applications in the life of the learner. In this way the mediator not only helps in creating new structures, the mediator creates linkages to other areas of the brain.

The mediator deliberately raises the level of abstraction used by the learner. This ability to develop

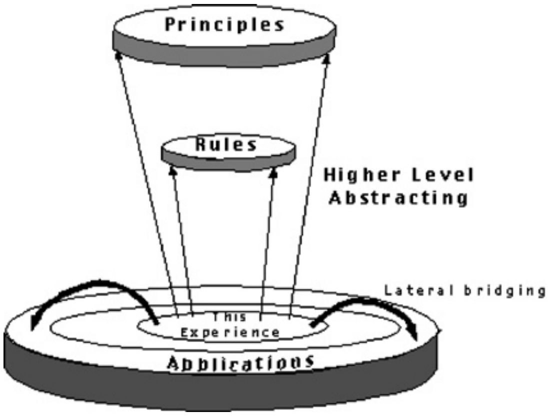


Fig. 6. Abstracting rules and principles from experience.

an abstract representation of lessons learned gives the learner great power. It enables a person to learn something in one context and then apply the lessons learned in another place at another time. The process of abstracting from experience and using the abstractions in another situation is the key to the improvement of intelligence and learning.

For example, some of the tasks given to the learner are deliberately framed so that the learner must examine *all* of the instructions before starting. When the learner discovers that his or her mistakes were caused by impulsively starting to work before understanding the problem, the mediator discusses this lesson and asks, "Has this impulsivity ever gotten you into trouble elsewhere in your life?" (Fig. 6)

Dr. Deming often said that a system cannot repair itself. He was referring to management systems and his many years of experience as a consultant taught him managers simply could not see errors in their fundamental assumptions about how they managed. They required someone from outside, a consultant, to bring about change.

Feuerstein has likewise defined how the intervenor, called a mediator, must approach the mediatee. From Fig. 5 we may see that the decision space is surrounded by *preprocessors* of information, most of which act at an unconscious level, that is, outside the smaller white areas of the diagram. The mediator's challenge is to bring to the area of consciousness the dysfunctional preprocessors or, perhaps, to help the brain to develop a missing function, and to do so without energizing those other preprocessors acting to preserve the self-image of the mediatee.

Feuerstein recognizes the role of motivation in his prescription for successful mediation. He identifies these essential elements of mediation, which I can say from personal experience, apply equally well to a consultant in management:

1. *Intentionality*: The person (the manager or the learner) being influenced needs to understand the purpose (intention, approach, aim) of the mediator or consultant and understand that this purpose is consistent with his or her own objectives.
2. *Reciprocity*: The mediator/consultant cannot pretend to know all the answers but rather should treat the mediatee/client as a coequal in the investigation of the cognitive (managerial) processes under study.
3. *Mediation of Meaning*: The mediator/consultant should help the learner (manager) to understand the implications of what is learned. Since these implications all lie in the future, they will influence the mediatee's (manager's) emotional state. This influence plays a large role in the willingness of the mediatee (manager) to allocate resources, both mental and physical, to the pursuit of the aim.
4. *Transcendence*:Whenever a specific application of the new or enhanced cognitive function (managerial approach) has been identified as beneficial, the specific example should be connected to other situations. This step provides a generality for the process and enhances the potential that the cognitive function will be used more often and, therefore, made more robust against changes in the future.

Figure 7 illustrates the concept of transcendence. Note that the mediatee must be an active participant in the process.

The Learning Propensity Assessment Device (LPAD)

The LPAD differs greatly from the kinds of evaluations normally used in education. Lev Vygotsky once said, "The only legitimate reason to give an examination is for teacher and learner to decide what to do next." This is the spirit behind the LPAD. On the other hand, conventional educational testing is used to grade and rank students, not improve them. Conventional testing provides an after the fact inspection which seldom provides insights into what the learner needs to learn next.

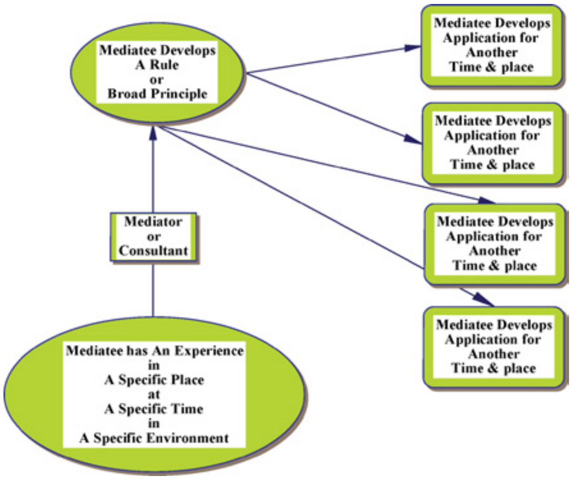


Fig. 7. Transcendence as a process in mediation or consultation.

To understand why conventional testing does not give the information required to improve the learner's functioning, it is necessary to analyze both the nature of a task and the cognitive functions invoked when the task is attempted. A task may be characterized by three parameters:

1. *The content of the task* the learner must know before undertaking the task.
2. *The modality in which the task is presented.* Is it literal, figurative, ikonic, symbolic? Does it depend upon graphs, charts? Does it use special jargon?
3. *The level of complexity of the problem.* Complexity depends upon the degree of novelty as well as the number of different elements comprising the task.

The mental acts required to do the task may also be characterized into four parameters:

1. *The phases of the mental act.* In a manner reminiscent of computer programming, we may recognize three phases:
   (a) input,
   (b) elaboration or operation, and
   (c) output.
2. *The cognitive operations required to perform the mental act.* They may be simple, such as identification or comparison. They may involve categorization. The operation may require the ability to reason about spatial or temporal relations. Dr. Feuerstein has recognized over a dozen different specific cognitive operations commonly required in problem solving.
3. *The level of abstraction.* The solution of a problem may require the learner to function at a very high level of abstraction, as for example, applying the differential calculus to the optimization of a structure. Or the level of abstraction may be very low, as for example, answering the question "How much is half of four?"
4. *The level of efficiency.* The task may, in and of itself, impose a time or other resource constraint. The task or its solution may require care and attention to details or accuracy. Or, the learner may not operate efficiently and thereby create extra difficulties for himself or herself. The low level of efficiency may be the result of fatigue, anxiety, lack of motivation, or a host of other affective reasons.

The LPAD Is *Dynamic* Not *Static*

The LPAD is a form of *dynamic assessment* as contrasted to the *static assessment* associated with tests such as the IQ test. In an IQ test, the examiner provides a standardized environment, independent of the needs of the learner. The examination materials are given to the examinee in a prescribed manner. After the test begins, the examiner is supposed to refrain from interaction with the person being tested. It is a sterile situation. The purpose of the examination is to rank the person being evaluated against other persons taking the same test in another place and time. The purpose is not improvement; it is *to provide a normed reference*.

In an LPAD evaluation, the evaluator interacts with the learner, giving hints where necessary. The evaluator takes note of the kinds of help the learner requires, how the learner receives the help, and what the learner does with the help. The examiner studies the strategies the learner appears to be using and, on occasion, asks the learner to explain what is going on. It is not at all unusual for the learner to leave the examination with a better set of abilities than at the beginning. The purpose of the evaluation is to determine what the learner is prepared to learn next and to discover which cognitive functions need to be strengthened.

The LPAD has been under development for many years. As a result of observations of thousands of learners in many different countries, Dr. Feuerstein and his staff have listed the cognitive difficulties most likely to occur in learners. They have organized the information according to the phase of the mental act, i.e., input, elaboration, and output.

Potential difficulties of learners during the "Input" phase

1. Blurred and sweeping perception.
3. Lack of, or impaired receptive verbal tools that affect discrimination, (e.g., objects, events, and relationships are not appropriately labeled).
4. Lack of, or impaired spatial orientation and lack of stable system of reference by which to establish topological and Euclidian organization of space.
5. Lack of, or impaired temporal concepts.
6. Lack of, or impaired conservation of constancy.
7. Lack of, or a deficient need for precision and accuracy in data gathering.
8. Lack of capacity for considering two or more sources of information at once. This is reflected in dealing with data in a piecemeal fashion rather than as a unit of facts that are organized.

Potential difficulties in the "Processing" phase

1. Inadequacy in the perception of the existence of a problem and its definition.
2. Inability to select relevant as opposed to irrelevant cues in defining a problem.
3. Lack of spontaneous comparative behavior or the limitation of its application by an inhibited need system.
4. Narrowness of the mental field.
5. EPISODIC GRASP OF REALITY.
6. Lack of need for the establishment of relationships.
7. Lack of need for and/or exercise of summative behavior.
8. Lack of, or impaired need for pursuing logical evidence.
9. Lack of, or impaired ability to use inferential or hypothetical (if) thinking.
10. Lack of, or impaired ability to use planning behavior.
11. Nonelaboration of certain categories because the verbal concepts are not part of the individual verbal inventory on a receptive level, or because they are not mobilized at the expressive level.

Potential difficulties of learners at the "Response" phase

1. Egocentric communication modality.
2. Blocking.
3. Trial and error responses.
4. Lack of, or impaired verbal or other tools for adequately communicating elaborated responses.
5. Lack of, or impaired need for precision and accuracy in the communication of one's responses.
6. Deficiency of visual transport.
7. Impulsive, random, unplanned behavior.

Why Do Feuerstein's Methods Work?

I believe the answer to this question lies in the way a mediator brings to a conscious level mental processes, which have been carried out at a subconscious level. By making the learner conscious of his or her own mental processes, the learner is in a position to do something about them. *How* these processes are brought to a level of awareness is the key to modifiability. The mediator has to establish a relationship with the person being mediated which does not threaten the portion of the brain we associate with "self-image" and thereby cause it to "shut down," and draw upon its protective mechanisms.

If the transcendence process has succeeded, the structures thus created may, over time, become one of the islands of culturally-developed preprocessing (See Fig. 5). Note, especially, that Fig. 7 shows that the mediatee participates very actively in developing the applications in another time and place.

There are some topics, which cannot be discussed seriously with people who lack direct experience with the topic. Women tell me that no man can ever understand what it is like to give birth to a baby. You do not know what it is like to be in a war if you have not been shot at. You cannot have a serious discussion of sex with virgins.

Appendix 1 has been prepared to give the reader a small experience with MLE and one of Feuerstein's Instrumental Enrichment tasks. I urge the reader to work through the examples in Appendix 1 with a friend and then to re-read some of the explanations of why Feuerstein's methods are so powerful.

Putting Feuerstein's Methods to Work

In section IV, I shall address how to put Feuerstein's methods to work in a school of

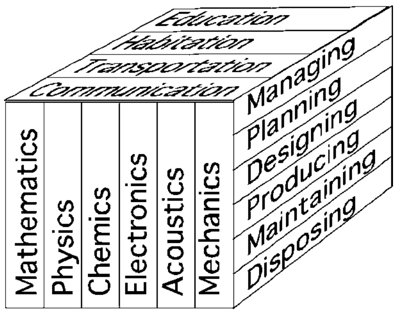


Fig. 8. The three facets of an engineer's career.

engineering. Feuerstein's methods require individual attention. How to provide this attention in an economical and efficient manner requires a combination of both the methods of Deming and Feuerstein.

SECTION II: QUALITY MANAGEMENT ACCORDING TO THE TEACHINGS OF DR. W. EDWARDS DEMING

Why Quality Management Is Integral to Engineering

The above figure (Fig. 8) provides insight into why every engineering student should be taught about management.[11]

As suggested in Fig. 8, the student begins at the "-ics" face, studying various subjects ending in "-ics." These subjects are approached using mathemat*ics* as the common mode of discourse, and as independent topics, treating them as scient*ific*. Typically at this phase, the student has only a vague idea of how these topics will work together. As normally presented, the subjects have vertical walls between them; often they are taught in different departments. The human aspects of engineering are excluded.

The second face may well be called the "-ing" face, for it is concerned with "do*ing*". Here the activities are presented in layers, with manag*ing* at the top. The topics at the "-ing" face are orthogonal to the "-ics" face. For example design*ing* a car or an airplane requires the designer to cut across all the subjects at the "-ics" face, plus many other topics not included in the standard curriculum. At this "-ing" face human considerations are presented as a constraint on engineering, mostly through legal considerations of safety, economy, usability. Engineering designs are expected to produce "customer delight."

Finally, engineers encounter the "-tion" face, where they work with the institu*tions* of society. Here the engineer encounters the politician and finds that engineers must work closely with other professionals to get anything done. Human needs and desires dominate the work at this face. At this face the engineer needs to understand management practices and the psychology of human behavior. These are topics, which require experiential learning. Work at the "-tion" face requires intensive involvement with other people of diverse backgrounds and beliefs. Just as no man ever became a great lover by reading a book, so no student can begin to understand what goes on at the "-tion" face without at least a small experience with it.

Does Quality Management Work?

The following diagram was given to me by an executive at the Motorola Corporation in the early 1980s.[12] This was a time when the Japanese were competing so successfully with American electronics manufacturers that many were going out of business. Motorola staff collected data on various manufacturing and service enterprises and prepared Fig. 9 below.

The vertical scale represents expected failure rates in parts per million. The horizontal line represents the number of standard deviations (Sigma) on the manufacturing process spanned by the customer's specification limits. Under certain assumptions about the process and specifications, Motorola predicts the failure rate (parts per million) from Sigma as described in Appendix 2 and shown by the line on the graph.[13]

On examining the data in Fig. 9, the executives at Motorola noticed that there were many "good" companies on the left side of the graph, with failure rates of a few per thousand. There were some companies at the right side, with error rates measured in a few per million. Differences in the profitability of the low failure rate companies compared to the high failure rate companies were very large. Then Motorola executives made a crucial observation: *There were*

[11] University Administrators and Professors of Engineering also need this kind of knowledge.

[12] Unfortunately, I cannot now retrieve the information surrounding the acquisition of this diagram.

[13] There are some arguments of a theoretical nature which question the exact location of the curve shown, but these arguments are irrelevant to the conclusion to be drawn here.

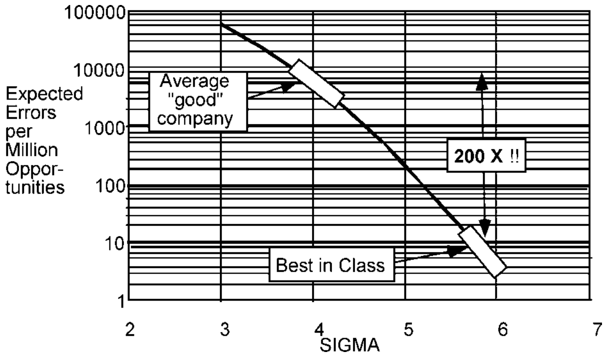


Fig. 9. Motorola's analysis of failure rates.

no companies with failure rates between the parts per thousand and parts per million rate. They were puzzled over this gap. Either a company produced failures measured in parts per thousand or parts per million. No companies seemed to produce values between. Why?

From these data the top management of Motorola concluded that the difference was due to a change in the way the people were managed. The old fashioned way, depending upon inspectors and rework, could not assure lower defect rates without prohibitive costs of inspection and rejection.

The new way did away with inspection and instead, relied upon the workers themselves. The secret lay in the human side of management, guided by statistics. We now call this new way to manage "Quality Management." Quality Management has a very simple premise:

> The system, not the people, is responsible for most of the goofs, flaws, and errors in any production system. Only the people working in the system know what is going wrong. Only the managers can change the system. Therefore, workers and managers must form a partnership to drive down errors, reduce costs, and provide better quality goods and services. Inspection after production is ineffective and too expensive.

The Basic Ideas of Quality Management

Quality Management differs from conventional management in a number of ways. To make the distinction clear, we begin by describing what we mean by "conventional management." Conventional management has at its root the concepts of Frederick Winslow Taylor, whose book "Scientific Management" was very popular at the beginning of the 1900s. Taylor's methods were so popular that there were even debates in the U.S. Senate over whether or not to declare scientific management the favored mode of management in the United States. Taylor's views have been tempered over the years, but the fundamental ideas remain alive and well in the heads of many of today's managers. Here are a few of the ideas of conventional management:

1. The manager's task is to issue clear, crisp directives to those who report directly. Lower level managers are expected to follow the same practice.
2. Workers are to do exactly as they are told; they are not to inject their own ideas.
3. All work should be standardized.
4. Workers always try to do as little as possible; they will try to make the management believe they are working as hard as they can. They work only because they need the money.
5. Education of workers is an expense, not an investment.
6. Management, viewed as a science, represents skills transferable from one situation to another with very little retraining required.

There are many other ideas in Taylor's system, but the above six points should suffice to provide an overview. Deming's views, on the other hand, are very different as illustrated by the following:

> The people work *in* a system.The manager's job is to work *on* the system, *Improving it continually*, With their help.

This orientation requires very different actions and attitudes on the part of both the managers and those who do the work. This perspective is based on some obvious facts of life regarding work in organizations:

1. Only the people actually engaged in doing the work know when things are going wrong.
2. Managers, removed by one or more levels from the place of work cannot know what happens there.
3. Workers are powerless to change the system of work because they lack an overview of the system.
4. Managers have the power to change the system of work but they lack the information that would allow them to know the difference between *change* and *improvement*.
5. In changing times, an enterprise must be swift to change according to changing demands.

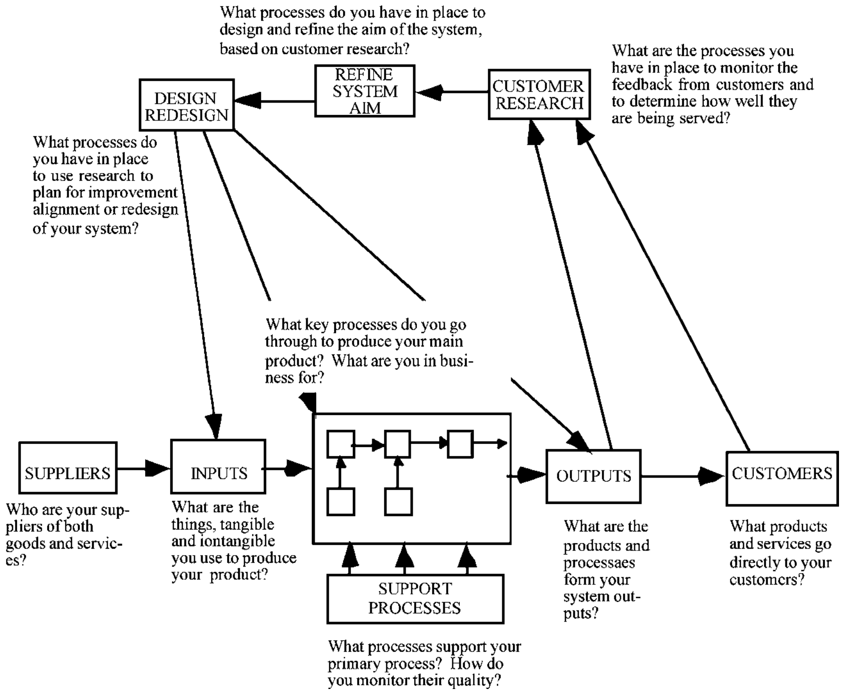


Fig. 10. Viewing an enterprise as a system.

6. Job descriptions become out of date as soon as they are written.

Quality Management requires that both workers and managers learn to use new tools and techniques.

1. They need to learn the fundamentals of "Systems Thinking," that is, to consider how a change in one component's activities will affect the activities of other components and the system as a whole.
2. Since changes are made in anticipation of the future, managers should see their tasks as the *making of predictions*. These predictions are always made under conditions of *uncertainty*; managers need to learn to speak in the language of probability.
3. When a change has been agreed upon, carrying out the change involves many factors not under anyone's control. Statistical Process Control (SPC) provides an important tool to take into account the variability inherent in every process, whether it be in the receipt of incoming materials, the variability inherent in any measuring process, the weather, or worker training. Managers and workers need to abandon *deterministic thinking*.
4. Workers should be intimately involved in examining the work they do and looking for ways to improve their processes. The emphasis shifts from managing people to managing (i.e., improving) processes.

The above remarks should serve to underscore the differences between "conventional management" and Quality Management. Let us now turn our attention to some examples drawn from practice.

Thinking About Systems and Processes

Every system may be viewed as a *subsystem* of a larger system. A system diagram shows how the components of the system interact.[14] The work of each subsystem occurs through processes (Fig. 10).

The *components* of a system (departments, sections, etc., etc.) will each have suppliers, which may be other departments or sections. Each will have outputs going to customers, which may also be other departments or sections.

[14]My thanks to Susan Leddick and Elaine Torres for this diagram.

The Concept of an Internal Customer

Thomas Bata originated the idea of the internal customer. In the early part of the 1900s, Bata created the world's largest shoe manufacturing company. His aim was to produce a company, which would run by itself, requiring a minimum of managerial interference, "run like a clock," as he put it. He wanted to do away with the need for constant oversight and inspection. He told his employees, "The next man in line is your customer" and then told everyone they did not have to accept unsuitable results from anyone. He invented an internal economy in which one department purchased goods and services from another with the prices fixed by a central body. If a team in one department could figure out how to reduce costs, they were entitled to part of the savings. Today I know of no companies who take these ideas as far as Bata did (and there are no companies which come close to the successes he had). But the concept of an internal customer, as he originated it, has remained.

In a system managed for quality, each "supplier" endeavors to please each "customer." The manager of a system asks "What constitutes a quality performance on your part?" and "Who is your customer?" The manager then asks, "If I ask your customer, will I get the same definition of quality that you just gave me?" By this technique the manager attempts to move the decision making deeper into the system, closer to where the work gets done.

Systems get their work done through *processes*. A very useful way to visualize a process is to draw a "process deployment flow chart." An example is reproduced in Fig. 11, which displays the "top level" diagram describing the process by which the "Impossible Missions Force" of the famous television program "Mission Impossible" gets its orders from "The Secretary" and carries them out.

The top row in Fig. 11 represents the cast of characters in the process. A rectangle represents a task. The names appearing above the task show the participants in that step of the process. A shadow around the box indicates more detailed information will be found on a separate page. (When proper software is used, clicking on a shadowed box on the computer screen brings up the next page.) Figure 12 shows the page that appears when the box labeled "Planning Phase" is selected.

This process of "layering" makes it possible for a very complex process to be displayed in the same way that complex parts are displayed in drawings, that is, with overall views, assembly views, subassembly views, etc., etc., down to individual part levels.

In the above diagram, for example, we see that Jim Phelps will arrange travel (with details shown on another sheet. Cinnamon Carter will research the prisoner's history while Rollin Hand assists her. The

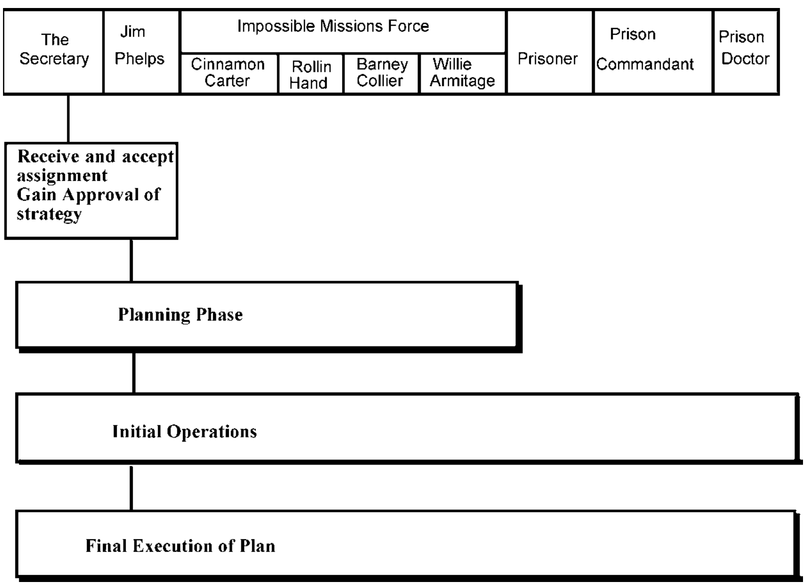


Fig. 11. The "top level" flow chart for the IMF.

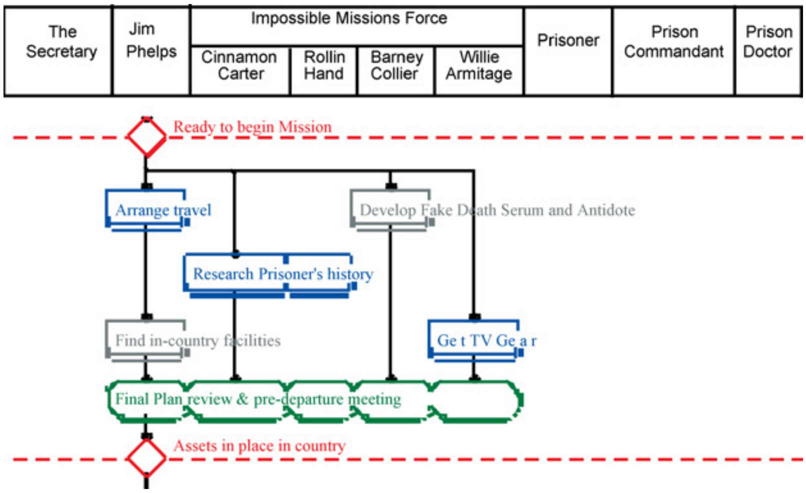


Fig. 12. Start of planning phase.

vertical line shows that Cinnamon has leadership responsibility in this task. Details are to be found on another sheet.

The Unique Importance of Graphical Methods in the Improvement of Quality

Certain words appear in the language of quality management, such as:

System
Process
Customer–Supplier
Trend
Stable process
Organization

These words describe *concepts*. They describe ideas originating in our heads but they do not necessarily have realworld *percepts.* A percept is something we can sense directly with our senses. We cannot *see* a process unless it is shown to us in a graphical representation. In baseball we understand that a ball or a strike depends upon the definition of a batter's zone. A batter's zone exists only by definition. It cannot be "seen" otherwise. System diagrams, flow charts, and run charts are essential tools in quality management for they allow people to "see" the same thing when they discuss improvement.

Figure 13 shows a "deployment flow chart," making visible the process my secretary used to arrange a public meeting. It would have been possible, of course, for her to have prepared a list of the steps she followed, but then the interactions among the people would not have been easy to see. It was possible, after the meeting, for all of us to go back over the process and, working together, look for possible improvements.

The chart in Fig. 13 illustrates an important property of flowcharting. A horizontal line describes a transfer of responsibility from one person or organization to another. This line defines a "customer–supplier" relationship. The horizontal line between the "meeting arranger" and the "facility operator" defines the step in the process in which the room for the meeting is confirmed. The facility operator is the "customer" and quality principles require that the form be prepared carefully to the facility operator's specifications.

Every flow chart should be the responsibility of a designated manager. That manager should examine the flow chart to identify customer–supplier relationships and then determine if the suppliers are attempting to please their customers.

Another advantage of Deployment Flow charting lies in the fact that in a complex process, all of the people involved in the process may look at the diagram and understand what is happening beyond their own workstation. They may then participate in process improvement. For example, at one defense contractor I helped a team from across the company examine the process they used in preparing a contract bid. When they saw the entire process they saw that there was no step at the beginning that involved looking at their prior experiences in bidding. A lost bid was never examined to understand the cause. Likewise, at the end there was no review of the

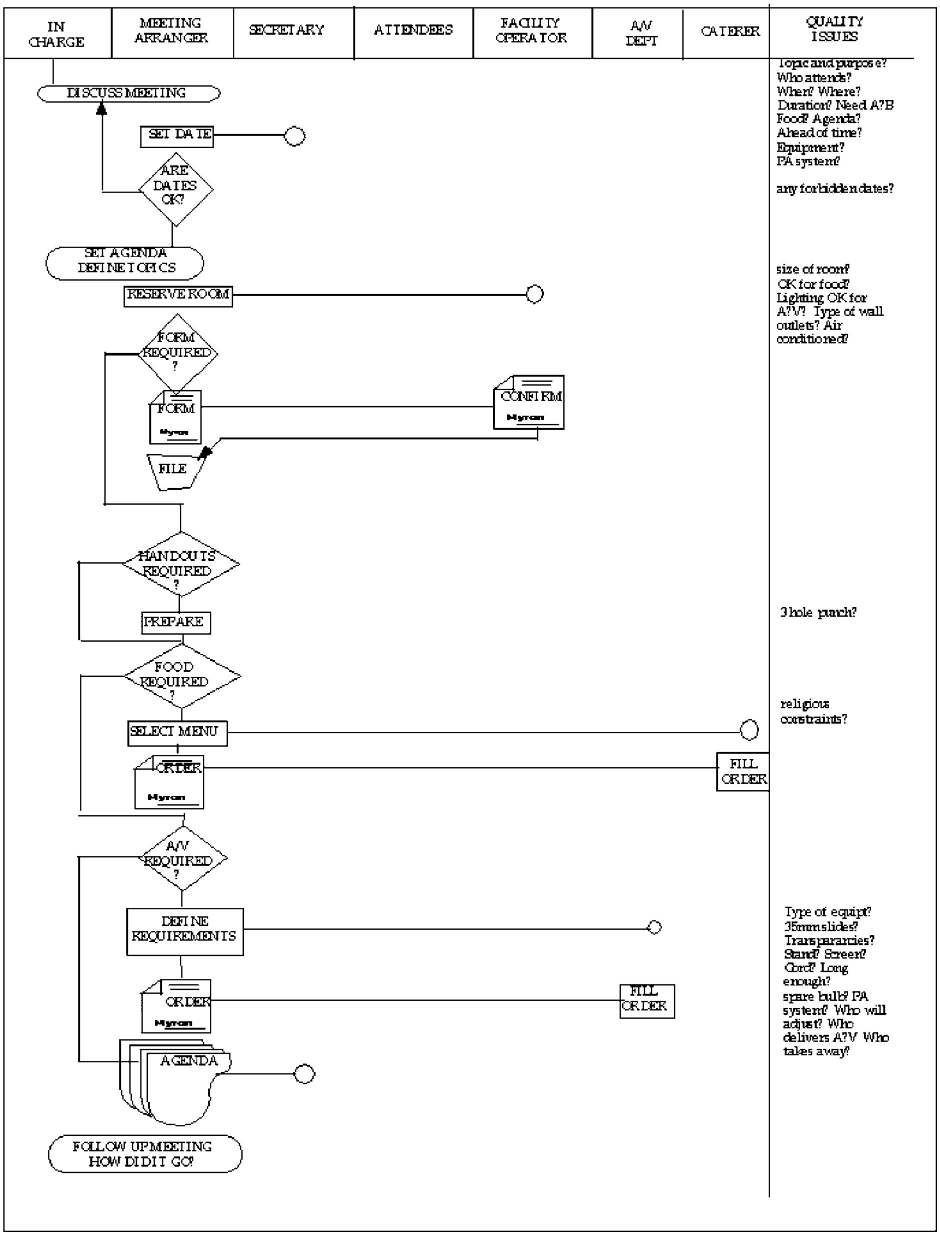


Fig. 13. Deployment flow chart for arranging a meeting.

process, looking for opportunities to improve their chances of winning next time.

The Tools and Techniques of Quality Management

The tools and techniques are of three types:

(A) Problem Formulation
1. Fishbone (Cause and Effect, Ishikawa) diagram
2. Quality Function Deployment
3. Quality Characteristics Evolution Diagram
4. Affinity Diagram
5. Telling the QC Story—a method for problem formulation and reporting
6. Force-Field Analysis
7. Interrelationship Digraph
8. Means-Ends Chart

(B) Problem solving
1. PDSA cycle
2. Data Collection using Check Sheets

3. Pareto Analysis, to prioritize tasks
4. Histograms
5. Scatter Diagrams
6. Control Charts
7. Process Capability analysis

(C) Group and Managerial Methods
1. Nominal Group Technique
2. Consensogram
3. Policy Deployment
4. Planning a Quality Visit

The tools and techniques are described in many books, so I shall not go into them here.[15] Engineers generally have no difficulty learning these tools and techniques. When first shown these tools, senior engineers are apt to laugh and say they already do these things, when in practice they do not. They are apt to dismiss the tools as trivial and not worth the effort. These tools are surprisingly useful, however, especially when used in a group setting. They make it possible for engineers to discuss improvements in the process with factory workers and their supervisors. The flow chart gives them an assurance they are talking about the same thing.

To be successfully applied, these tools and techniques require cooperation and teamwork. Unlike most of the tools of engineering, many quality tools cannot be applied by one person working alone. Instruction in schools of engineering is beginning to change, but when I was a student and later when I was a Professor, it was the custom for students to do their work alone and to demonstrate prowess as problem solvers in the "Lone Ranger" tradition. The quality tools in an engineering curriculum therefore serve two purposes: They provide important knowledge and capabilities and they also help students learn to work together, efficiently, in groups.

Bringing Quality Management to Schools of Engineering

Not only should quality management be brought into the education of future engineers, the School of Engineering should be run using quality principles. When the School of Engineering is managed by quality principles, the faculty and students will work together to improve the processes of the school. The students will see quality management in action. I shall discuss this in detail in Section IV.

SECTION III: BLOOM'S TAXONOMY BY DONALD CLARK

Why Have We Added Bloom's Teachings?

There is more than one type of learning. A committee of colleges, led by Benjamin Bloom, identified three domains of educational activities. The three domains are cognitive, affective, and psychomotor. Since the work was produced by higher education, the words tend to be a little bigger than we are normally used to. Domains can be thought of as categories. Cognitive is for mental skills (Knowledge), affective is for growth in feelings or emotional areas (Attitude), while psychomotor is for manual or physical skills (Skills). Trainers often refer to these as KAS, SKA, or KSA (Knowledge, Attitude, and Skills). This taxonomy of learning behaviors can be thought of as "the goals of the training process." That is, after the training session, the learner should have acquired these new skills, knowledge, or attitudes.

The committee then produced an elaborate compilation for the cognitive and affective domains, but none for the psychomotor domain. Their explanation for this oversight was that they have little experience in teaching manual skills within the college level (I guess they never thought to check with their sports or drama department).

This compilation divides the three domains into subdivisions, starting from the simplest behavior to the most complex. The divisions outlined are not absolutes and there are other systems or hierarchies that have been devised in the educational and training world. However, Bloom's taxonomy is easily understood and is probably the most widely applied one in use today.[16]

Cognitive[17]

The cognitive domain involves knowledge and the development of intellectual skills. This includes the recall or recognition of specific facts, procedural patterns, and concepts that serve in the

[15] See for example, *The Team Handbook*, Edited by Peter Scholtes, Joiner Associates, Madison, Wisconsin. See also *The Memory Jogger* and *The Memory Jogger Plus+* edited by Michael Brassard, Goal QPC, Methuen, MA 091844 and *Total Quality Tools*, PQ Systems, PO Box 750010, Dayton, Ohio.

[16] HYPERLINK "http://www.nwlink.com/~donclark/hrd/bloom.html"

[17] HYPERLINK "http://www.nwlink.com/~donclark/hrd/bloom.html#one"

Category	Example	Keywords
Knowledge: Recall of data.	Recite a policy. Quote prices from memory to a customer. Know the safety rules.	defines, describes, identifies, knows, labels, lists, matches, names, outlines, recalls, recognizes, reproduces, selects, states.
Comprehension: Understand the meaning, translation, Interpolation, and interpretation of instructions and problems. State a problem in one's own words.	Rewrite the principles of test writing. Explain in one's own words the steps for performing a complex task. Translate an equation into a computer spreadsheet.	comprehends, converts, defends, distinguishes, estimates, explains, extends, generalizes, gives examples, infers, interprets, paraphrases, predicts, rewrites, summarizes, translates.
Application: Use a concept in a new situation or unprompted use of an abstraction. Apply what was learned in the classroom into novel situations in the workplace.	Use a manual to calculate an employee's vacation time. Apply laws of statistics to evaluate the reliability of a written test.	applies, changes, computes, constructs, demonstrates, discovers, manipulates, modifies, operates, predicts, prepares, produces, relates, shows, solves, uses.
Analysis: Separates material or concepts into component parts so that its organizational structure may be understood. Distinguishes between facts and inferences.	Troubleshoot a piece of equipment by using logical deduction. Recognize logical fallacies in reasoning. Gather information from a department and select the required tasks for training.	analyzes, breaks down, compares, contrasts, diagrams, deconstructs, differentiates, discriminates, distinguishes, identifies, illustrates, infers, outlines, relates, selects, separates.
Synthesis: Builds a structure or pattern from diverse elements. Put parts together to form a whole, with emphasis on creating a new meaning or structure.	Write a company operations or process manual. Design a machine to perform a specific task. Integrate training from several sources to solve a problem. Revise and process to improve the outcome.	categorizes, combines, compiles, composes, creates, devises, designs, explains, generates, modifies, organizes, plans, rearranges, reconstructs, relates, reorganizes, revises, rewrites, summarizes, tells, writes.
Evaluation: Make judgments about the value of ideas or materials.	Select the most effective solution. Hire the most qualified candidate. Explain and justify a new budget.	appraises, compares, concludes, contrasts, criticizes, critiques, defends, describes, discriminates, evaluates, explains, interprets, justifies, relates, summarizes, supports.

development of intellectual abilities and skills. There are six major categories, which are listed in order below, starting from the simplest behavior to the most complex. The categories can be thought of as degrees of difficulties. That is, the first one must be mastered before the next one can take place.

Affective[18]

This domain includes the manner in which we deal with things emotionally, such as feelings, values, appreciation, enthusiasms, motivations, and attitudes. The five major categories listed in order are:

[18]HYPERLINK "http://www.nwlink.com/~donclark/hrd/bloom.html#two"

Category	Example	Keywords
Receiving phenomena: Awareness, willingness to hear, selected attention.	Listen to others with respect. Listen for and remember the name of newly introduced people.	asks, chooses, describes, follows, gives, holds, identifies, locates, names, points to, selects, sits, erects, replies, uses.
Responding to phenomena: Active participation on the part of the learners. Attends and reacts to a particular phenomenon. Learning outcomes may emphasize compliance in responding, willingness to respond, or satisfaction in responding (motivation).	Participates in class discussions. Gives a presentation. Questions new ideals, concepts, models, etc. in order to fully understand them. Knows the safety rules and practices them.	answers, assists, aids, complies, conforms, discusses, greets, helps, labels, performs, practices, presents, reads, recites, reports, selects, tells, writes.

Category	Example	Keywords
Valuing: The worth or value a person attaches to a particular object, phenomenon, or behavior. This ranges from simple acceptance to the more complex state of commitment. Valuing is based on the internalization of a set of specified values, while clues to these values are expressed in the learner's overt behavior and are often identifiable.	Demonstrates belief in the democratic process. Is sensitive toward individual and cultural differences (value diversity). Shows the ability to solve problems. Proposes a plan for social improvement and follows through with commitment. Informs management on matters that one feels strongly about.	completes, demonstrates, differentiates, explains, follows, forms, initiates, invites, joins, justifies, proposes, reads, reports, selects, shares, studies, works.
Organization: Organizes values into priorities by contrasting different values, resolving conflicts between them, and creating a unique value system. The emphasis is on comparing, relating, and synthesizing values.	Recognizes the need for balance between freedom and responsible behavior. Accepts responsibility for one's behavior. Explains the role of systematic planning in solving problems. Accepts professional ethical standards. Creates a life plan in harmony with abilities, interests, and beliefs. Prioritizes time effectively to meet the needs of the organization, family, and self.	adheres, alters, arranges, combines, compares, completes, defends, explains, formulates, generalizes, identifies, integrates, modifies, orders, organizes, prepares, relates, synthesizes.
Internalizing values (characterization): Has a value system that controls their behavior. The behavior is pervasive, consistent, predictable, and most importantly, characteristic of the learner. Instructional objectives are concerned with the student's general patterns of adjustment (personal, social, emotional).	Shows self-reliance when working independently. Cooperates in group activities (displays teamwork). Uses an objective approach in problem solving. Displays a professional commitment to ethical practice on a daily basis. Revises judgments and changes behavior in light of new evidence. Values people for what they are, not how they look.	acts, discriminates, displays, influences, listens, modifies, performs, practices, proposes, qualifies, questions, revises, serves, solves, verifies.

Psychomotor[19]

The psychomotor domain includes physical movement, coordination, and use of the motor-skill areas. Development of these skills requires practice and is measured in terms of speed, precision, distance, procedures, or techniques in execution. The seven major categories listed in order are:

[19]HYPERLINK "http://www.nwlink.com/~donclark/hrd/bloom.html#three"

Category	Example	Keywords
Perception: The ability to use sensory cues to guide motor activity. This ranges from sensory stimulation, through cue selection, to translation.	Detects nonverbal communication cues. Estimates where a ball will land after it is thrown and then moving to the correct location to catch the ball. Adjusts heat of stove to correct temperature by smell and taste of food. Adjusts the height of the forks on a forklift by comparing where the forks are in relation to the pallet.	chooses, describes, detects, differentiates, distinguishes, identifies, isolates, relates, selects.
Set: Readiness to act. It includes mental, physical, and emotional sets. These three sets are dispositions that predetermine a person's response to different situations (sometimes called mindsets).	Knows and acts upon a sequence of steps in a manufacturing process. Recognize one's abilities and limitations. Shows desire to learn a new process (motivation). NOTE: This subdivision of Psychomotor is closely related with the "Responding to phenomena" subdivision of the Affective domain	begins, displays, explains, moves, proceeds, reacts, shows, states, volunteers

Category	Example	Keywords
Guided response: The early stages in learning a complex skill that includes imitation and trial and error. Adequacy of performance is achieved by practicing.	Performs a mathematical equation as demonstrated. Follows instructions to build a model. Responds hand-signals of instructor while learning to operate a forklift.	copies, traces, follows, reacts, reproduces, responds
Mechanism: This is the intermediate stage in learning a complex skill. Learned responses have become habitual and the movements can be performed with some confidence and proficiency.	Use a personal computer. Repair a leaking faucet. Drive a car.	assembles, calibrates, constructs, dismantles, displays, fastens, fixes, grinds, heats, manipulates, measures, mends, mixes, organizes, sketches.
Complex Overt Response: The skillful performance of motor acts that involve complex movement patterns. Proficiency is indicated by a quick, accurate, and highly coordinated performance, requiring a minimum of energy. This category includes performing without hesitation, and automatic performance. For example, players often utter sounds of satisfaction or expletives as soon as they hit a tennis ball or throw a football, because they can tell by the feel of the act what the result will produce.	Maneuvers a car into a tight parallel parking spot. Operates a computer quickly and accurately. Displays competence while playing the piano.	assembles, builds, calibrates, constructs, dismantles, displays, fastens, fixes, grinds, heats, manipulates, measures, mends, mixes, organizes, sketches. NOTE: The key words are the same as Mechanism, but will have adverbs or adjectives that indicate that the performance is quicker, better, more accurate, etc.
Adaptation: Skills are well developed and the individual can modify movement patterns to fit special requirements.	Responds effectively to unexpected experiences. Modifies instruction to meet the needs of the learners. Perform a task with a machine that was not originally intended to do (machine is not damaged and there is no danger in performing the new task).	adapts, alters, changes, rearranges, reorganizes, revises, varies
Origination: Creating new movement patterns to fit a particular situation or specific problem. Learning outcomes emphasize creativity based upon highly developed skills.	Constructs a new theory. Develops a new and comprehensive training programming. Creates a new gymnastic routine.	arranges, builds, combines, composes, constructs, creates, designs, initiates, makes, originates.

SECTION IV: PUTTING THE TEACHINGS OF DEMING, FEUERSTEIN, AND BLOOM TOGETHER TO CREATE A NEW VISION OF ENGINEERING EDUCATION

Introduction—Why a Complete Transformation Is Necessary

Just as I began to write this portion of my report Dr. William A. Wulf, President of the National Academy of Engineering published a paper in the Spring 2004 issue of *The Bent of Tau Beta Pi*, "An Urgent Need for Change." He called for a redesign of engineering education to meet a number of challenges. I have taken the liberty of copying the following list of reasons for change directly from his paper:

1. The need to place stronger emphasis on creativity, making design a central theme.
2. As global competition increases, we must engineer in a global, cultural, and business context.
3. We must educate engineers for the jobs that will be, not the jobs that are or were.
4. Curriculum and pedagogy must change.
5. Diversity of the student body must increase because we shall be designing for ever more diverse populations. Men, women, underrepresented minorities view life differently and will be able to create differently
6. Only about half the students who enter engineering graduate as engineers—the retention rate must be increased.
7. The engineering-science curriculum, created after World War II must now be expanded to include new areas such as information technology, nanoengineering, biological processes and materials.

Dr. Wulf also called for nonengineers to become literate in science and technology. The proposals I am about to make provide a basis for addressing these topics as well.

The Flaw in the Current Paradigm of Teaching and Learning

The current approach to teaching involves one teacher with 20–40 students in one room. The teacher teaches a subject and the students are all supposed to learn it at the same pace. Since students do not all learn at the same pace, the result is a distribution of learning, with the fastest students "getting it" while the slower students only "get" some of it. The teacher and the learners confuse speed of learning with ability to learn and so the students become labeled, not only in the teacher's mind, but in their own minds as well. The slowest learners build a self-image in which they see themselves as incapable of learning. Unfortunately for them, the failure to make a distinction between ability to learn and speed of learning has enormous consequences to them and to their society. Under this scheme of teaching and learning, the slower learners fall farther and farther behind, become less and less confident, and finally drop out of the educational system at the earliest opportunity.

Engineering education must be treated as a *system*, i.e., a set of components working together to achieve an aim. The aim should be to provide the knowledge, knowhow, wisdom, and character required to perform as an engineer in modern practice. If the fundamental paradigm of the teaching/learning process is to be changed, then the entire system of teaching, including the management of the overall process, must also be changed. More than just the management must change; the *belief* system upon which the system is founded must also change.

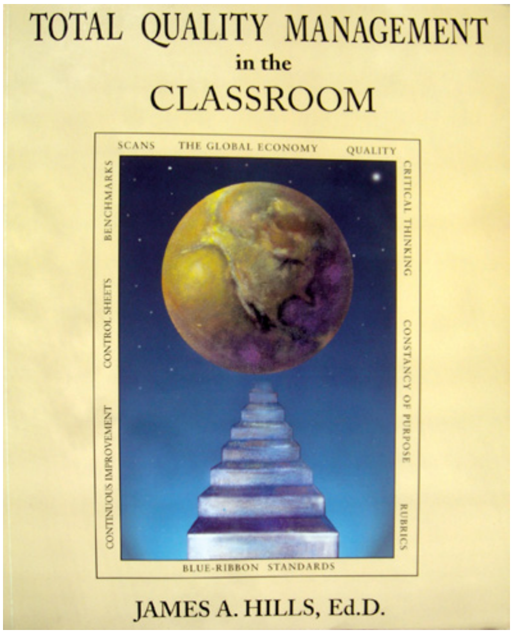
In the 1930s Benjamin Bloom pointed out that research had shown that given the time and attention required, slow learners could learn just as much as fast learners. Some years ago (I cannot now find the specific reference) IBM conducted an experiment to examine at what early age a child could learn to use a typewriter. They hooked up a selectric typewriter to a computer, equipped it with a microphone and placed the system in a room with one-way mirrors. A child was introduced into the room. The typewriter rattled its keys and spoke, "I'm a talking typewriter. What is your name?" If the child said "Mary" the typewriter would then type "MARY" and invite the child to come over and look. "See I can write 'Mary', like this 'MARY'. Can you type 'MARY'?" As the child pressed keys randomly, the typewriter would give various hints. As soon as the child progressed beyond a certain stage, the computer's "Teach Typing" program took over, enabling the computer to teach Mary to type without human intervention. By studying the records the computer produced, the research staff could keep records of learning for different children. After a while, the child could type sentences and finally write stories. The staff at IBM was pleased at the results, having gotten good responses from a number of children. Then someone had the idea to introduce a child with "severe learning difficulties." To everyone's surprise, this child eventually learned to do all the things the "normal" child could do. The difference was it might take 20 or even 100 times as long. This result confirmed Bloom's claim that, given the right support, anyone can learn anything that someone else can.

Even though it has been 70 years since Benjamin Bloom made his point about the difference between ability to learn and speed of learning, our current system of education does not take the difference into account. Under the existing paradigm, individual attention is just too costly.

There is another way. I have found it in the works and writings of James Hills. He has successfully introduced a new paradigm and proven that it not only can provide individualized instruction for a wide range of learners but it is more effective at lower cost. Fortunately, Dr. Hills has worked through the details of his system sufficiently that we have only to translate it to the field of Engineering Education, a task I have undertaken to do in this report. In the process I shall demonstrate how the teachings and methods of W. Edwards Deming and Reuven Feuerstein provide the theoretical basis and justification for the new paradigm.

Dr. Hills has also published a book and provided several papers on the Internet,[20] describing details of the paradigm in action.

[20]Hills, James A., *Total Quality Management in the Classroom*, published by FairPlay Services and Publications, 48 Winona, Lawrence, KS 66046-4848 <http://fairplaypublications.com/Documents/>, <http://fairplaypublications.com>



Fundamental Practices in the New Paradigm

Hills' system is based upon a combination of the teachings of Deming and Bloom. I propose to add the teachings of Feuerstein to the method. Here are the characteristics of the proposed system:

1. For every topic to be studied, a "Matrix of Competencies" is prepared by the instructor and made available to the student. This matrix defines what it means to achieve *mastery* for the topic. I have appended two matrices as examples, one for quality management and the other for the teaching of Feuerstein's methods.
2. The Matrix of competencies shows, in the columns, the essential topics to be mastered. The columns show the levels of mastery. The student and the instructor, collaboratively, enter notations in the matrix to indicate the student's progress.
3. When filled out, the matrix is used to provide the official record of student achievement.
4. Each learner proceeds at his or her own preferred pace.
5. A second matrix displaying study resources is provided for the student, keyed to the matrix of competencies. An example of such a matrix is also appended.
6. There are no grades. Students are not compared one with another, nor are their records forced into a "normed" distribution. Instead, notations on the competency matrix, entered by the instructor, describe the students' state of development.
7. Classrooms are eliminated. Meeting rooms are provided for those occasions on which it is desirable to speak with all of the students at the same time, as for example when guest lecturers are invited. Teachers spend all their teaching time at a "help desk," working one-on-one with students.
8. Each instructor is responsible for developing and maintaining a *glossary* of important terms and concepts and for keeping the glossary up to date on a central computer, available to all students. Over time the glossary, since it will have been built cumulatively out of student inquiries, should provide answers to almost all the questions students ask. In due course students will learn to consult the glossary before going to the help desk.
9. As the work of the students reveals new needs, the instructor adds terms and definitions to the glossary.
10. Students visit with the teacher at the "help desk" to discuss their work. These visits provide an excellent opportunity to engage the students in Feuerstein's Mediated Learning Experience for those who require it, can engage students in discussions of their work and correct misconceptions before they become "hardened."
11. Depending upon the teacher's understanding of where the student is in his or her journey toward mastery, the teacher adjusts the student's next assignment. Over time teachers will accumulate a large number of example assignments, aimed at improving one or another cognitive function, changing the assignments to fit the student's needs.
12. If the work is acceptable, the teacher accepts the written assignment, studies it, and writes a critique. The teacher's comments, along with an update on the student's "competency matrix" are then placed in the student's mailbox along with a new assignment.
13. From time to time the instructor will arrange for a lecture demonstration or for a joint meeting at which students may pose and answer questions as a group. The instructor may also propose project work for students to pursue together. The help desk, however,

will continue to be used for individual evaluations.

14. Student records will show that they have or have not achieved mastery in a topic.
15. When mastery has been attained in the required subjects, the student will be granted a degree.
16. Time previously spent managing classrooms, recording attendance, maintaining discipline, etc., etc., will be now devoted to working with students.

Although the Hills' method has not been applied in Engineering, it has been successfully used in different disciplines and with a variety of students. The main barrier to its acceptance is the change in the fundamental paradigm of teachers. They are taught in and are habituated to the classroom and its practices. They have difficulty appreciating that they will be more effective, work with less stress, and be happier in a different mode. According to Dr. Hills, the students like the new system. It puts them in charge of their own education. The teachers, however, tend to be apprehensive. However, when they have made the investment of time and energy to transform their methods to the new system, according to Dr. Hills, they generally like it.

Sample competency matrices are shown in the appendices to Section IV. Note that these matrices are concerned with the competency of the teachers in the two areas we wish to emphasize: Quality and Cognitive Modifiability.

Continuous improvement implies continuous training for teachers. In schools of Engineering, teaching assistants and new staff are currently appointed to teach with very little concern for their teaching abilities. I am not concerned over subject matter competence; usually a school of engineering will be sufficiently concerned over that issue. Rather I am concerned whether the teachers understand and can use quality methods in their work and can teach these methods, as needed, to their students. Likewise, I am concerned that the teachers learn how to use MLE in their work when counseling students.

Training in Feuerstein's methods will provide a sense of reward to both teacher and learner. I say this on the basis of my own experience, as well as discussions with many persons who have been trained as mediators and have practiced in different countries around the world. I urge ABET to investigate the continuing education of teachers and, in particular, examine whether they are taught using the methods proposed herein. It is well known that "teachers do not teach as they are told, they teach as they are taught."

At this point in time we are concerned only with a change in the structure of education, not the educational content. Organizations such as ABET and the Engineering Societies will, from time to time, have things to say about content. Schools, such as the Thayer School of Engineering and UCLA may decide, as they once did, that the unified curriculum is the way to go. Some schools may choose to make entrepreneurship or, perhaps, system design their main theme and build their curriculum around it. Whatever the choices concerning curriculum, the methods of Deming and Feuerstein are built in to the system described here.

Advantages in the New Paradigm

(1) *It is easy to get started*. Although I have presented this material as a *system*, it is not necessary to wait to begin until the entire system is in place. A single faculty member can try, with perhaps a little cooperation from other faculty members. A dean or a department chairman can lead a subset of the faculty in an experiment, just to see how it works.

(2) *The Students become partners*. The students can become partners in the transformation. For example, since the basic tools of quality management are very simple, compared to topics students learn in their engineering classes, some of the more proficient students can set up their own teaching sessions and help desk, to provide counseling to other students on when, where, and how to use the tools to save time and effort.

(3) *Savings in time, effort, and space*. Dr. Hills has documented the savings in space, through the elimination of classrooms. I have served on various "space" committees and engaged in the "space wars" that occur every semester as classrooms are assigned. These battles are eliminated in this system.

(4) *Grades are eliminated*. Now we can get down to serious study. No more concern over "grade inflation." No more asking "will it be on the test?"

(5) *Examinations are eliminated*. Vygotsky once said, "The only legitimate purpose for an examination is for the teacher and learner to

decide what to do next." In this system, the teacher and learner are in almost continuous conversation about how the learner is progressing. The learner regularly provides a demonstration, a documentation, or a defense of what has been learned. Formal examinations can only cover a portion of what has been learned. We have learned long ago in manufacturing that inspection at the end of the line does not improve or assure quality of product.

(6) *Using Feuerstein's methods*. the teacher becomes continuously aware of a student's cognitive dysfunctions or even the absence of a function. Through the use of Feuerstein's Mediated Learning Experience, the learner learns to understand his or her own reasoning processes and, as a result, becomes a faster learner, a more autonomous learner, and requires less and less help as he or she progresses.

(7) *Records keeping is simplified*. The completed competency matrix becomes the record for the course. No more concern over grade point averages. In a very short time the graduates of this form of education will have made a name for the schools adopting it. The portfolio of documentation of competencies will suffice to convince admissions officers.

What Might the New System Look Like in Practice?

Engineers know that for every *given* general specification, many different designs may satisfy the specifications. We have only to look at the different designs of aircraft or of automobiles to see this principle in action. In the following paragraphs, then, I shall describe one way, not *the* way, to achieve the above characteristics. In this description I shall lean heavily on materials supplied to me by Dr. James Hills, to whom I freely acknowledge his mentoring. We begin by following Prof. Therm as he teaches a particular course of instruction.

Prof. Therm teaches elementary thermodynamics in the preengineering curriculum at a junior college. On the first day of class, he meets the students in a conventional classroom and begins by teaching them the introductory concepts in the conventional way. He gives each student the address on the school time share computer where the "Thermodynamics Competency Matrix" is stored and available for download. He advises each student to download his or her own copy of the Competency Matrix and use it to track learning progress, as described in instructions accompanying the downloaded matrix.

The matrix is organized with columns keyed to Bloom's taxonomy. The students are given a brief paper describing Bloom's taxonomy, with examples from Thermodynamics. Prof. Therm has indicated, by shading the cells of the matrix, the minimum levels of competency expected for a student to just barely "pass" the course. The students are expected to indicate on the matrix the levels of competence they believe they have attained. The students use the matrix, plus discussions at the help desk, as a guide as to what they should study next. The student's self-evaluation, via the matrix, is used as the basis for discussions at the help desk.

Dr. Therm also calls students' attention to a glossary of terms he has prepared and posted on the time-shared computer. This glossary, which contains about 200 definitions used in Thermodynamics, should be consulted before the students seek help.

He gives the students homework assignments, which require only 20–30 min to complete, and corrects them (with the use of assistants if the class is large). During this time he gets to know the names of the students and because the assignments he gives all relate to fundamental concepts (i.e., forms of energy, types of forces, strict definitions of heat and work) he also begins to get a feeling for students who will need extra help.

As the third week begins, he announces that there will be no class meeting on Friday, but instead all students are to stay in the classroom and study there. Dr. Therm tells them that a "help desk" is to be established at a particular location and he intends to be there at fixed times for students who wish to have consultation. On the basis of his preliminary meetings with students, some of the students will be invited to confer at the help desk so the help desk starts out with an initial cadre of clients. At the same time, a sign up sheet, provided on the wall near the help desk, displays times available for consultation.

Based on the students' questions and comments, Dr. Therm regularly adds terms to the published glossary. (After a few semesters, the glossary should be essentially complete.) Students are encouraged to inform Dr. Therm about words they think should be added to the glossary.

By about the fourth week, the students are now spending most of their time in the study hall and there are no more class meetings. The students no longer proceed in lock step, studying the same things at the same time. Instead, the students who can go more rapidly do so and are given additional assignments which lead them into more advanced areas.

The students are also involved in the continuous improvement of the course. A second matrix, the "Resource Evaluation Matrix" is prepared and placed on the central computer, with a copy allocated to each student. A sample of this matrix is also appended. The rows correspond to the rows in the competency matrix but the columns are each headed by the names of the various resources available to the students. Examples of resources include: (1) the required text, (2) the handouts prepared by Prof. Therm, (3) reference works placed on "reserve" in the library, (4) class lectures, (5) guest lecturers, (6) special locations on the Internet. The students are requested to enter in each relevant intersection their evaluation of the value of the resource with respect to the topic. I show a sample evaluation on the attached Evaluation Matrix.

CONCLUSION

The proposed change in the paradigm of engineering education can provide a superior experience for the students and greater satisfaction for those members of the faculty for whom the education of the student is important (I have never been able to enlist those members of the faculty who were interested only in research and considered the teaching of undergraduates a nuisance!) It will be more effective for all students and can reduce the cost of engineering education.

APPENDIX 1: AN OPPORTUNITY TO EXPERIENCE MLE [TO GAIN ANYTHING FROM THIS APPENDIX, YOU MUST ACTUALLY DO THE TASKS]

Thinking

When we set out to learn something, it means that we try to put our mind to it. But what does it mean to say we "put our mind to it?" Do we understand what we are doing when we "think about it?" What is going on in our heads when we say we are "thinking?"

Consider the constellation Ursa Major, also known as the "Big Dipper," and sometimes called the "Plough." Can you find it in the following photograph of the night sky? (Fig. A1.1)

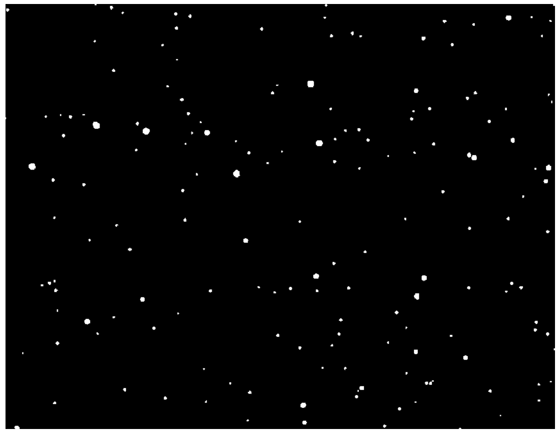


Fig. A1.1 Night sky, northern Hemisphere.

At this moment, if you do not see the constellation, do not fret. Instead, ask yourself the questions: "How am I searching?," "What is my strategy?"

Suppose, for a moment, that you can see the Big Dipper. Suppose, further that you are outside, one starry Summer night, with a friend and you point to the sky and say, "Look, there's the big dipper." If your friend cannot see it, what will you do to help? How do you help him or her to "see it?" For that matter, how did you manage to see it yourself? How

Fig. A1.2 You see what? [DENNIS THE MENACE (R) used by permission of Hank Ketcham Enterprises, Inc. and (c) North America Syndicate.]

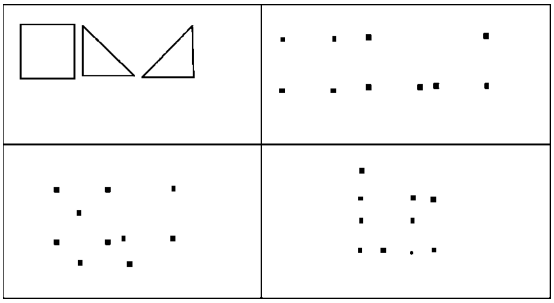


Fig. A1.3 A square and two triangles.

do you do it? What is going on here? What is your brain doing when, without much effort on your part you can impose a shape on what would otherwise be just a bewildering array of points of light? How did your brain learn to do that?

Picking out shapes from a bewildering scene is the most primitive form of learning. Babies begin, very early in life, recognizing their mother's face and discerning shapes and sounds in a confusing world.

When we look for our eye-glasses among the items scattered on our desk we must begin with a mental picture of what the eye-glasses look like.

We have learned from our ancestors how to "find" shapes in the patterns of the stars. The shapes we recognize in the sky were not out there we *imposed* them. Our ancestors showed us a particular way of looking at the heavens that turned out to be very useful. The big dipper, for example, can be used to find the North Star.

Like the little boy in the cartoon (Fig. A1.2), we are unaware that we are *imposing* order on what we see. The man starts with a mental image of what he

I have one more question: "Is there really a big dipper up there?" Most people will say "No." In other words, they can see something that is not really there. The friend cannot see it and they are trying to help him?

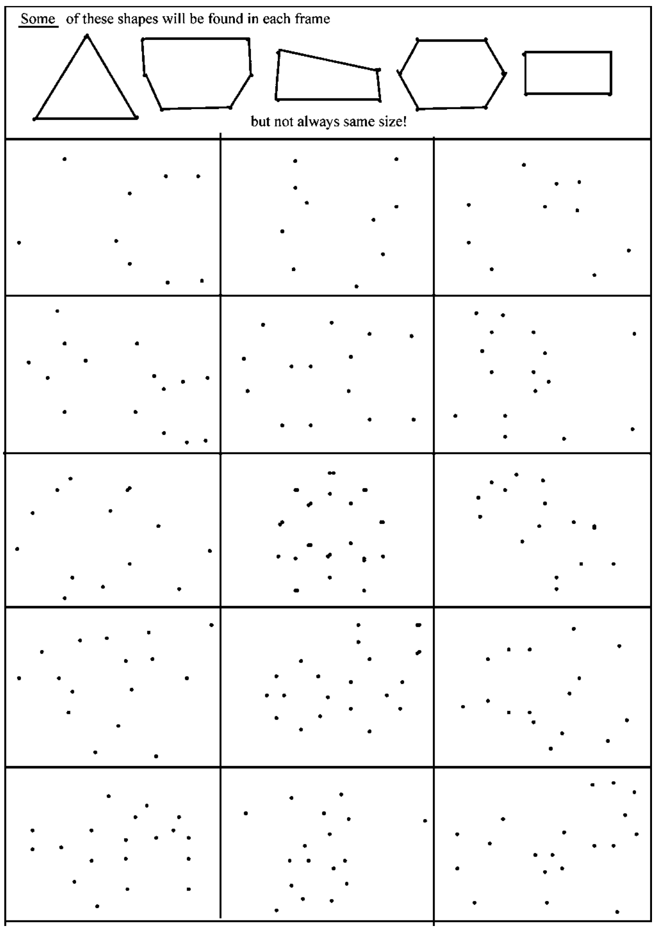


Fig. A1.4 Some difficult challenges. GOOD LUCK!

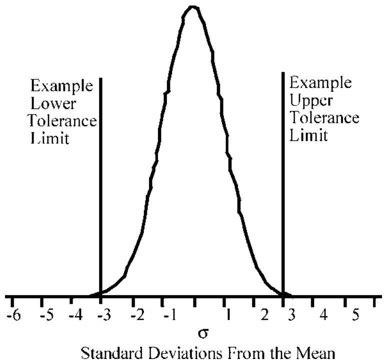


Fig. A2.1 Producing many defects, 6 per *thousand*.

seeks to find. In that sense he "sees" something that is not there.

The most important question is: How do we do it? How does our brain manage to see something that is not there? Consider the four frames in the diagram (Fig. A1.3). In the first frame (top, left) there are three shapes, a square and two triangles.

Can you construct these same three shapes using all of the dots in the frame at top right to define the corners of the figures? Now, consider the two frames at the bottom. Can you find the same square and two triangles, using all the dots and each one only once? (The shapes are the same size but may be overlaid and rotated)

If you can find the square and triangles, can you explain to someone else how you did it? Do you just stare at the cloud of dots until the images pop out? If you do, then you get the answer without consciously thinking, without knowing how you did it! This is certainly the way you recognize the face of a loved one in a crowd.

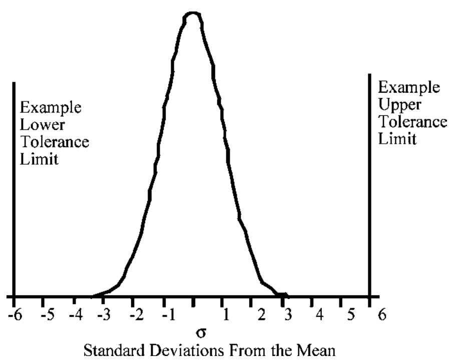


Fig. A2.2 Producing extremely few defects, 3 per *million*.

In this exercise we are not interested in whether you can find the three figures. The question is: "Do you know *how* you do it?" Or if you cannot, do it, "Do you understand *how you are trying* to do it?" What is your strategy for searching? *I strongly urge the reader to discuss with a friend, the strategy for finding a shape in the cloud of dots. Try to teach the other person your strategy for doing this task. Then, with your friend, try the strategy using the challenges on the diagram* (Fig. A1.4).

APPENDIX 2: THE BASIS FOR THE MOTOROLA ESTIMATE OF FAILURE AS A FUNCTION OF SIGMA

The figure below shows a Normal Distribution with the tolerance limits of a part superposed. In the figure we see that the distribution of the part dimensions does not lie entirely within the tolerance limits. With such a distribution and tolerance limits, we would expect to see about 6 defects per *thousand* parts (Fig. A2.1).

Now imagine that the distribution of part dimensions lies entirely within the tolerance limits, as in the figure below (Fig. A2.2).

Here we show the tolerance limits as ±6 sigma from the mean. The probability of a part being at 6 sigma from the mean is now so small, 3 per million, as to be invisible on the graph.

The probable failure rate per million parts may be computed using the properties of the Normal Distribution. In preparing the following table, Motorola has increased the calculated failure rate to allow for a drift of the center point by 1.5 sigma. This modification of the calculations has been considered controversial but in view of the difficulty of making measurements at such low failure rates, the controversy is more philosophical than of engineering significance.

Departure from the mean in Sigmas	Defects per million opportunities
1	690,000
2	308,537
3	66,807
4	6,210
5	233
6	3.4

The estimates in the Motorola diagram, Fig. 9, were computed using the above table.