Systems Thinking: *A critical set of Critical Thinking Skills for the 90's and beyond*

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Abstract

The problems we are facing at all levels in the world today are growing more intractable. In particular, our problems are becoming increasingly resistant to unilateral solutions. I will argue that this growing resistance and intractability result from the fact that while the evolving web of interdependencies, of which we all are part, is rapidly tightening, the development of our capacity for thinking in terms of dynamic interdependencies has not kept pace. As the gap between the nature of our problems, and our ability to grok this nature grows, the planet will face increasing peril on a multitude of fronts. System Dynamics and Systems Thinking -- the larger framework of which it is a subset -- are an important part of an effective strategy for closing the gap between challenge and capacity for addressing challenge. Unfortunately, we as System Dynamicists and Systems Thinkers have been woefully inadequate in transferring our framework, skills and technologies to the population at large. Although we have "seen the light" for some thirty years now, we have not opened the door to our inner sanctum wide enough to let others share in our insight-generation capabilities with respect to the inner workings of closed-loop systems. In order to be more effective in transferring our very valuable capabilities to a broader swath of humanity, we need to see more clearly precisely what these capabilities really are, and also to understand the forces driving the evolution of the education system into which these capabilities -- if they are to be transferred on a broad scale -- must be assimilated. My purpose in writing this paper is to shed some (hopefully new) light on both what it is we have to bestow, and also on where the educational system that is to receive our bounty is headed. My intended audience therefore is both Systems Thinkers *and* educators. My highest hope for the paper is that it will serve to further eradicate the distinction between the two.

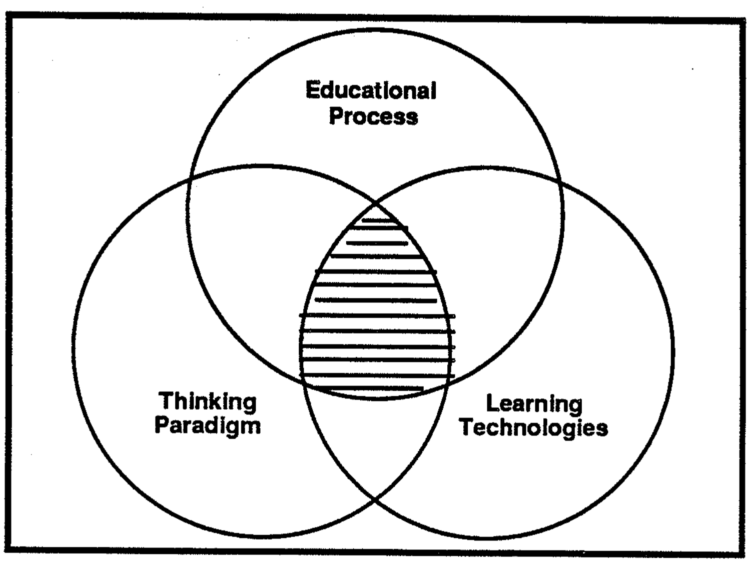
Introduction: ***The coupling is growing tighter*** The problems that we currently face have been stubbornly resistant to solution, particularly unilateral solution. As we are painfully discovering, there is no way to unilaterally solve the problem of CO_2 buildup which is steadily and inexorably raising temperature around the globe. The problems of crack cocaine, ozone depletion, the proliferation of nuclear armaments, world hunger, poverty and homelessness, rain forest destruction, and political self-determination, also fall into the category of "resistant to unilateral solution". Why is it no longer possible for some world power to pull out a big stick and beat a nasty problem into submission? The answer is that it probably *never was* good enough! It's simply that the coupling between the various sub-systems conspiring to manifest the problem was less tight. As such, it was possible to score a pyhrric victory by essentially pushing the problem either "off into the future" or "off into someone else's backyard". Unfortunately, as our esteemed colleague Dana Meadows is fond of saying, "There is less and less away to throw things into". By "away", she means both space *and* time! We have less and less space remaining to serve as receptacle for our "garbage". And, we have less and less time before we must endure "the morning after". Both are artifacts of sustained material growth in our finite earthly dominion. *Every* generation of human beings has been playing by these rules. It's just that *our* generation is the first to have to begin taking them seriously!

System Dynamics/Systems Thinking to the Rescue? If you accept the argument that the primary source of the growing intractability of the problems that we face is a tightening of the couplings between the various physical and social sub-systems that make up our reality, then you'll agree that System Dynamics/Systems Thinking holds great promise as an approach for augmenting our solution-generation capacity. The systems thinker's forte is interdependencies! Their specialty is understanding the dynamics generated by systems composed of closed-loop relationships. Systems Thinkers use diagramming languages to visually depict the feedback structure of these systems. They then use simulation to play out the associated dynamics. These tools give people the ability to "see" a neighbor's backyard -- even if that backyard is thousands of miles away. They also give people the ability to "experience" the morning after -- even if the morning after is tens or hundreds of years hence.

Although the quality of the "seeing" and the "experiencing" underwritten by current systems thinking tools is improving, these tools remain quite primitive today. In three years, they will be much less so. In ten, available tools will be capable of effectively compressing space and time so as to produce "virtual realities". In these electronic realities, people will be able to *participate* in creating powerful, visceral experiences for themselves. But no matter how sexy the technology gets, it always will be only *part* of the solution. If people are to make sense of their experiences in "virtual realities", they must have the capacity for understanding the underlying closed-loop framework that is generating these experiences. They must be capable of thinking both systemically and dynamically. In short, they must be Systems Thinkers! This, in turn, brings us right back, face to face with a long unanswered question. This question has plagued the systems field from its outset some thirty years ago at that venerable little technical university on the Charles river in Cambridge. The question is: *How can the framework, process and technologies of systems thinking be transferred to the rest of the world in an amount of time that is considerably less than what it currently takes to get a Master's or PhD degree in our field?*

I will argue that to successfully answer this question, it is necessary to confront two aspects of the transfer process. We first must better understand the evolution of the education system into which the transfer must be made (this system offers the best potential for large-scale transfer). Second, we must better understand the "thing" we are seeking to transfer. Specifically, we must recognize that this "thing" is multi-faceted. As such, for people to swallow and digest it, it must be broken down into more consumable pieces. I now will examine both aspects of the transfer process in turn.

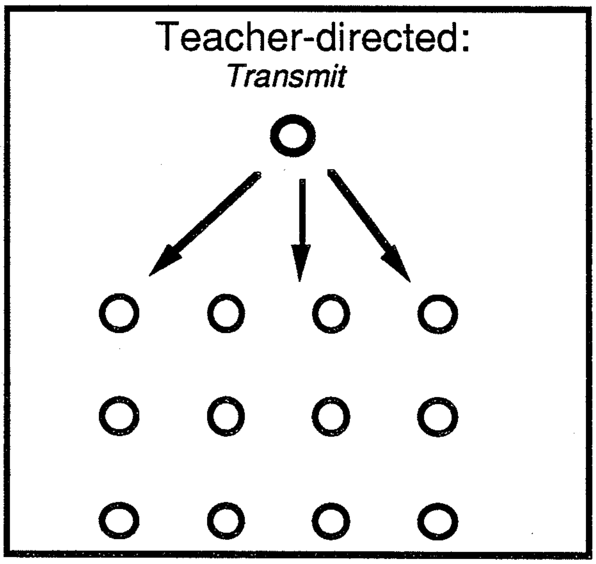
Aspect 1: *The evolution of the Education System* As with any viable system, our system of formal education is evolving over time. The last several decades have seen numerous innovative experiments in educational process and technology. Open classrooms, computer-aided instruction, and interdisciplinary course offerings are but a few of the initiatives that have, and are, being tried. It is my perception that the time now is ripe for three evolutionary threads to "come together", fusing to form a new learning gestalt. The three threads, as illustrated at left, are: *educational process*, *thinking paradigm*, and *learning tools.*



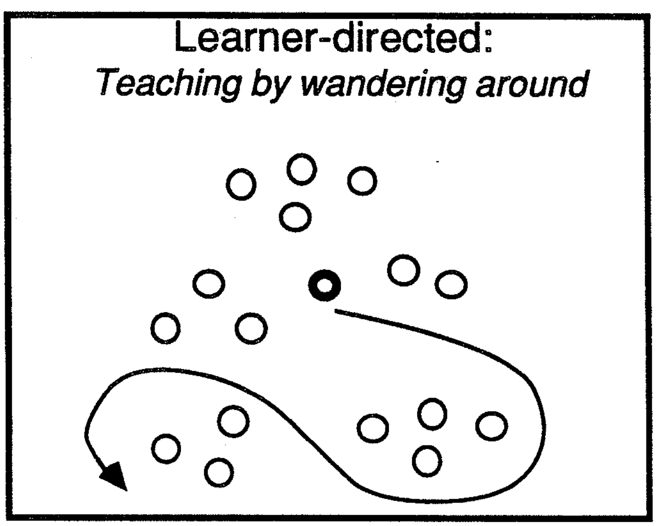
The evolutionary fusing of these three threads can successfully create a *permanent* change in the way people learn. The evolution of each thread, taken independently, can not.

Thread 1: Educational process I will refer to the newly emerging educational process as *Learner-directed learning*. I like this phrase because it positions the process in sharp relief against the process which has dominated for at least the last two hundred years. This, currently dominant, process I'll refer to as *teacher-directed learning*.

We are all, to varying degrees, products of a teacher-directed learning process. In this process, the classroom is arranged with students facing front -- be they arrayed in rows, or nested "U's". At the front is "Herr Professor". Herr Professor's job is to transmit what he or she "knows" to the students. The students' job is to "take in" as much of this knowledge transmission as possible. This is why it's important for students to "be quiet" and pay attention in the classroom. A schematic representation of the teacher-directed process appears below.



It's important to reveal the implicit assumption about learning which underlies a teacher-directed educational process. It is that learning is primarily an *assimilation* process. This assumption, in turn, defines appropriate roles for both teacher and student. Teacher is transmitter, or content dispenser. Student is receiver, or content receptacle. The objective of the educational process then also becomes easy to define. It is for the teacher to "fill up" the student. Measuring performance in this system is straight-forward. Simply ask the student to *re-transmit* what has been previously transmitted by the teacher. If the student can "dump" a full load, they are performing well. It's interesting to note that the teacher-directed process tacitly assumes that the students do not have much to contribute to each other's learning experience. Otherwise, they would not be arrayed in a physical arrangement in which they face the back of each other's heads.



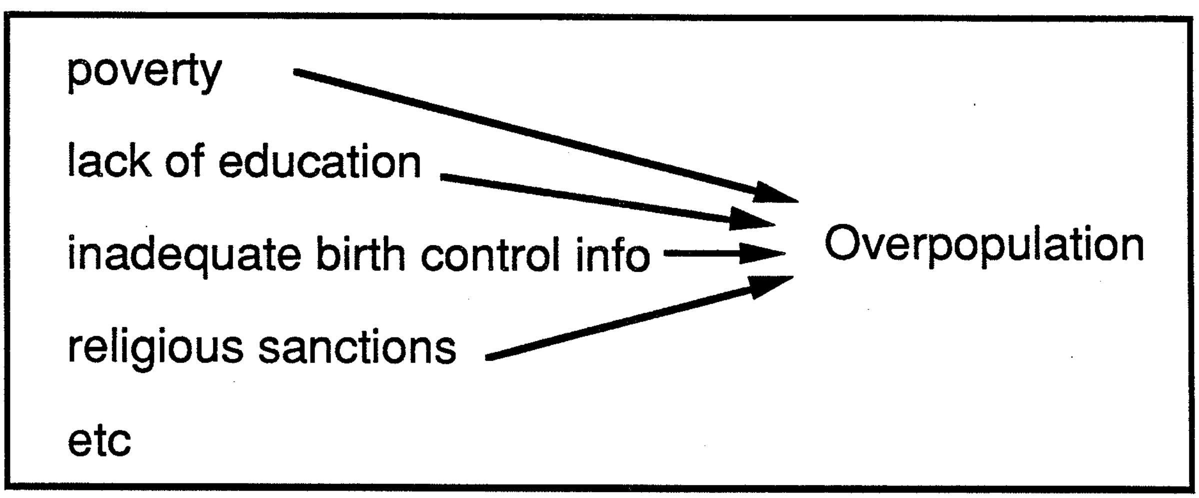
Contrast the teacher-directed process with what unfolds in a *learner-directed* approach, illustrated at left. The learner-directed approach is founded on the assumption that learning is fundamentally a *constructive*, rather than an *assimilative*, process. This means that to learn, the student must *reconstruct* what is being "taken in". Meaning and understanding are "making" processes, not "imbibing" processes. Extending the assumption leads to the conclusion that because there are many strategies for "making", learning can not be standardized. People construct in *different* ways, at *different* paces and in *different* sequences. Construction also is an active process. Being quiet and listening often can be antithetical to constructionist activity. Both teacher and learner, in this process, have new roles. Teacher now is charged with providing materials and alternative strategies for "constructing". In a sense, they create the building environment. Once the "building process" begins, they "wander around" playing the role of project manager -- keeping the process on track, but not doing the construction. Students are the construction workers. They design and then construct the knowledge edifice. And, like construction crews, they often can accomplish more, reaping more enjoyment in the process, by working in teams rather then alone.

In order for a learner-directed approach to work, it is essential that both teachers and students rethink their roles and respective contributions to the learning process. Teachers must be willing to abdicate their position as "all knowing" fonts of knowledge and wisdom. Students, in turn, must be willing to take personal responsibility for their learning process. Students must also learn to *cooperate* with each other as learning partners, rather than viewing fellow students as competitors in a zero sum grade-game. These are easy words to write. The shifts in perspective and process needed to bring these changes about, however, are quite profound! Fortunately, the benefits that appear to be achievable -- from looking at the results of some experiments in several learner-directed processes -- promise to be equally profound.

To begin with, the echo of the age-old question -- *why do we have to learn this?* -- is likely to cease reverberating through the halls of our institutions of formal learning. The active learning process will provide an outlet for the inherent need that all humans have for activity. The cooperation involved will model the very processes needed to live in an increasingly interdependent world community. And, all these gains can be achieved with no necessary forfeiture of content assimilation, because when students can see the *why*, content assimilation becomes a means to an end -- rather than an end in itself. There are thus many "free lunches" to be eaten here. We have only to avail ourselves of the opportunity. Availing, however, will require not only the profound shifts in role, administrative stucture, and performance measurement already alluded to, but in addition that the two other threads -- thinking paradigm and learning tools -- also "come together". No mean feat. Let's now look briefly at the other two threads.

Thread 2: Thinking Paradigm The first of the two is thinking paradigm. It's very difficult to see what you use to see. But that's what is involved in confronting your thinking paradigm. It's the water you swim in, so pervasive it's completely transparent. To bring it to front, try answering the following question: *What is causing the overpopulation problem being faced in so many countries in the world today?* Take a moment to jot down a few thoughts before proceeding.

If you took the time to record your thoughts, I'll bet they took the form of a list. If you reflect on the structure of the mental modeling process that generated this "laundry list", I think you'll find that it looks something like this:



I like to refer to the mental modeling process that produces such lists as "laundry list thinking". I think you'll find it to be the dominant thinking paradigm in most of the Western world today. If you ask most Westerners (and a good number of Easterners, too) a "what causes what?" type question, you are very likely to get a laundry list of causal "factors" in response. Implicitly, people also are weighting each of the factors in the list. This one is most important. This is second, and so on. This brand of mental modeling has been given analytical expression as a multiple regression equation. Many of us are familiar with this type of expression:

$$y = f(a_1X_1 + a_2X_2 + \ldots a_iX_i)$$

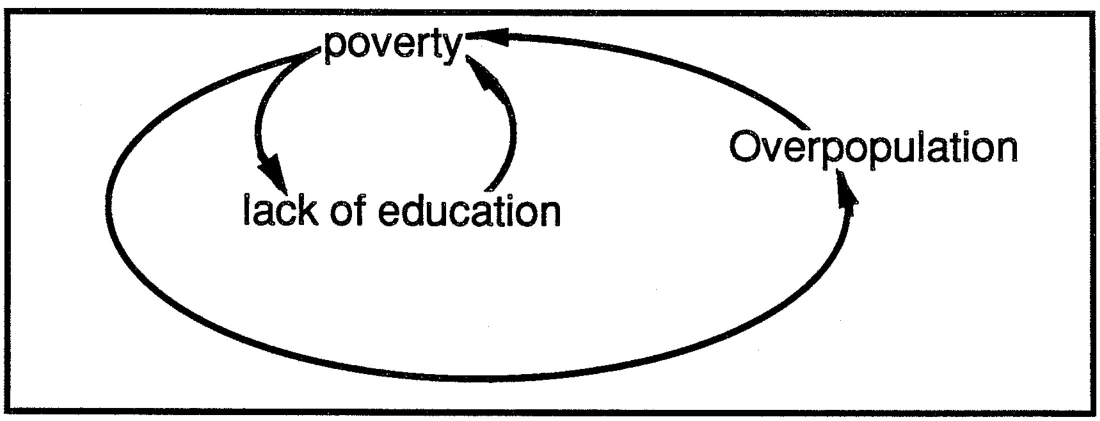
where:

- y is the dependent variable
- X_i are the independent variables
- a_i are the coefficients (or weighting factors) for each of the independent variables

Notice that the implicit assumptions in the laundry list thinking process are that: (1) each factor contributes as a cause to the "effect"; i.e., causality runs "one way", (2) each factor acts *independently*, (3) the weighting of each factor is fixed, and (4) the way in which each factor works to cause the effect is left implicit (represented only by the sign of the "alphas"; i.e., this factor has a positive or a negative influence).

The Systems Thinking paradigm offers alternatives to each of these assumptions. First, according to this paradigm, each of the "causes" is linked in a *circular process* to both the "effect" as well as to each of the other "causes". Systems Thinkers refer to such circular processes as "feedback loops". The diagram shown below illustrates a few such loops.

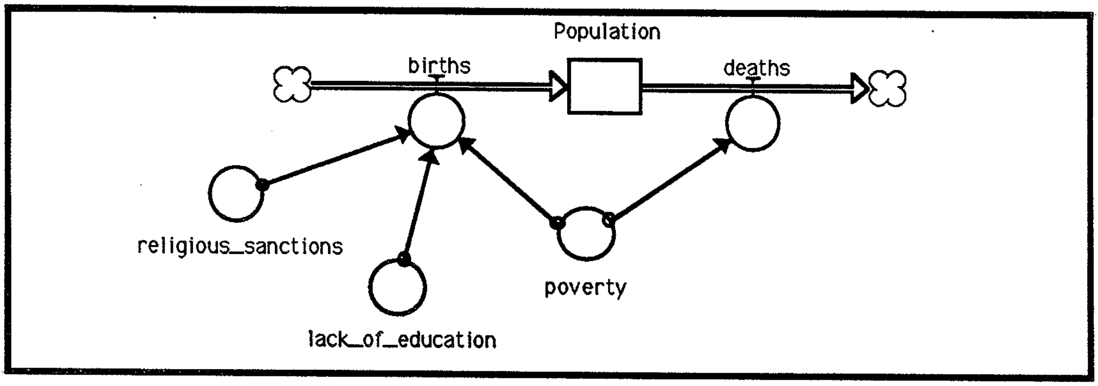
The shift from one-way to circular causality, and from independent factors to interdependent relationships, is a profound one. In effect, it is a shift from viewing the world as a set of static, stimulus/response relationships, to viewing it as an ongoing, interdependent, self-sustaining, dynamic process. Yes, that's a mouthful. It also will cause a students to think in a very different way about what is going on in the world around them.



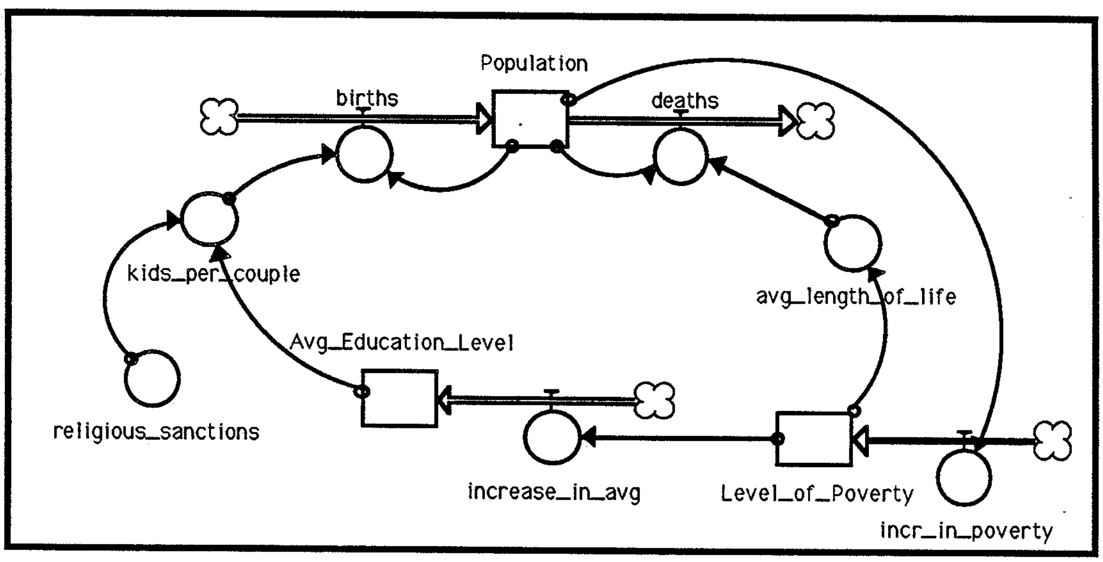
The third assumption implicit in the laundry list paradigm is that the "factors" have a static weighting. By contrast, in the systems thinking view, as the diagram at right suggests, the strength of the closed-loop relationships is assumed to wax and wane over time. Some loops will dominate at first. Other loops then will "take over". And, so on. Therefore, addressing a problem is not seen as a one-shot deal. Rather it is considered necessary to think in terms of ongoing, interdependent relationships whose strengths are varying over time -- in part in response to interventions that may have been implemented into the system.

The final assumption associated with laundry list thinking is that correlation is good enough for explaining how a system works. The systems thinking paradigm challenges this regression analysis approach, offering in its place *operational* models of how things work. Thus, for someone steeped in the systems thinking paradigm, it would not be enough to identify the factors that are correlated with "overpopulation". Instead, it would be necessary to actually offer an operational explanation for how overpopulation is generated. The contrast between correlational and operational models of the overpopulation process is illustrated in the diagrams below.

A correlational model



An operational model



The Systems Thinking *thinking paradigm,* when combined with a learner-directed learning *educational process* will breed students who are hungry for understanding how things *really* work, and who will continually be looking for how these workings might change over time as a consequence of shifts in the relative strengths of the underlying dynamic relationships.

Thread 3: Learning Tools To fully meld a learner-directed learning process with the systems thinking paradigm, it is essential to have the right set of learning tools available for classroom and out-of-classroom use. The tools of a teacher-directed, laundry list process -- textbooks and blackboards -- will play a smaller role in a non-transmit, active learning process. Textbooks operate, in effect, as purveyors of "silent lectures". Students read them, for the most part, for the same reason they currently go to class -- to assimilate content. On blackboards teachers can chart static relationships and display lists. However, blackboards are not well suited to analyzing a system's dynamics. To support an inquiry-oriented, learner-directed learning process, textbooks and blackboards must share the stage with an emerging tool: *the personal computer.* The personal computer, with its rapidly expanding sound and graphic animation capabilities, holds the potential for effectively compressing space and time. As such, these devices can serve as personal theaters in which the aforedescribed "virtual realities" can be played out. Students literally can have the experience of wandering around in both space and time, stashing content -- which has been embedded in appropriate nooks within the electronically-based learning environment -- into their "intellectual knapsacks" as they go. And, the content needn't be limited to "facts". Video segments, sounds, animations, puzzles, and all other forms of intellectually stimulating challenge are fair game. What's more, the wandering needn't be choreographed by a teacher. Both the pace and sequence of discovery can be left under the control of the individual learner, or group of learners.

In order to elevate a *learning environment* above the status of "video game", it is essential that it be equipped with the capacity for enabling learners to "understand why". Without this capacity, the interplay between learner and computer can too easily deteriorate into "beat the machine". It is encouraging to see that even with today's relatively primitive software tools (Richmond; Peterson; Vescuso, 1987; Peterson, 1990), a few truly excellent learning environments have been created, and are now in use (Draper, 1990; Peterson, 1990). The results have been extremely promising! Students who previously had "gotten off the bus", tended to "get back on". The opportunity to design something (like, for example, a mammal, a state park, or a policy for managing an ecosystem) in a learning environment, in effect, seemed to reset the counters -- giving all students a chance to succeed once again. Motivation was high, and hence disciplinary issues for the most part evaporated. Students assimilated content at higher rates, in several cases doing "research" (on their own!) in order to be able to do a better job in their design project. At the same time, depth of understanding of the concepts increased, and students' capacity for "critical thinking" was enhanced. Students began to think in terms of the long-run, as well as the immediate-run, implications of their decisions and actions. They began to anticipate the second and third-order impacts of their choices.

These results begin to suggest what is possible when a new learning gestalt comes together. But, even when all three threads -- educational process, thinking paradigm, and learning tools -- within a particular educational setting are ripe for fusion, there remains the issue of how to bring teachers up to speed in the underlying framework, process, and technologies of Systems Thinking. Let's begin by emphasizing that is *not* reasonable to expect teachers, on a wide scale, to stop what they're doing and move en masse to one or more of the institutions of higher learning that offer formal degrees in System Dynamics. Teachers, like most other people, are very busy. And, many could not secure the financial resources, even if they *did* have the time. Furthermore, there is not sufficient System Dynamics teaching capacity to process the demand! So, what then can be done to facilitate the fusion process when things are ready to fuse?

Aspect 2: ***Transferring Systems framework, process & tools*** I taught System Dynamics in the Thayer School of Engineering at Dartmouth College for nine years. During this time, I experienced considerable frustration at the fact that after three (or more) courses, even the good Master's student ("good", in this case, being a pretty select breed!) often encountered considerable difficulty in constructing and analyzing a model from scratch come thesis time. This being the case, what hope was there, I used to muse, for any widespread dissemination of Systems Thinking?

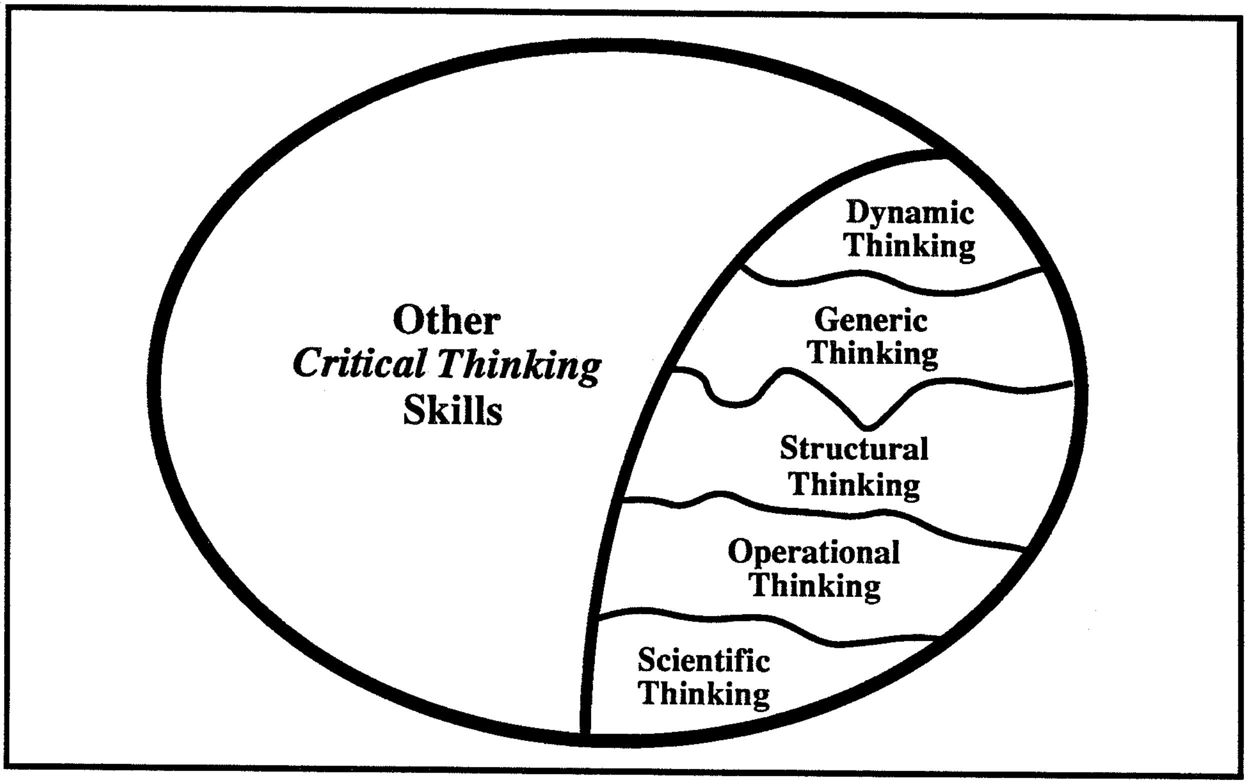
Since leaving Dartmouth three years ago, my colleagues and I at High Performance Systems have embarked upon a mission designed to answer the question: *just how far is it possible to go in cutting the up-to-speed time for the serious, yet not whiz bang, pilgrim?* Now, after offering more than fifty Workshops for educators, business folk, and all manner in between -- both in the

US and abroad -- I believe that I can begin to shed some light on an answer to this question. The answer is: *pretty damn far!* In recent Workshops, after 21/2 days, participants had produced models -- from scratch -- which addressed issues of their own choosing. The models were initialized in steady-state, had been subjected to a rigorous testing program to establish robustness, and in many cases did a credible job of replicating the observed behavior pattern of interest. The quality of the better models, in terms of their "tightness" and insight-generation capacity, was equivalent to what I used to receive from a good Master's thesis effort. How was this achieved?

First of all, over the three year period, we carefully monitored performance and continually fed back the results. We maintained no "attachment" to what we had done before. Indeed, we turned over our curriculum materials and process *at least 50 times* each (and continue to do so). My intention here is not to summarize this closed-loop evolutionary process. Instead, I wish to stand back from the process, and to focus on what we discovered to be the most fundamental gait to learning productivity. Simply stated, it is *cognitive overload.*

What has become apparent over the course of the last three years' workshops is that doing good Systems Thinking means operating on at least *five* thinking tracks *simultaneously*. This would be difficult, even if these tracks were familiar ways of thinking. But, they're not! And the result, in the vast majority of cases, is cognitive overload. Nevertheless, we've found that it is possible to take certain steps which can prevent people from becoming overloaded. Specifically, you can: (1) tell people that they're going to be asked to juggle multiple thinking tracks, simultaneously (2) be explicit about what these tracks are, and (3) align the curricular progression so as to sequentially develop the skills associated with *one* thinking skill at a time.

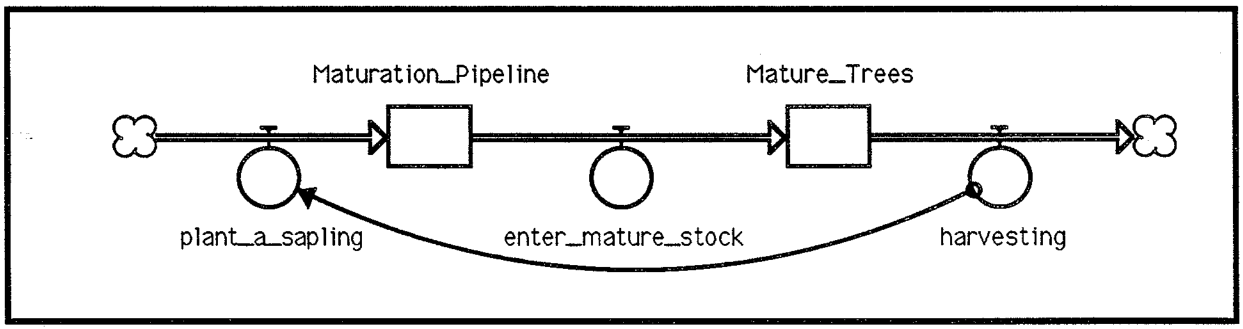
It helps to begin by placing the five systems thinking skills into a broader context. That context, in Education, seems most appropriately labeled "Critical Thinking Skills". The five tracks which I would construe as constituting systems thinking skills are depicted in the diagram below.



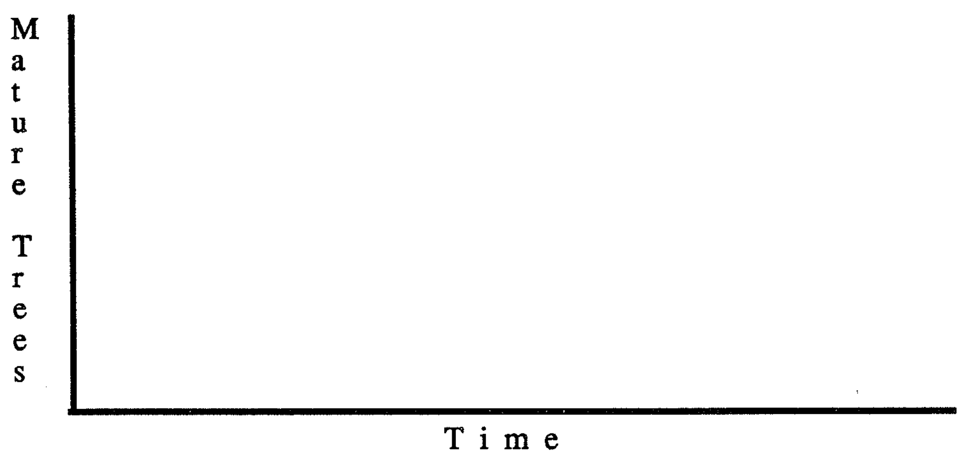
Critical Thinking Skills: *The Systems Thinking Piece*

I now will briefly discuss each of the five systems thinking skills in turn.

Skill 1: Dynamic Thinking Dynamic thinking is the ability to see and to deduce *behavior patterns* rather than focusing on, and seeking to predict, events. It's thinking about phenomena as resulting from ongoing circular processes unfolding through time, rather than as the result of a set of "factors". Dynamic thinking skills are honed by having people trace out patterns of behavior which change over time, and by thinking through the underlying closed-loop processes which are cycling to produce particular "events". Having students think about the processes that produce an earthquake, or that generated the events in Tienneman Square, the smashing of the Berlin Wall, or the fall of Nicolae Ceaucescu would be good exercises for developing dynamic thinking skills. Causal loop diagrams are a nice technology to use in developing a person's ability to think dynamically. Also very helpful is the use of simple models in real-time exercises in which students are asked to hypothesize what behavior pattern will result when a particular system is "disturbed" in a particular way. As an illustration of this kind of exercise, consider the simple system depicted below:



In this system, Mature Trees are harvested. Each time a Mature Tree is removed via harvesting, a sapling is *instantaneously* planted to replace it. Saplings take exactly 6 time periods to pass through the Maturation Pipeline (entering the Mature Tree stock). *All* saplings mature (none die, all germinate). Given these structural assumptions, next assume the system is initially in steady-state. This means that: (1) mature trees are being harvested at the same rate that they're being planted (by definition, this is true), and (2) that the maturation process "pipeline" is primed up such that trees are entering the Mature Tree stock at this same rate. Thus, both the stock of Mature Trees, and the number of trees in the Maturation Pipeline, are constant. Now, suppose that the harvest rate all of a sudden "steps up" to a new higher level, and then remains there forever. What pattern do you think the stock of Mature Trees will trace over time in response to this permanent step-increase in the harvest rate? Sketch your guess on the axis provided below.



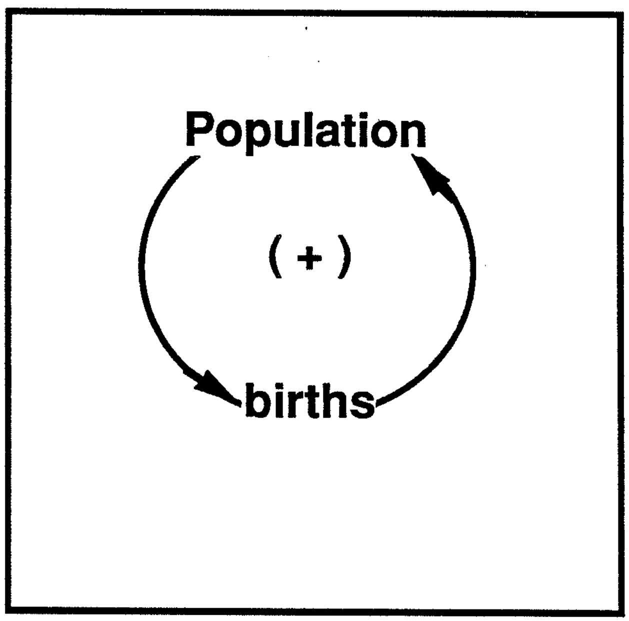
In our experience, with widely diverse audiences (across education levels, occupations, age, and cultures), only about 20% of people who guess at the answer guess correctly! This says something about the level of our dynamic thinking skills. It also says something about the potential for an extremely fruitful union of computer and human. Computers could never construct, or "understand", the preceding illustration. However, *100%* of the computer population will correctly deduce the dynamic pattern of behavior that the Mature Tree stock will trace in response to the step-increase in the harvest rate. Combining the human being's ability for making meaningful "structure", with the computer's ability for correctly tracing out the dynamic behavior patterns implied by that structure, holds great promise for leveraging our capacity for addressing the set of intractable problems previewed at the outset of this paper.

The correct answer to the illustration, by the way, is that the Mature Tree stock will decline linearly for six time periods. It then will level off and remain at this lower level *forever.* If you are having trouble understanding why this is true, I suggest that you trace out the pattern charted by each of the three flows in the system, following the step-increase in harvesting. Then, think about what will happen to the Mature Tree stock when this pattern of flows unfolds.

Skill 2: Generic Thinking Just as most people are captivated by "events", they are similarly generally locked into thinking in terms of specifics. Thus, for example, Gorbachev is seen as the man who brought glasnost and peristroika to the Soviet Union. He's also the man who allowed freedom to ring out in many of the Soviet satellites. But is it Gorbachev, or is freedom an idea whose time has come? Similarly, was it Hitler? Napolean? Joan of Arc? Martin Luther King? And, so on. The notion of thinking generically rather than specifically does not apply only to history. Seeing the commonality in the underlying feedback loop relationships which generate a predator-prey cycle, a manic-depressive swing, the oscillation in an L-C circuit, and a business cycle, illustrates how generic thinking can be applied to virtually any substantive arena.

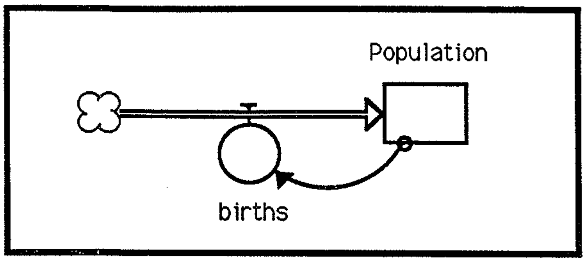
To develop generic thinking skills, people can work with the series of generic structures which progress from those which generate simple exponential growth and decay, through S-shaped growth, to overshoot/collapse and oscillation (Richmond; Peterson;Vescuso, 1987). They also can do exercises with the classic "policy insensitivity" structures (e.g., Shifting the Burden to the Intervener, Floating Goal, First Response in the Wrong Direction, Promotion Chain, etc) (Richmond, 1985).

Skill 3: Structural Thinking Structural Thinking is a one of the most disciplined of the systems thinking tracks. It's here that people must think in terms of units-of-measure, or dimensions. Physical conservation laws are rigorously adhered to in this domain. The distinction between a stock and a flow is emphasized.

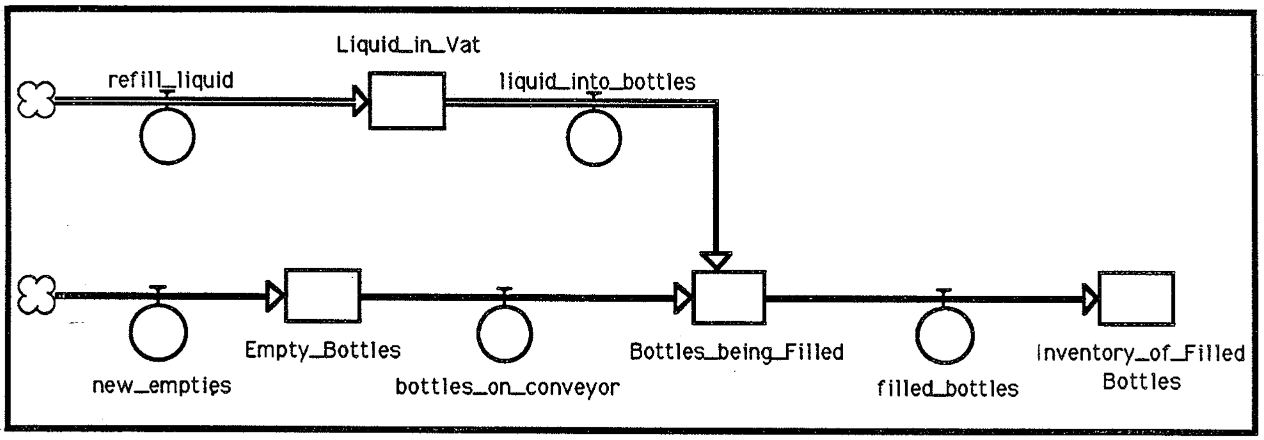


To catch a glimmer of the kind of skill being developed here, consider the simple causal loop diagram shown at right. The notion here is a simple, intuitive one -- one that would work pretty well if you were preceding along the Dynamic Thinking track. Beginning with births, the diagram says simply that as births increase Population increases. And, as Population increases births follow suit. This is a simple positive feedback loop process. Left unchecked, it will generate an exponential increase in the population over time.

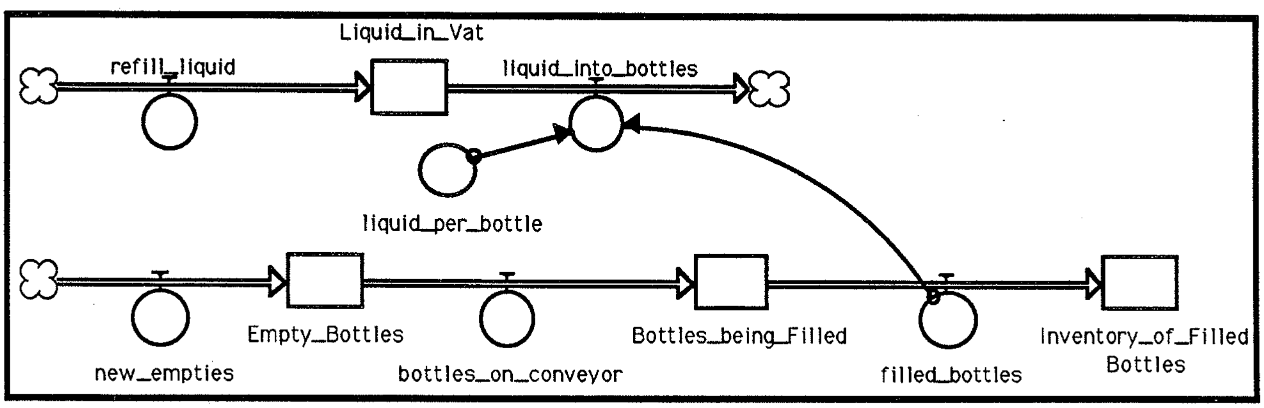
When the same two variables are represented using a structural diagram, a subtle, but important dynamic distinction between the two variables becomes apparent. This distinction is depicted in the diagram which appears below. The same positive feedback process that was depicted in the causal loop diagram is shown here. And, once again, we can see that if births increase, Population would follow suit.



However, now return to the causal loop diagram and run the thought experiment in reverse. That is, begin by *decreasing* births. According to the causal loop diagram, a decrease in births would result in a *decrease* in Population. Clearly this is not necessarily true. Population would only decrease, following a decrease in births, if births fell to a level *below* deaths. The causal loop diagram, a tool for engaging in Dynamic Thinking, is thus not well-suited to doing Structural Thinking. That's why the Structural Diagram was invented. As you can see by looking at the simple structural diagram above, a decrease in births will only serve to slow the rate at which Population is increasing! When engaging in structural thinking, such subtle distinctions (which can be very important in understanding dynamics) must be made.



Another simple example will further illustrate the rigor associated with the Structural Thinking track. Consider the following diagram:



In this alternative representation, notice that the flow of liquid and the flow of bottles are kept *distinct*. This is not the case in the first, more intuitive representation. If you took a snapshot of the actual process, the picture would more closely resemble the first diagram. The fact is that liquid really does pour *into* bottles. However, the reality of the situation, from a units-of-measure standpoint is that you still have two quantities: bottles and liquid. If you flowed liquid into bottles in the model, you'd end up with a very strange quantity in the box labeled "Bottles being Filled". That quantity would have the *mixed* units of measure, bottle-liters (or some such).

When engaging in Structural Thinking, it is essential to maintain units-of-measure integrity within each Stock/flow sub-system. "Loose" notions, like "I put a lot of effort into that project", and "I'll give you all my love" simply "don't compute" when doing Structural Thinking. Quantities that flow into a stock must have the *same* units of measure as that stock. Maintaining unit integrity ensures that physical conservation of all quantities is maintained. This, in turn, keeps you from getting something for nothing. It also exerts a very strong discipline and preciseness on the thinking process.

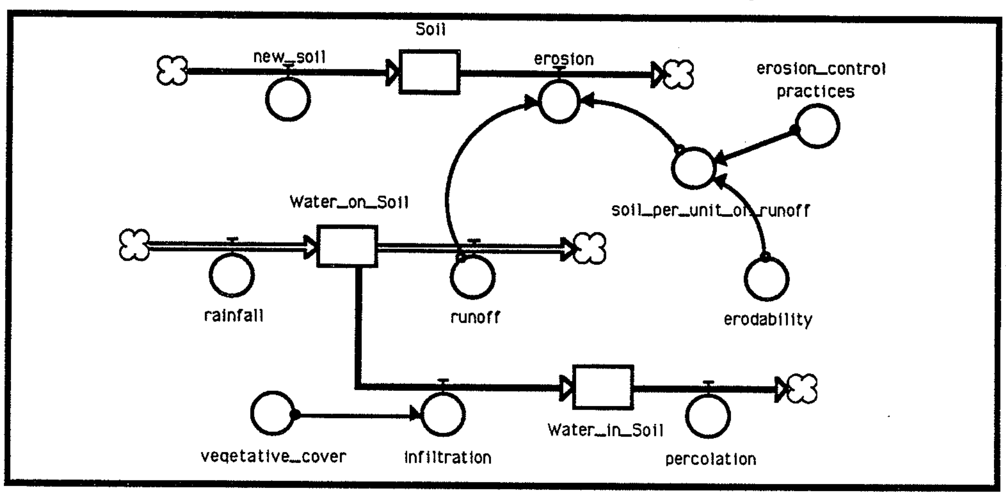
We have evolved a set of Stock/flow koans (Zen paradoxes) that are quite effective in facilitating peoples' attempts to internalize the distinction between stocks and flows, as well as providing practice in maintaining unit-of-measure integrity.

Skill 4: Operational Thinking Operational Thinking goes hand in hand with Structural Thinking. Thinking operationally means thinking in terms of how things *really work* -- not how they theoretically work, or how you might fashion a bit of algebra capable of generating realistic-looking output behavior, but how they *really* work. One of my favorite examples of the distinction between operational and non-operational thinking is provided by the "universal soil loss equation" -- this equation expresses a "fundamental law" in soil physics. The equation, which is used to predict the volume of erosion that will occur on a given parcel of land, can be represented as:

$$Erosion = RKLSCP$$

where:
R is rainfall
K is soil erodability
L is slope length
S is slope gradient
C is vegetative coverage
P is erosion control practices

Now, no self-respecting soil particle solves this equation before it rolls on down the hill! In fact, the erosion process, if you were to ask how it really works, probably would look more like this:



A second brief example should make it clear what Operational Thinking is all about. A popular economic journal published the research of a noted economist who had developed a very sophisticated econometric model designed to predict milk production in the US. The model contained a raft of macroeconomic variables woven together in a set of complex equations. But nowhere in that model did cows appear! If you ask how milk production actually is generated, you'll discover that cows are absolutely essential to the process. If you were thinking operationally about milk production, you'd be centering your thinking around cows. You'd focus on the real rhythms associated with farmers' decisions to increase and decrease herd size, the relationships governing milk productivity per cow, and so on.

Operational Thinking grounds students in reality. It also tends to be perceived as relevant -- because the student is thinking about it *like it really is*, rather than dealing with abstractions which may bear little relationship to what's going on in reality. It's easy to create exercises that develop Operational Thinking. Simply look around at real-world processes (like learning, becoming friends, experiencing peer pressure, pollution, drug or alcohol addiction, etc) and ask: *How do these processes really work?* Let the students diagram their resulting observations. Then, have them challenge each other's depictions, asking: *Is this really how it works?*

Skill 5: Scientific Thinking The final component of Systems Thinking that we have identified is Scientific Thinking. Let me begin by saying what Scientific Thinking is *not*. My definition of Scientific Thinking has *virtually nothing* to do with absolute numerical measurement. Too often science is taken to be synonymous with "measuring precisely". To me, Scientific Thinking has something more to do with *quantification* than *measurement*. Again, the two are not synonymous. There are very few things that can be measured unambiguously. Length, width, height, concentration, magnitude, and velocity offer a few examples. But think of all the things that can not be measured precisely. How much wisdom you possess. How nice a person you are. What the quality of life in a city or country is. How good you feel. What it's like to go to a particular school. How hungry you are. How much you love someone. How much confidence or self esteem you have. How frustrated you feel. I think you'd agree that all of the aforementioned non-measureables are important to you. Yet, no one can measure them in any absolute numerical sense. *But you can quantify all of them!* It's simple, you pick a scale -- say, 0 - 100 -- and then you assign a value. 0 means "the absence of". 100 means the "maximum possible amount". Because you've assigned a scale does mean that you could specify exactly what any of these values are in the real system. It means only that you've established a rigorous convention for thinking about the dynamics of the variable. You now can ask questions like : *What keeps Self Confiidence from rising above 100?* Since you've defined 100 as the "max possible", then some processes must exist in the real system which prevent this accumulation for overflowing! Because you've been rigorous (scientific) about your quantification, you now have the opportunity to think rigorously about the dynamics of the variable.

But quantification is not all there is to Scientific Thinking. Thinking scientifically also means being rigorous about testing hypotheses. This process begins by always ensuring that students in fact have a hypothesis to test. Once again, in the absence of an *a priori* hypothesis, the experimentation process can easily degrade into a "video game". People simply will flail away trying to get one of the Super Mario Brothers to the Princess. Insisting upon having an explicit hypothesis to test before engaging in any simulation activity helps to guard against the video game syndrome. The hypothesis testing process itself also needs to be informed by Scientific Thinking. People thinking scientifically modify only one thing at a time -- holding all else constant. They also test their models from steady-state, using idealized inputs to call forth "natural frequency responses". This set of rigorous, hypothesis-testing concepts really is at the heart of what I mean by Scientific Thinking.

Exercises abound in which simple, already-constructed models are used as the basis for a disciplined testing regimen. These exercises can be used to bolster Scientific Thinking capacity.

The Five Track Melee When you become aware that doing good Systems Thinking entails working on at least these five tracks *simultaneously,* it becomes a lot easier to understand why people trying to learn this framework often go on overload! When these tracks are explicitly recognized, and separate attention is paid to developing each skill, the resulting bite-size makes the fare much more digestible. You can consume quite a large chunk of food if you do it in a succession of small bites. You will gag if you try to swallow it whole! We've found that explicitly separating these five tracks, and then attending to skill development in each, *greatly* increases learning productivity.

Summary

The coupling between the various physical, social, and ecologic sub-systems which go to make up our reality is tightening. There is indeed less and less away, both spatially *and* temporally, to throw things into. Unfortunately, the evolution of our thinking capabilities has not kept pace with this growing level of interdependency. The consequence is that the problems we now face are stubbornly resistant to our interventions. To "get back in the footrace", we will need to coherently evolve our educational system along three dimensions: *educational process, thinking paradigm,* and *learning tools.* At the nexus of these three threads is a learner-directed learning process in which students will use personal computer-based *learning environments* to build their intuition and understanding for complex interdependent systems by participating in "virtual reality"-based experiences. One of the principal factors gaiting this exciting evolution is the capacity for transferring the Systems Thinking framework to educators, and then on to their students. By seeing Systems Thinking as lying within the broader context of Critical Thinking Skills, and then recognizing the multi-faceted nature of the thinking skills involved in Systems Thinking, we can greatly reduce the time that it takes for people to internalize this framework. This is an extraordinarily exciting time to be in the education profession!

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