

**Writing and Modeling:
using a notebook to learn about system dynamics**

by

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Writing and Modeling Series

Volume I: using a notebook to learn about system dynamics

Volume II: writing scientific papers to accompany dynamic models (Summer '03)

Volume III: writing scenarios to capture systems understanding (Fall '03)

Volume IV: composing interactive stories with STELLA (Fall '04)

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Abstract

The intellectual step of distinguishing a stock from a flow to constructing system dynamics models is awkward and many stumble, but using a notebook in this early stage can help students (and teachers) make these strides with some ease and purpose. Teachers will find the necessary guidelines for using a systems notebook as well as a long list of writing and mapping exercises that integrates the writing process with system dynamics instruction. These guidelines and exercises are especially helpful for middle and high school students who are building some early confidence in basic stock and flow mapping as well as those students ready for model building and testing.

The writing process offers not only a good metaphor for model building; it also offers a means to composing the models themselves—a clearly told story will help the model builder, and a well built model will help the story teller.

Students discover they cannot write accurately and effectively without a sound understanding of the feedback, nor can they trace the model feature terribly well without having appropriate and consistent language. The more fluent students become at telling the story, the more facile they are at building the model.

Every page of a systems notebook reveals the mental model of its creator. These are what we wish to expose, to lay bare, to test, to evaluate, and ultimately to improve—we want students (and ourselves) to have better mental models.

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*Writing and Modeling:
using a notebook to learn about system dynamics*

*Good writing and good modeling go hand in hand.
Jay Forrester, 23 February 2000*

Writing wells up from a deep tradition in human thought and lifts the writer into a realm of creative, though disciplined, thought wherein various choices hold the author responsible for an idea called “story”—printed on a page, awaiting an audience. Before this, however, a writer reviews, revises, edits, rewrites whole scenes, possibly tossing out some story elements as he attempts to weave a seamless tale, what noted author John Gardner called the “fictive dream.” And then a reader accepts the dream, borne along in a plausible story that rings true and takes a reader to some place he had not been before.

Writing, with all its leaps and minutia, offers not only a ripe metaphor for building computer models, it also offers a means to compose the models themselves, a way to test them, to hone the model’s language, to edit its ideas and logic, to tell its compelling story. Indeed, composing a model without composing words may set the modeler adrift. It is for this reason that these notes are set down—some guidelines and hints for you and your students as you venture into the tangled beauty of system dynamics.

Keeping the students' work in notebooks

Writing is not hard. Just get paper and pencil, sit down, and write it as it occurs to you. The writing is easy—it's the occurring that's hard.

Stephen Leacock

George Richardson once reported that somewhere in Jay Forrester's house reside all the notebooks from Forrester's earliest days in system dynamics right up to the present—all his drawings, all his annotations, all his equations, all his essays into new territory, all his lucid writing. For a moment, we drenched ourselves in that thought: "Oh, to look at those books." And, so, our students should learn from the master: keep a notebook to capture *every* system dynamics thought.

A number of stationers make notebooks available, but these favorites I use in my English classes:

- Mead Composition Notebook, approximately 9" x 7", college-, wide-, or quad-ruled
- Scientific Notebook, approximately 8 "x 11"

They have a serious side to them: no spiral or glue binding. Go with a sewn binding. Of course, choose what you want, but I have always preferred that students compose in something closer to a book than a mere spiral notebook. Even binders, which allow considerable flexibility, do not have permanence, nor will they necessarily maintain the historical flow of a student's intellectual journey, a clearly important piece of their record.

Students will draw reference behaviors in time graphs, paste in short stories or excerpts from novels and identify stocks and flows, draw and annotate models, cut and paste news articles from all manner of periodicals, draw graphical converters and write the story of the line, draw multipliers—then defend or refute the line which defines it, amend their own models, zoom in on one sector of a model and elaborate, draw ALL the models that each student in the class may build, write equations and compose a story to

replicate it, record (or paste) graphical and tabular outputs and explain the results, compose questions, tell feedback tales, trace the influence of a multiplier on a single feedback loop, tell how loop dominance shifts as a system moves through time, paste in system jokes, compose drafts for SyM•Bowl papers. In short, students ought to commit some measure of systemic thought to paper EACH day. So it needs to be a big book.

Some students will want this to be a private place, but make it plain that the notebook is NOT a diary; rather, it is an intellectual record that has some measure of public access to the teacher and, possibly, classmates.

Organizing the notebook¹

- **Maintain an easily adaptable table of contents or index.** Many writers simply leave the first two or three pages blank (some choose the last pages), allowing the user to label each day’s entry with a brief descriptor so that models and ideas would be easy to find:

Date	Brief title	Pg#
Sep 12	Population model in equilibrium	6
Sep 15	Forrester quotation on feedback	8

- **Always date and label each entry.** Whatever index you establish is worthless without this information. Keeping a page-by-page record is as crucial as keeping the Table of Contents.
- **Be neat.** Someone else will need to read this, not the least of whom is the teacher. If a student’s handwriting borders on the illegible, ask for printed documents taped or glued in. Also, students will be reviewing their own work from time to time, so legibility is very important.
- **Each model entry must include a clear diagram and labeling.** This is just obvious. The continuous hand drawing and writing of *all* models or causal

loops or notes help students internalize these ideas. Drawing stocks and flows reinforces their ubiquity in the world.

- **Each model entry ought to include a reference behavior graph.** Some class assignments, as mentioned above, will include models from news items, and even these models will need graphs, even though they are thoughtful guesses. The model has *some* meaning alone, but the structure and its conceptual algebra come to life with a graph. Every entry that pairs a graph with a story stitches together these disparate fabrics.
- **Each graph ought to include a one- or two-sentence summary statement.** Before a note-creator turns a page past a graph, the meaning of the graph—its key lines, its abrupt shifts and plateaus—begin to fade from clarity. Every graph needs a narrative corollary.
- **Each model entry should include a one- or two-sentence summary statement.** George Richardson calls these “lessons-learned bullets,” a brief catalog of what’s important about the model. It’s the “so what?” of the model. The continuous practice of *narrating* some part of a model underwrites a young modeler’s capacity to learn the language of systems.
- **Leave space for later notations and teacher commentary.** This can easily be done by leaving a 1” to 2 “ margin on the right or left. Even students will want some notation space, since they may—months later—revisit the model and note additions or corrections.
- **Weekly summation.** One sentence, perhaps a question, that captures the day’s or week’s thoughts. You may encounter some resistance initially, but this will pay off as students start out *the next day*.

Notebook types

Notebook style, akin to fishing style, depends on the keeper (or the fisher). It also depends on the purpose. Here's a brief look at a few styles, though you will likely want your students to do a little of each. Each has its advantages.

- *The dialectic*: students record (or paste) information on the left-facing page only, leaving the right-facing page for commentary, using lines and arrows back to some particular item in the model or article. Essentially, the object studied is like a specimen, and notations made surround it. Some students use colored pens or pencils. This may be best with articles, models, or parts of models you would like students to think about for a while. Such entries are sometimes called reflective, or if you collect jargon, "metacognitive."
- *The historical record*: students record models, notes, data sequentially, completely, leaving annotation and organizational notes for later. It's good to ask students, say, once a week (or biweekly at the least) to revisit all the previous work and make summary notes. This method provides a detailed accounting of a semester's (or a year's) study. Therefore, *everything* should be in here: every model, every graph, every conclusion. Items or documents that do not fit ought to be filed in an easily accessible place.
- *The classic copybook*: students copy *verbatim* very sound models—diagrams, equations, graphs, all of it. The notion here is that writing is *visceral, sensual* as well as intellectual. Copy three pages of John Steinbeck's *The Grapes of Wrath* and your capacity to compose a good sentence improves. Imagine the impact of copying the *Urban1* model or Forrester's *World2?* I would not advise this in the first week, but, eventually, this is a valuable tool. *Special Note*: These must be handwritten! The pace of doing by hand forces the

copier to ingest the model methodically, to *feel* the connection drawn from, say, capital investment to pollution. And there is time to consider that connection. In the glory days of classical rhetoric, the copybook was the warm companion of monks and scholars throughout Christendom.

Helping students do this

- Most students are NOT in the habit of such painstaking and habitual note-taking. You will need to coax them. For instance, you might want to collect the notebooks every two or three days in the first two weeks just to move them along, keep the feedback swift and upbeat, and then back away to a more tolerable, biweekly regimen. They will come to thank you for it.
- Show them good examples. If students have a clear model, they have something concrete to emulate. This ALWAYS works.
- As you well know, modeling is an intensive exercise and students will need you to keep them calm. They will lose track of time and perhaps forget to compose the summaries. A gentle reminder that five minutes remain before the bell, for example, allows them time to collect themselves, note what's necessary, and perhaps compose a statement or question.
- Students will have (or ultimately establish) their own methods and preferences in the notebook, but initially you would do well to give considerable direction early so they at least have a clear method. After some familiarity with a common method, students could pursue their peculiar means (and they will, whether you release them or not).
- Pay close attention to commenting in the book. Occasionally, ask students to simply exchange notebooks among themselves, a habit that should

eventually come as second nature. See further comments in “Evaluating What Students Give You.”

As in all things, some thoughtful attention to minutiae early on will establish good habits of thought and pay off profoundly. Remember, these are minds and ideas at the beginning of new exercise—be gentle and uplifting.

Telling stories

It's all a matter of keeping my eyes open.
Annie Dillard

At a most primary level, students need to recognize a stock from a flow. This takes practice. From the outset, the teacher ought to present students with myriad opportunities to seize upon these recognitions: use articles from newspapers such as those from the Science section in *The New York Times* or The West section in Portland's *The Oregonian*. Students paste in the article and draw a stock/flow-feedback diagram, or perhaps a causal loop diagram, depicting the system as they see it. Such practice makes thinking explicit and can serve as an act of discovery: discerning stocks and flows clarifies thought and leads to insight. For obvious reasons, start with small articles, relatively apparent systems, and then ratchet up in complexity as the weeks go by. But don't be surprised if an ostensibly simple story becomes complex! Stock and flow diagrams, as well as their reference behavior graphs, are rich, leading to discussions that will make every social science teacher jealous of you.

Telling stories is a good habit to get into. Regardless of how simple a story may seem initially, just tell it. A good story has all the markings of a good model: a clear focus and some internal consistency. Here are two I tell every course:

Rain fell steadily for two hours; then a squall moved through, dumping huge amounts of rain in about 15 minutes. The storm drain overflowed.

and

Nick bothers Mr. Joy every time he talks, but Mr. Joy can usually take it. Some days Mr. Joy *can't* take it because the other students have been ridiculing him constantly. When Nick talks on such a day, Mr. Joy becomes enraged and throws chalk. Then, he's fine.

I tell these about a week or two apart. The second initially overwhelms them because students often see it as too complex. However, someone will come to the rescue and note that these two seemingly different stories carry a similar structure. Just how important is that? When students note the similarity of structures, this is cause for widespread jubilation; for when gold is struck at any time, halloo and shout: here, students have discovered that fabled lode, the generic or archetypal structure, a core model piece that transfers across disciplines.

We all know that any ostensibly simple system rapidly sends tendrils to other systems. And this is quite instructive, not only to students, but to any storyteller—you're on to something big when the story taps a source for another story. It is the sign of a well-told story and a well-built model.

If it comes to it, you may need to talk to yourself. Write brief stories in your notebook. Collect a dozen, two dozen three- to ten-sentence stories that convey apparent stock/flow-feedback structures. (See "Just Right Stories" in the next section.) Note them, for instance, as you walk around the block on a fall day: trees sloughing leaves—a leaf stock conveyed to another locale at a varying rate—students can certainly draw the reference behavior and a discussion might follow about a critical biota. Start with leaves and, if so desired, Chaucer and Frost will ensue.

Writing projects around the country give strong evidence in this key point: when teachers write with their students, student writing improves. Why? Teachers who write provide a model of thoughtfulness students can see; teachers and students are more likely to form the so-called, and much desired, "community of writers," wherein each contributes writing and criticism; and students, therefore, are even more likely to contribute their writing samples and writing judgments when there's a payoff; students see teachers as experienced writers rather than solely as reservoirs of writing knowledge meted out in daily lessons.

It is so, also, in modeling. Teachers who tell modeling stories, search out stock/flow-feedback stories in newspapers and magazines as well as the world around them, will engender students inclined to do the same. Since students will often work on independent projects, this practice of seeing systems on their own is crucial.

There are numerous writing analogs for modeling, but the upshot is this: the instructional emphasis on teaching the writing *process* over the writing *product* has gained acceptance because it does two things: it closely follows what actual writers do, and, it works—student writing improves. So, too, in teaching modeling.

Students will gain felicity as they tell systems stories. It is no surprise, of course, that the more stories one tells, the easier it is to tell them. You can likely see the feedback loop in your head. And the telling redounds in that other critical area—building computer models. In other words, storytelling—that most primal art form—informs and refines modeling, giving the teller and the modeler a *skill* in rendering structure to meaning, a *sensibility* about feedback relationships, and a *template* to discern patterns over time.

Just Right short stories for drawing small stock and flow diagrams

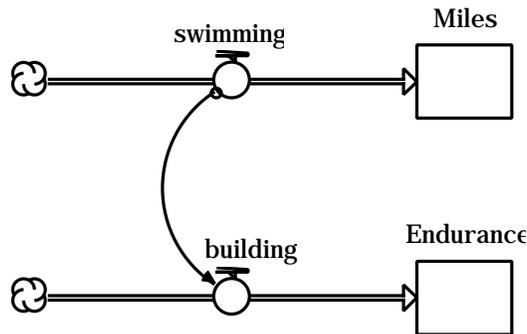
These fifteen “Just Right” stories are ideal class starters. Start class by writing one on the board and ask students to create a stock and flow diagram that captures it. It is wise to implore students to stick *primarily* to stocks and flows, to minimize converters and connectors. Doing so will keep students focused on the key elements in the system. Certainly, *some* use of connectors and converters is inevitable and even necessary to convey connections and feedback. True. However, the key to these exercises is stock and flow mapping.

Allow students a few minutes to draw, to talk, to compare their drawings, and then ask two or three students (with differing models, preferably) to draw their models on the board. Students should tell the story of their map, to include their decisions to leave some things in and some things out. Once done, ask other students to agree or disagree, but also to state their case on their disagreement. These discussions on the nature and assumptions on stock and flow construction help build up student felicity and understanding with maps.

You will note these stories are both universal and local; that is, most of them can be read and used in *any* class, and some of them are too local, but might easily be adapted to your purposes. For the narrow local stories, read them to get the gist and then change the story to fit your geography or political hot buttons. I include some *possible* solutions for a few just to get you started. Last, these are relatively easy to come up with, and you'll soon have a long list of your own.

1. Swimmers build endurance by swimming miles every day.

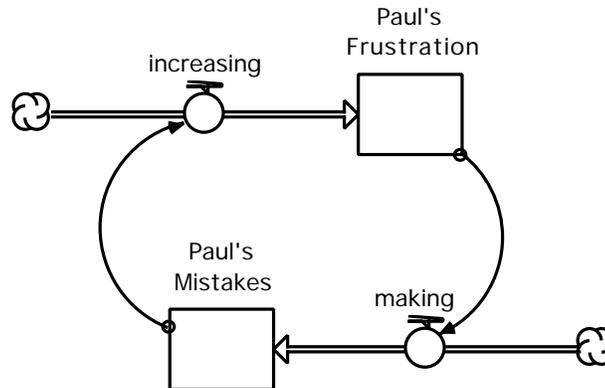
For example,



{An insightful student may see that an outflow from *Endurance* would make sense here. Let the student tell why.}

2. Paul gets frustrated a lot. The more frustrated he gets, the more mistakes he makes. The more mistakes he makes, the more frustrated he gets.

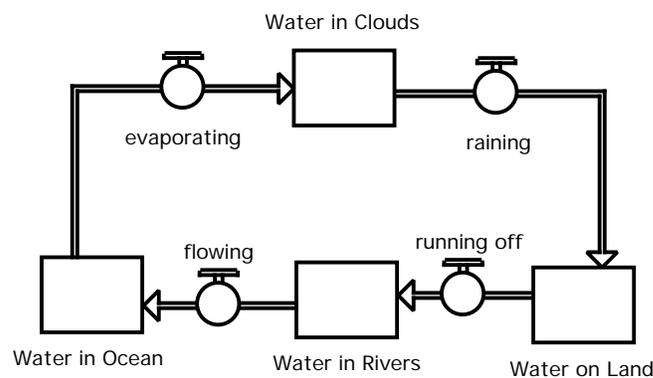
For example,



{Technically, there are intervening graphical functions between stocks and flows that control the rate based on the stock level. Depending on the expertise of your students, go there or avoid it. The key here is the stock to flow connection.}

3. The sun's energy evaporates water from the ocean, which then falls as rain on land, and then runs into rivers and back to the oceans.

For example,



{You will likely get some variations on this one. Keep students focused on the cycle and, in this early stage, do not worry overmuch about differing rates, except to acknowledge that they exist.}

4. It rained all day, water in the street draining into sumps. Then, a squall moved through, and in about ten minutes, the sump overflowed. Once the squall passed, the water drained and then light rain followed.
5. Mr. Joy's anger often increases because students continuously degrade him, but he manages to control it. One day, Max insulted him and it was more than Mr. Joy could bear. He yelled and threw chalk, but then he was fine.
6. Chris did the exercise dutifully for about two minutes. Then, as he grew bored, he started telling jokes and playing with software. I yelled at him, and he stopped . . . for a while. Then, he just did what he wanted.
7. As the school year goes on, more and more students cheat. Teachers remind students of the consequences of cheating; a few students are caught, but cheating seems to just go on.
8. Sheila's work excels, and her confidence increases. Her higher levels of confidence inspire further improvements in her work.
9. As average speed on a freeway increases, the State police set up more speed traps, which brings the average speed levels back down. (HPS-Inc.)
10. As fans stream into the stadium, they wait in lines at the turnstiles, always choosing the shortest line.
11. People have been moving into the Sunnyside area since Interstate 205, Kaiser Medical Center, and Clackamas Town Center were built 25 years ago. Even though house prices are high and traffic is horrible, people are still moving in.
12. The more homework Hercamer is assigned, the less he wants to do it.
13. "People move here for the view. But if people move here, we won't have the view anymore." (A frustrated Californian from the Central Valley, Fall 2002)
14. The more congested the traffic gets, the more likely we are to add some lanes. But, after we add lanes, it seems just as congested as ever.

15. Why is it that when I make minimum payments, I can never seem to make any headway on what I owe?

Finding stories

Let the fiction grow out of the land beneath your feet.
Willi Cather

Once your students *hear* stories and can decipher stocks and flows in a manner similar to deciphering setting or character or metaphors, they are then ready to search on their own. Jay Forrester is fond of a story about a young modeler who once told him that system dynamics had helped him read the newspaper. One of the byproducts of such reading is that it underscores the ubiquity of systems as well as the occasional gaping holes in the logic of some journalists or the people they are reporting on. Scott Guthrie (Wilson High School – Portland, Oregon) has used this specific tool extensively; his students, over time, garner a keener understanding of the *nature* of a stock and a flow. Further, George Richardson recently proposed that identifying stocks and flows in stories, whether as news or literature, comprises a foundational piece for system dynamics, *a skill set that children in primary grades can master*. Consequently, such a practice ought to be in *every* systems related course, whether in the sciences or the humanities.

Students at La Salle High School (Portland, Oregon), a Roman Catholic institution, take a junior religion course called Social Justice. A pervasive theme of that course, as distilled through centuries of Catholic social teaching, is the *common good*: sustaining the dignity of all humans in the face of social or political challenge. Most recently, the Catholic Bishops of the Pacific Northwest issued *The Columbia River Watershed: Realities and Possibilities*, a reflection on the Columbia River Basin as “sacred waters.” Juniors examined portions of that document and studied a few elements of the systems involved in that grand story encompassing British Columbia, Montana, Idaho, Washington and Oregon. From the mythos of Native American lore to the divisive

rhetoric of dam politics, each vignette of the overarching story of the Columbia carries downstream a variety of system structures, a current rich for discussion among students.

An effective means of getting students to this level of discernment is for them to do on their own what you began earlier, providing simple system stories from news sources. On a bi-weekly basis, for instance, students come to class with articles and a stock/flow-feedback drawing that they share with the class by drawing it on the chalkboard. All the other students draw the same diagram, leaving space below or on an opposing page for amendments, disagreements, and any notes. Once drawn, the presenter tells the story using the diagram, draws some conclusion about the article and/or the model, and then takes audience queries or assertions. Usually, sessions can occupy a full period, but do not worry whether this time spent has merit. It has. Any prolonged discussion using stocks, flows, and feedback loops is an acute intellectual exercise that hones a person's systems sensibility.

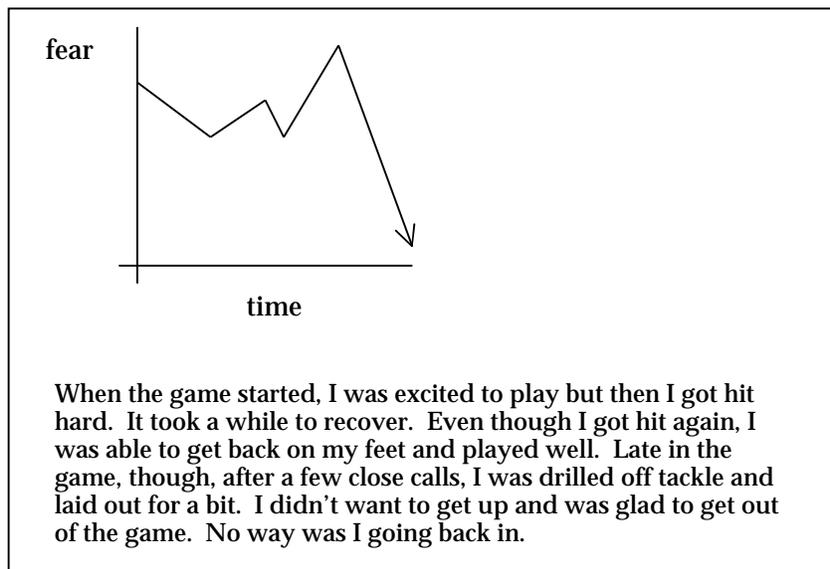
The happy alignment of storytelling and mathematics

Computers are often being used for what the computer does poorly and the human mind does well. At the same time the human mind is being used for what the human mind does poorly and the computer does well.

Jay Forrester, "Counterintuitive Behavior of Social Systems," 1971

Of all the unintended consequences of system dynamics instruction, this surprising alliance of storytelling and mathematics quickens the poetic impulse of this erstwhile math teacher disguised for 17 years as an English teacher. Years of dark frustration with grammar and stodgy literature instruction peel and curl away—here is the power of two disparate disciplines sharpened by each other, angled to cleave an idea.

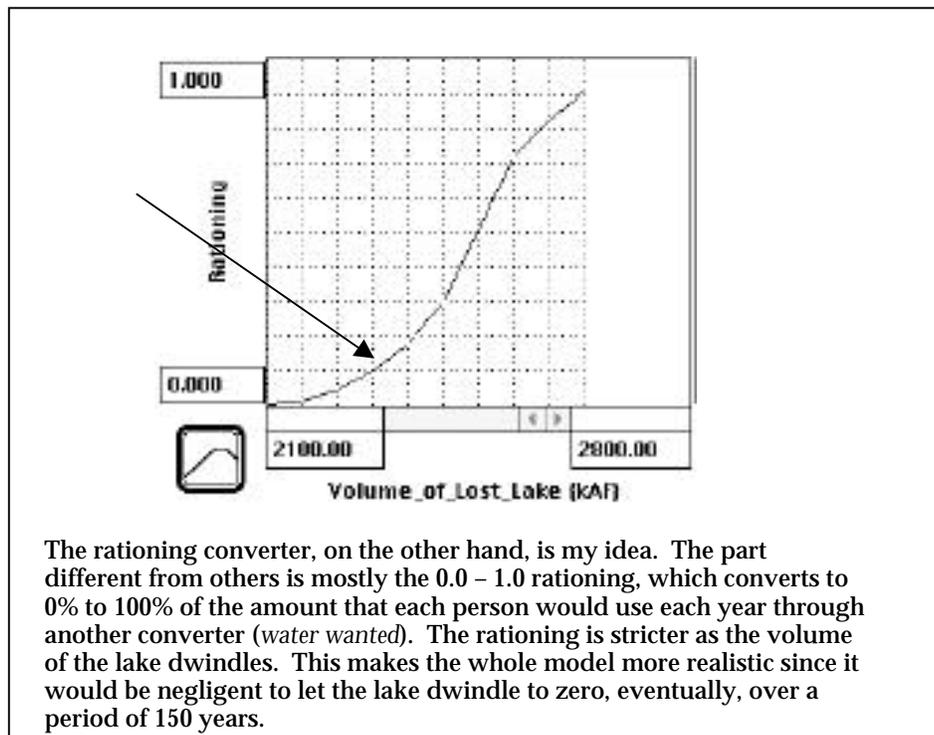
At its simplest, students merely draw behavior-over-time graphs (reference behaviors) and, beneath them, compose a brief story which might tell of real events described in that line, *but make no reference to the mechanics of the graph or a model.*



As students gain proficiency, complicate the y-axis: not just a single variable such as houses built, but something relative to something else such as the fraction of houses to apartments built over some length of time. Another worthy exercise goes a step past simple behavior-over-time graphs. Students plumb dynamics more deeply, for instance, when they can step away from time and use a graph to represent one change relative to another *regardless* of time: the amount of guilt Pip acquires as he learns of his benefactor's efforts, or the effect of a declining food supply on a population's death rate. Such graphs *can* be used in the STELLA² software and are known as "graphical converters."

Such complication in a graph, just as in storytelling, provides richness and breadth readers covet. Using words to describe the points on a fluctuating line within well-defined axes helps students understand that a given number has a meaning; numbers need not be abstract, but have real construct in the world they inhabit. Let me repeat that. *Students will understand that numbers have a real construct in their world.*

A word of caution is warranted here: using graphs in these ways opens a world of variability that arises from a hierarchy of specific graphical uses, such as multipliers, within a system dynamics model. From readily accessible reference behaviors to the more demanding graphical converters, each use provides a richer story component for the modeler to draw on. (See Leslie Martin's *Mistakes and Misunderstandings: Table Functions* for more on this topic³.) This capacity for deep learning is especially true when students draw portions of a model and the details of a graphical converter within that model section. Their assignment was to study the converter's workings and determine how it impacts the feedback of that model section. Then, tell a story that details the curve of the line and how its *shape* redounds throughout the model.



A student sample gives a clearer picture: this student's work demonstrates how he is thinking through the *idea* of the graph. Even though he alludes to both the model lake and the actual lake, he is at a dialectic stage wherein the one informs the understanding of the other.

As Huck Finn might say, this is powerful hard to do. But it is also exquisitely useful. Each model construction is, in fact, a rhetorical position, an ancient idea that folks like Aristotle, Cicero, and Coleridge would advise on. Students discover they cannot write accurately and effectively without a sound understanding of the feedback, nor can they trace the model feature terribly well without having appropriate and consistent language. The more fluent students become at telling the story, the more facile they are at building the model.

Notebook topics and activities

*The world is so full of a number of things,
I'm sure we should all be as happy as kings.*
Robert Louis Stevenson

As students work through these topics and activities, please keep ever in your mind—and in theirs—that *engaged reflection* is critical to understanding. Make sure that students will have some time to synthesize their thoughts, bundle them up and place them alongside some thoughts they already know. This debriefing is absolutely critical. Otherwise, these activities will yield little more than a worksheet.

1. **Identify key STOCKS** you have witnessed today—beginning from the time you woke up until the time you walked into this room. Students ought to list as many as possible, but certainly no less than ten. You will note that students are likely to recognize and report only *physical* stocks, such as cars, students, boxes of cereal, water in puddles; therefore, be certain to give some time over to listing *non-physical* stocks such as trust, worry, boredom, frustration. As a closing activity, ask students to choose one or two (or more) stocks and add *unit-consistent* flows to them. Sharing a few of these with the whole class would complete a very commendable warm up activity.
2. **Identify key FLOWS** you have witnessed today—beginning from the time you woke up until the time you walked into the classroom. Just as with the stock exercise, students ought to list as many as possible, keeping in mind to label each flow with an “-ing” ending. Likewise, once the list reaches some satisfactory level (say, ten), students should begin to imagine what stock is being filled or emptied by these flows. As a challenge item, it may be worthwhile to ask students if any two or three flows on their list are related; ask how they are

related; ask if one flow *depends on* or is *influenced by* another flow. Can anyone close a loop? Tell the story.

3. **Start with a FLOW drawn and listed on the board**, something fairly common, such as *driving*, or *reading*, or *eating*, or *raining*. Ask students to connect this flow to a stock that is filled or emptied by this flow. Next, students might ask, as the stock is filled or emptied, what other related *flow* might be directly accelerated or diminished by this changing stock. As a check for both narrative and modeling accuracy, ask students to name the units in each connected stock and flow strand (they should be the same). Starting with a common flow experience takes students into their personal experience, something they intuitively know but do not readily scrutinize. This is an excellent practice—to see system connections in their personal lives.
4. **Start with a STOCK drawn and listed on the board**, stocks one might find in the classroom or in a student's common experience, such as *Books*, *Garbage*, *Clothes*, *Teachers*, *Homework*, or *Amount of Reading*. Ask students to identify the flows that fill and empty these stocks. Further, ask students to identify influences that *speed up* or *slow down* the changes in these stocks. How might these influences be included in a map? Can students draw a closed loop from one stock to another?
5. **Use some strategies from the *Systems Thinking Playbook*⁴**, such as the Paper Fold sequence, a set of steps to walk students through “half-times,” a particularly difficult concept to understand because it involves two concepts *at once*—volume and time. Additionally, the Paper Fold sequence can also be used to describe exponential growth. While the *area* is “halving,” the *thickness* is doubling. This is a lovely thing for students to contemplate. Drawing out the graph that depicts the paper fold is very helpful. You might depict a stock and flow diagram of the exercise. You might also simply write out the doubling sequence through a 10th doubling; sometimes, the neuromuscular connection will help seal the

understanding. Some questions worth considering here: where might we see this phenomenon in the world? In school? In our lives?

6. **Consider long and short patterns.** Ask students to draw two graphs: one of a short pattern—say, one that recurs in a year or less, such as rainfall, and one of a long pattern—say, one that recurs over a decade or a century, such as growth of dam building. Students may need some examples to get them rolling. For instance, each year we undergo seasonal changes; over decades and centuries, we also undergo climatic shifts. Students flow into and out of hallways every period of the day; school populations shift from generation to generation. Long and short patterns need not be related to be useful thoughts: the use of pesticides on farmland has an ebb and flow to it; so, too, does the volcanic activity under the Cascade Range. Asking students to gather a series of long and short patterns, to *note what is similar in both* and compose some thoughts about these connected patterns is crucial. Ask students to note how human activity *changes* or *is changed* by some of these patterns.
7. **Respond to a specific systems question or statement.** Ask students to respond with both a map or graph and a narrative that describes their position or understanding:
 - a. Limits cause a shift in loop dominance. Why so, and why is this a concern?
 - b. We need to decide the kind of world we'd like to live in, or the system will decide it for us.
 - c. The key to the *attractiveness principle* is that people must choose the level of unattractiveness they're willing to live with.
 - d. The source of a system problem is often distant in time and space.
 - e. There is no *away* into which we throw things.There are many more of these available from a number of sources.
8. **Ask students to read an article** from a newspaper or magazine that strikes them as a systems issue—these might include references to change over time, shifts in

human population, shifts in the natural world, or unexpected things happening as a result of a policy. Usually, students will find these articles contain references to things changing over a long period of time, say, at least ten years. It is good for students to allow *two notebook pages* for this assignment:

- a. Supply a copy of the article
- b. Write a brief summary (~ a paragraph)
- c. Draw a behavior-over-time graph, providing a caption sufficient to tell the story of the line the student drew
- d. Identify key STOCKS and FLOWS, and draw a preliminary map
- e. Identify the feedback that is either *described* or *omitted*; to the extent students are able, identify the feedback as either reinforcing or balancing.

This particular assignment can have considerable impact on students and can effectively engage students for whole class periods. Do not shy away from this possibility, since their building and grappling with *real systems* is what engenders understanding. (See work by Diana Fisher⁵ on this.)

9. **Ask students to share their newspaper reading.** A student provides everyone with a copy of the article she read, draws her map on the board, and tells of her understanding of the story. All students glue the copied story in their notebook, draw the map, and then discussion follows. Often, there are amended maps, comments that connect this current story with something we have studied or considered earlier. Doing this on a weekly basis, allowing a different student to share each time, ensures that all students will have double-pages of stories and stock/flow diagrams throughout their book.
10. **Use the “Story of the Month”** from the High Performance Systems web site (www.hps-inc.com) as a starting point for mapping. For instance, in Fall 2001 HPS published a series of small models to think about terrorism; specifically, the models helped people think about the unintended consequences of the war in Afghanistan and how the U.S. bombing campaign might *increase* the number of terrorists rather than reduce them. Draw the map on the board, telling the story

as the map unfolds, and discussion will follow. Students will need to capture this map in their notebook, and may have to turn their notebook sideways to allow it. With each discussed point, *add to the map*. With each addition, ask students to compose a one or two sentence narrative that details how the new piece adds to and enlarges the story. At some point, the discussion will reach saturation—you will run out of room on the chalkboard.

Once this happens, go to a next step: as a class, begin to identify *the closed loops* in the system, using a different color chalk, and ask students to “tell the loop story.” This process of identifying the closed loops is among the most important things you can do as a systems teacher—*recognizing closed loops is the most incisive work our students do*.

11. Identify a series of related STOCKS by simply listing them on the board:

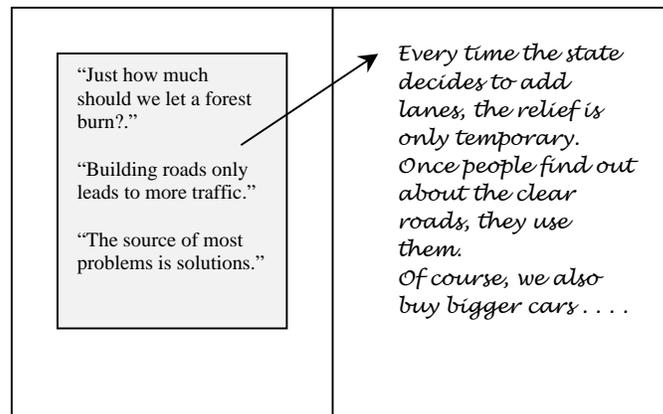
students, classrooms, teachers, books, and homework. You may want to list more, but you might choose a topical list from the news or recent events in school.

Whatever the case, ensure the list has some gritty meaning for students. Ask students to compose a brief story/diagram that links two or three or four or more of these stocks; that is, students will need to imagine the connections among the stocks, and fill in the appropriate FLOWS and CONNECTORS that make the connections plain. (I typically tell students to avoid converters in this exercise, as they will unnecessarily complicate the map.) This practice of *deriving closed loops* from a related list is a first step toward ultimately doing the same thing with an ostensibly unrelated list. A few imaginative maps on the board and the discussion is off and running. As usual, I ask students to draw the other maps in their own notebooks.

12. Draw maps with graphs of some significant timeline. For instance, draw a map of a local watershed that also includes graphs of population change, road

building, annual water cycle, and home construction. These data tell a critical, dynamic story and can launch some fascinating discussions about key stocks, about growth, limits, trends.

13. **Set up a special section for glossary of terms.** The quickest method is simply for students to indicate a special section by folding over a page diagonally, probably for the last ten pages or so. It may be possible to set up quasi-alphabetical listing of terms, or you may simply allow students to list terms as they come up in class. (Recently, I have taken to placing boxes around key terms on the chalkboard as they emerge in discussions, and students also do this so the words/phrases can be readily found in context. That these words/phrases also match the defined terms in the glossary is a plus.) Another possibility is that you provide a list of key systems terms typed out and students can glue them in the notebook.
14. **Follow-up questions** to experiments and observations. After a class experiment with, for example, the Pharmokinetic Lab developed by SimHealth at Oregon Health Sciences University⁶, student discussion is typically lively and their observations can fill a board (or two). Other times, student discussion may take us down an interesting road based on any of the previously mentioned methods. A thoughtful follow-up is to extract one or two highly charged statements or provocative questions, type them out with sufficient space, make necessary copies, and ask students to glue them into the book, thus:



Students can *choose* which statement or question they are interested in and write a response about a page long. This method is called the *dialectic*, as the student is engaged in a dialogue about an idea. It could be that students will find some synthesizing idea in a grouping of statements. The more connections, the better. This is a superb way to open a session since students are compelled to compose their thoughts before they open their mouths.

By no means is this only the province of high school. This may be most beneficial for the middle school students, allowing them time and some structure to put together ideas. It will help all thinkers see relationships.

15. **Ask students to look back and do an occasional review** of the last two weeks or so. Essentially, students would establish a new page, labeled “Review” and compile “lessons-learned bullets” over a key period of instruction or observation or inquiry. Some students might compile, for instance, a list of crucial questions or critical insights, or key knowledge, or synthesizing ideas that connect these new insights to prior learning. The metacognitive benefits of this approach are significant since the reinforcement of learning, admitting to themselves (and, thereby, *committing*) that they learned it, really does drive the message deep into neural folds.
16. **Writing stories and scenarios** ought to be a more regular feature of what we do. Using regular language to compose the loop stories, and the more complicated multiple-loop stories of a short story writer, will clearly benefit systems learners as they grapple with the long-run implications for, say, traffic on their neighborhood streets if gasoline prices rise too fast or remain at their current levels. A fairly simple story all students can tell is to describe their neighborhood as if we were walking through it just as it is now; then, tell a

second story of what it might look like 20 years from now if water uses were restricted due to droughts; further, tell a third story of what it might look like 20 years from now if water were *not* restricted at all. In each case, the writer must imagine the implications of 20 years of feedback, but in a very personal way.

This is especially excruciating but very instructive to excellent math students who seem to intuitively understand dynamics and modeling, but struggle with the basic rhetorical requirements of explaining systemic change.

17. Use **warm-ups repeatedly**, such as the “Just Right” stories, as starting points. See the section before this for a series of examples and some basic methods for using them. The only cautionary note is that even these stories can swallow hunks of time. Therefore, do not burden yourself or the class with capturing a full model all the time; being able to note the stocks and flows and perhaps a simple feedback connection is sufficient to warm the synapses for class. This nearly “Cliff Note” approach to small stories helps students see the ubiquity of stocks and flows; for instance, you might ask, “What are the key stocks on my person right now, and how are they adjusted?”
18. **There are a number of provocative quotations** that can be useful: those that speak of feedback and those that ignore it. Ask students to tell, first, what they believe the quotation means. Perhaps this sounds trivial, but it is starting point: everyone needs to begin with a common understanding before *any discussion* can proceed. Second, students should state whether they agree with it or not, and then state their case. This second piece, obviously, is also critical: how is a student’s thinking connected to things we have studied in class?

Here are a few:

- a. “Five percent annual growth will ensure a stable community for the foreseeable future.” (Boulder, CO, town councilor)
- b. “All things, everywhere, all the time, are controlled by feedback.” (J.W. Forrester)
- c. “I should be able to build my house anywhere on my property.”
- d. “Do vaccines do more harm than good?”

All one need do is pay attention to the news, whether at school or city or state or international level, for someone to say something you might use in a class.

Collect these statements in your own notebook and use them.

19. **Send students out to collect data.** Presumably, students are collecting data for class use: amount of garbage the school collects and disposes of weekly, the number of students passing a given hallway point at a given time of day, the number of cars entering and leaving the parking lot after school. This provides the teacher a wonderful opportunity to give instruction on data collection: What is reliable? What is valid? How to be accurate? What’s the best way to report a particular type of data?
20. **Occasionally, students may find themselves conducting an interview** or collecting information over the phone or in a face-to-face conversation. Students should note the name, title/job description, company name of the interviewee, as well as note date, time, and location of the interview. Careful paraphrasing, direct quotations, key references, phone numbers, all types of information and leads should be so noted.

Evaluating what students give you

*What ultimately causes a paradigm to change
is the accumulation of anomalies—observations that do not fit into
and cannot be explained by the prevailing paradigm.*
Thomas Kuhn

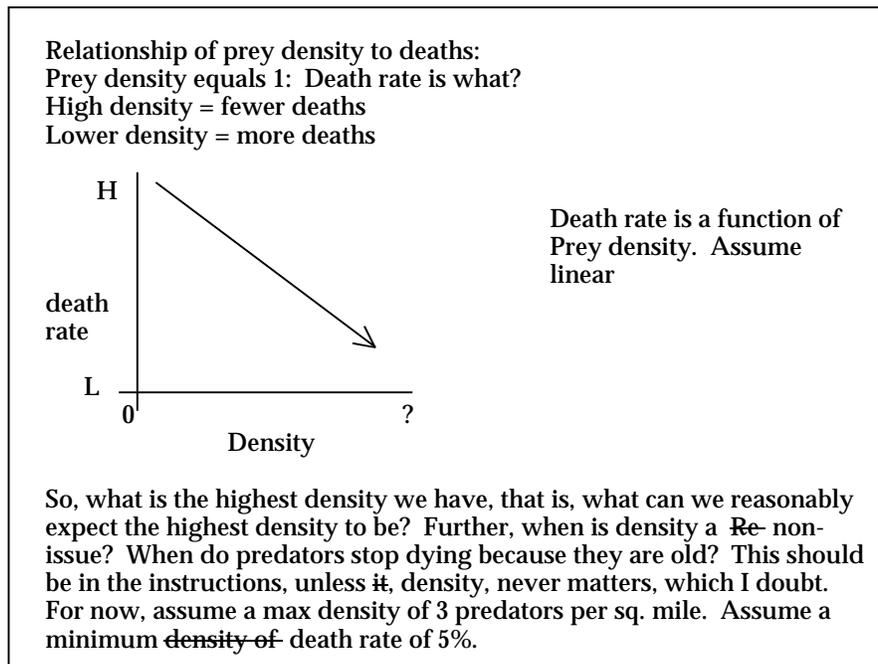
Oh, yeah, right . . . all your students write something every day and you collect it, a stack of notebooks over a foot high, each book crammed with pictures, esoteric diagrams, graphs, criticisms, glued-in news items, compositions, half-baked and abandoned essays, cartoons, dialogues, and mathematical equations. What do you do with all that? With any of it? Should you grade it? Comment in it? If you grade it, how do you go about it? Rejoice at their efforts, all of it. Yes. Yes. Rather systematically, of course.

We are all young at this, innocents trundling off to classrooms to try anything and everything, aware enough that we recognize mistakes and then work to mitigate them. So, too, with the efforts of our students—they are intellectually heaving themselves out into one abyss after another; we should celebrate these efforts, what Faith Waters calls "thoughtful courage." This does not mean we ought accept everything willy-nilly; on the contrary, we wish to direct students toward excellence. Using notebooks to pitch an arc toward excellence, then, requires a different touch.

"Grading" is probably not the appropriate term for how one ought to handle this flood of handbooks. I evaluate and comment about every two weeks. Each daily entry, for example, might be worth up to five or ten points (your call), and there might be a finite number of entries, say, ten in a two-week period; thus, some amount earned over 50 (or 100) points. Notebooks that exhibit care for details and legibility, a relative range

of speculation and risk, some fullness in explanations and reflection, should receive every point available.

Here's an example that shows a 16 year old working through a problem, scratch outs included.



How can one legitimately subtract points?

Because this is a notebook, a place where experimentation, speculation, and creativity are to have free range, do not be stingy at all with points. Indeed, I have never corrected anything in a notebook. *Ever*. It is conversation, a place of generosity and persuasion, a place to model thoughtfulness and diligence. Though one ought to maintain a standard of thoughtful speculation for them to attain, push students to that range by posing questions in their notebooks and, before returning a batch of them, read a few great examples aloud. Over time, this will prove more effective than withholding credit for misguided, though authentic attempts. (Look carefully at the *Errors, Miscues and Rotten Stories* section.)

One aspect of Forrester's vision about education entails student-centered learning and so the quicker we relinquish some portion of the notebook evaluation, the better off for all. Students will sharpen their critical judgment. Indeed, we have repeatedly found that students *crave* this; though unpracticed, students want to reflect on their own work. This holds true in writing as well as modeling.

Students compose this self-evaluation *as an entry*, working through the critical logic step by step, good practice that ultimately guides them as they find their own way.

- Record the number of entries since the last submission.
- Each entry ought to be approximately one page of drawings, notes, models, graphs, and/or writing. In a sentence, tell to what extent this describes your entries.
- Approximately how much average time did you spend composing each entry?
- Choose your best entry (choose your own criteria) in this recent period. Provide a VERY brief summary, and then tell what you did in this entry that makes it better than your others? You are free to choose more than one, but give a good case.
- Judge the quality and level of experimentation in your modeling and writing. To what extent do you extend yourself, either technically or conceptually? In which excerpt is this most apparent? Record this in about one to two sentences.
- Make a qualitative statement about how you have *changed as a modeler* since your last reflection. As you do this, use a specific model to help illustrate your learning.
- You may receive up to five [5] points per entry. Based on time, fullness of thought, and growth, determine your points. For example, if you had seven entries, you are eligible for up to 35 points. Thus, please express your score as a fraction, e.g., 32/35.

Students submit their notebooks after the self-evaluation. I then flip through them, focusing on items that catch my eye, read something here or there, add a comment perhaps, and then record the score they gave themselves. Before I return notebooks, I always read or present the great examples, opening the floor for some discussion.

In the years I have done this as a writing instructor, students are more persnickety about themselves than I. Certainly, and for valid reasons, I retain the right to override a score, but in 14 years I have done so only once. Besides, as the course unfolds, I talk with students about models and stories and other ideas enough so that I have a pretty good idea of what each is considering.

In the end, the notebook is for them, their collected wisdom and understanding, some wild thoughts, some speculations that may later prove fruitful. In other words, it is akin to a studio, a place where things unfold, few ideas are complete, and every idea carries forward the prospect of insight. Annotating a notebook, justifying scores with effusive commentaries, only trivializes what they have done. Go lightly: a nudge, a Forrester quotation, a question, a kudo—knowing that what you write there will stay in that notebook for a long time, but is ultimately less important than what comes of a student's own hand.

Errors and miscues and rotten stories

*The most essential gift for a good writer is a built-in, shockproof shit detector.
This is the writer's radar and all great writers have it.*
Ernest Hemingway

Notebooks share a noble lineage in numerous professions. One need only glance through facsimile notebooks of Michelangelo, William Blake, Chiam Potok, Henry D. Thoreau, or Mary Shelley to understand that these books are conveyors of raw thought. They are also a profound gift of great intellects laid bare on a page. How do great thinkers think? Their notebooks show us—they are filled with mental models.

What kinds of things they show is crucial. Universally, they show raw ideas ruthlessly edited by a honed, artistic sensibility: rough drawings, erasures, glossings affixed to poems, whole lines struck, rewritten, struck again, maybe even summarily pitched into the abyss. Objectively, therefore, one might say that notebooks depict errors; subjectively, however, notebooks depict diligence. The problem, of course, is that our schools scorn the former and generally ignore the latter, tossing aside the whole approach and nullifying this noble virtue. Indeed, do we not all chant the systems' mantra, "All models are wrong, some are useful"? Our entire approach is to seek truth, to approximate the real, starting—as *all* humans do—with a limited understanding, and then, incrementally, *diligently* moving toward what's true. It is, as I've mentioned, hard to evaluate. At an institutional level, notebooks are inefficient; at a personal level, however, notebooks are invaluable.

Frustrations may appear, breakthroughs now and again, but in most cases, the notebooks display a steady paced, forward move through new territory. Just as an explorer hacks away at obstacles as he strikes out on a trail, so, too, the artist leaps out to

new vistas. There seems always to be a foot in the known, and another foot stretching into something new, one foot instructing the other: experience steadies, giving anchor to the reaching foot; risk pulls, giving impetus to the holding foot.

Every page of a notebook reveals the mental model of its creator. These are what we wish to expose, to lay bare, to test, to evaluate, and ultimately to improve—we want students (and ourselves) to have better mental models. The only way this will happen is to allow students to do this, to think. In a way, we need to *celebrate mistakes*, honor them for what they contribute to a modeler—the bracing fact of a start. So long as a student studies and thinks, the flawed model has a place in the notebook because the modeler will ultimately come to recognize the errors and incrementally work to reduce them. Error teaches. Insight and learning flow from such diligence.

This happens over time, perhaps a long time. The accumulated effect of this dialectic—the student proposing, the teacher suggesting—is that the modeler’s systemic intuition sharpens; she can see. But the notebook cycling of student to teacher back to student and onward must have an appropriately brief turn time: no more than two weeks in a student’s hands, and no more than two *days* in a teacher’s. Give the student time to battle the idea, the model; and then let her know as soon as possible what you think about her ideas. Honesty, affirmation, expectation will go a long way toward extracting the gold in your student’s mind.

If our task is to train a thinker, teachers ought to focus on the notebook, using it as a basis even for lesson planning. What it will show is a mind at various places of growth—skill sets at variant levels, concepts with omissions as well as insights, conclusions that are both faulty in one way and facile in others. In some cases, a young modeler will note the counterintuitive behavior of populations when connected to a resource (the fast rise in a population is only possible when sufficient resource is available, but it also spells the population’s doom; once the resource declines, the population stares into empty, or near-empty, bowls). That same modeler, however, may

also omit basic feedback loops as she draws or carelessly numerates an equation. Or, perhaps, after reading a round of notebooks, the teacher will note that most students did not adequately understand a multiplier; and how, for instance, it may mitigate a flow. Each of these instructional needs is crucial for a teacher to know. Consequently, a teacher ought to maintain a pedagogical or instructional journal of his own, noting the leaps and stumblings of his students. As the teacher works his syllabus against such weekly notes, he will undoubtedly ensure a closer connection between what he wants, and what the students need.

If we return for a moment to that notebook model of intellectual development, we should readily conclude that our mistakes—*errors* in our mental models—can guide us as ably as our answers—*accuracies* in our mental models. Therefore, acknowledge each student's attempt on a notebook page as *genuine, authentic*; doing so validates them as thinkers, as Socratic poets—as makers of meaning. And that is precisely what students are doing—constructing sense from the phantasm of life that shifts and shakes before their eyes each day.

Do we not honor “trial and error”? Why, then, do we so despise it in our schools, a relatively closed and safeguarded place wherein students ought to err; someone (in most cases, *many* someones) is ready to help and instruct. Out in the world, helpers are hard to find. A culture based on right answers construes such methods as weak, but it is exactly the way people learn, the way organizations learn, the way science unfolds, the way writers write, the way musicians compose, the way artisans create, and the way all thinkers creep closer to the truth.

I believe students really do want to know things—not so much the *what* and *when* of this world; schools have pummeled them with this minutiae for years. No—what they really seek is the *how* and the *why*⁷; their own curiosity compels them to seek it out.

Yet, all around, the world churns and blurs; it is a world at varied distance and speed, its lines hazy, a world of shadows and murky layers, things happening at such a frenetic pace that one can only glimpse darkly, and so students have little intimate understanding of it. Thankfully, good modeling and lucid writing, akin to adjusting a lens, focuses our time-bound, dynamic existence into discernible patterns—“a unity of mind and nature,” as Gregory Bateson would say.

Notes

¹ Barker, Kathy. *At The Bench: a Laboratory Navigator*. Plainville, New York: Cold Spring Harbor Laboratory Press, 1998.

² STELLA is produced and distributed by High Performance Systems, Inc. of Lebanon, New Hampshire. Check their website (www.hps-inc.com) for “Story of the Month” and subscribe to *The Connector*, an on-line magazine about systems thinking in a variety of venues including education.

³ Leslie Martin’s *Mistakes and Misunderstandings: Table Functions* is available through the Creative Learning Exchange at clexchange.org and catalogued as “SD1998-02MistakesTableFunct.” This is an excellent short paper on particularly thorny system problems for young modelers. It is a must read for anyone wishing to capture nonlinear change in a model.

⁴ Booth-Sweeney, Linda and Dennis Meadows. *The Systems Thinking Playbook*. Pegasus Communications, Waltham, Massachusetts, 2001. A wonderful accompaniment to any systems classroom as it provides teachers and students a variety of gaming simulations that illustrate a number of systems concepts.

⁵ *Lessons for a First Course in System Dynamics Modeling*, Fisher, Diana, published by Summer Creek Press, Tigard, OR. Diana and colleague, Scott Guthrie, both teachers at Wilson High School in Portland, Oregon, explain how they have used news articles.

⁶ SimHealth was a NIH-funded K-12 outreach institute led by Dr. Edward Gallaher and directed by Dr. Louis Macovsky. The organization created a system dynamics-based physical lab based on pharmacokinetics that includes a class set of labs with several lessons for middle and high school. Contact gallaher@ohsu.edu.

⁷ Sterman, John. *Business Dynamics*, Boston: Irwin McGraw-Hill, 2000. Many other lucid imperatives reside herein.