What Jay Didn't Tell Us:
Hidden Gems in the System Dynamics Practices of Jay W Forrester[1]

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Half of what I say is meaningless.
I say it so that the other half will reach you.
Khalil Gibran, *The Prophet*

Genius: A person who shoots at something
no one else can see, and hits it.
The Left-handed Dictionary

Preface

The works of Jay W. Forrester are numerous and deep. Beginning with *Industrial Dynamics* (1961) he was showing us and telling us how to take a stock-and-flow/feedback perspective to understand the dynamics of complex systems. He told us a lot. Even in that path-breaking first book, he has an appendix on Beginners' Difficulties, telling us bits and pieces of how to do good work in the field and how to avoid pitfalls.

Yet there is a lot that Jay knew -- what he did, what he wanted us to know -- that he did not explicitly tell us. Or if he did tell us, we missed some of it. This note reveals a few of Jay's insightful bits of genius he practiced, but didn't talk about or write down, that have emerged for me over the years. Some are forceful suggestions for practice; some are insights about dynamic systems or methods for understanding them; and the last is a challenging philosophical speculation, which, like the others, Jay never told us about.

This Note is very different from usual published articles: to keep the focus on Jay, it contains no review of related system dynamics literature. Where further explanations seemed necessary, I simply referenced bits I had written before. I have also written this note in unusually familiar form: it is Jay who is speaking to us as I think he wanted us to hear.

Some of the eight "hidden gems" here may be surprising. While the items do reflect Jay's actual practices, some often sound like they contradict current best practice in the field. We should expect nothing less from Jay.

[1] I am grateful for the contributions of reviewers this Note. A special note of thanks goes to John Sterman who read every draft and wrote such wise things I had to improve it in spite of myself.

[1] Don't publish sensitivity tests. Use your model to tell lots of compelling stories.

A jolting shock to get everyone's attention. It's true Jay never said "Don't publish sensitivity tests", and many would say he never would have, as he placed great importance on exercising a model that way. And if he ever said it, he would have phrased it in the postive way above. Yet I believe that after *Industrial Dynamics* (Forrester 1961) nothing he published referred to "sensitivity tests.”

It's natural to ask why, but first let's give some examples. In *World Dynamics* (Forrester 1972), the default simulation shows population rising, peaking, and then declining because of declining natural resources. His first effort to improve on that scenario began with this sentence:

> "Suppose we wish to assume that in year 1970 the usage rate of natural resources were to be sharply curtailed without affecting any other part of the system. This might correspond to either an altered estimate of the actual rate of consumption relative to the available stocks in the earth, or it might correspond to technology finding ways to be less dependent on critical materials."

"Sharply curtailing the usage rate of natural resources" was not presented as an abstract test of model sensitivity to a parameter change, but a simulation representing two plausible real-world scenarios described in concrete terms. Jay is asking a question about the real world and focusing the reader's attention on it.

Jay's next exploration of the system involved removing the limits to growth from natural resources and pollution, so that, as he said, "the third limit to growth can be examined." It turned out to be crowding. For Jay and his audience it is not an abstract sensitivity test of a computer model, but rather an experiment focused a potential policy change to see how the system might behave.

There follows an entire chapter in *World Dynamics* focused on Jay's findings that "obvious responses will not suffice." He tried to improve on the base run with

- Increased industrialization,
- Reducing the birth rate through birth control programs,
- Applying technology to reduce pollution generation,
- Higher agricultural production from reclaiming desert land, better crop plants, irrigation, clearing forests, and so on,
- And less obvious attempts: Reduced capital investment, Lower food productivity

... All real-world scenarios, all exploring how the model behaves, but none discussed as sensitivity tests.

More examples abound in *Urban Dynamics* (Forrester 1969), including the range of the urban renewal policies favored in the U.S. in the 1960s. For example, clearing out the worst of urban slums and replacing them with quality low-cost housing proved in the model to make things a bit better in the short run and actually worse in the long run. All of the model experiments in *Urban Dynamics* involved parameter changes, but none were referred to as sensitivity tests.

What's the point here? Jay, by example, was teaching us how to *reach and energize our readers*. He knew that the language we use channels our audiences into particular paths of thinking. The language of "sensitivity tests" tends to draw readers toward technical thoughts. We most want to pull our readers toward the potential real-world insights the work can show us. So he performed lots of parametric tests, but he always told us about them in real-world terms.

Jay's examples here constitute a very important lesson for us:

- Show your readers the rich, insightful range of behaviors the model can exhibit -- what they can learn from the simulations -- but always phrase them in real-world terms.
- Try never to focus single-mindedly on language that reminds readers of abstract parameters and tests divorced from real-world meaning.
- We want our readers to be thinking about potential implications of our work for the real-world problems we are addressing.
- Write that way. You will find it easier to reach your intended audiences and make the differences your work deserves.[2]

The fundamental principle here is to *write for our audiences.* Most of our readers want the strong real-world connections Jay repeatedly supplied. But some audiences for our work require more thorough sensitivity testing than Jay's treatment provides. We must give them the complete detail they need in a form they expect, either in the text of the publication but better in an appendix. My advice, and Jay's practice, is still to meet them only partway – make the real world the main focus of the story.

[2] Nonlinear systems can endogenously shift loop dominance. Linear systems can not.

Jay talked about linear and nonlinear models and systems from the beginning of the field (Forrester 1961, 50 & 305). For this discussion we need to know that a system is linear if its *structure* is linear, not its behavior.[3] Yet in Jay's early writings the phenomena didn't sound like it had any links to feedback loops. Perhaps appropriately, he phrased things in mathematical terms:

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[2] I came to this realization only relatively recently. My personal best is "Drawing Insights from a Small Model of the Growth of a Management Science Field" (Richardson 2014). That thirteen-page article contained eleven tests of the behavior of the model under various scenarios, all of which we could recognize as "sensitivity tests" but none were discussed that way. Deliberately practicing Jay's approach, all were phrased in real-world terms. That enabled me to end with a discussion entirely focused on potential policy insights for a management science field, with the attention of my readers focused firmly on the barriers and real potential for growth of a field like ours.

[3] In a linear model, every rate-of-change (net flow) is a linear combination of stocks in the model: $dX_k/dt = a_0 + a_1X_1 + a_2X_2 + ... + a_nX_n$. A nonlinear model is anything else, commonly involving products or divisions of stock variables. Models with linear *structure* can produce some splendidly curvy *behavior*; for examples, the simple model of an oscillating mass on a spring is linear, and exponential growth comes from the simplest possible linear model, $dX/dt = a X$.

> Linear external effects are purely additive... Only damped or sustained oscillations can exist in an actual linear system. ... Linear models are adequate for much of the work in the physical sciences but fail to represent essential characteristics of industrial and social processes... Nonlinear phenomena are the causes of much of the system behavior that we shall wish to study (op. cit, 50).

He gets closer to linking nonlinearity to feedback loops in a paper aimed at an engineering audience (Forrester 1964, 72):

> Consider the long-term, equilibrium influences in a company's sales rate. In sales, as elsewhere, we find interlocked loops, some with positive feedback and some with negative feedback. Equilibrium behavior depends on the relationships between the nonlinear gains in the several loops.

In his introduction to *World Dynamics*, he gets even more explicit about the changing the strength of feedback loops when he talks about the influences of birth- and death-loops on population growth:

> Taken together the two loops can describe either exponential growth or or decline toward zero, depending on which effect is stronger.

He follows that up in (Forrester 1971). In a figure in that article, reproduced here as Figure 1, Jay links feedback loops to constraints causing changes in loop dominance in global population dynamics. Jay wrote that that the map "shows a set of feedback loops that produce growth, cause growth to impinge on a fixed space limit, and then shift dominant control to an equilibrium-seeking set of relationships."

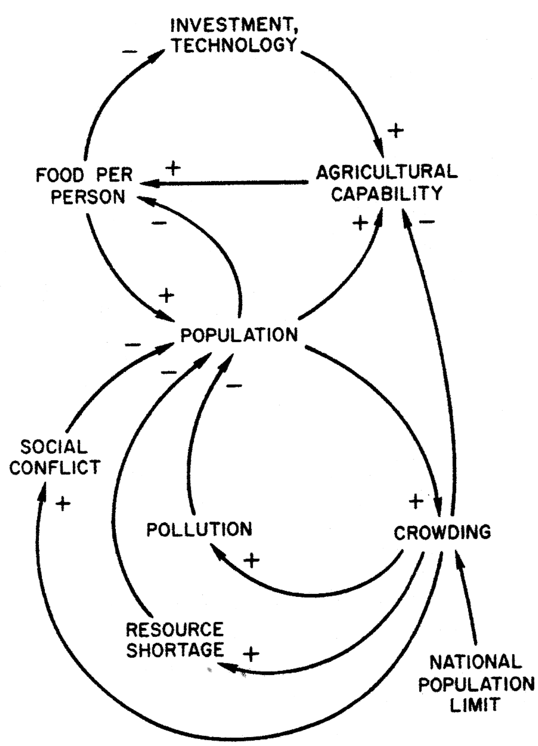

Figure 1: A set of feedback loops that Jay used to illustrate a shift in loop dominance from a reinforcing growth loop to balancing loops constraining growth. [Forrester 1971, p. 257]

We learn a key fact underlying the system dynamics approach:

- Nonlinearities are our endogenous model mechanisms for changing system structure on the fly.[4]

Our equations don't rewrite themselves to change model structure. Instead, nonlinearities in feedback loops can awaken latent system forces in the equations of the model, make new influences active, increase or decrease the strengths of feedback loops, and even completely overpower other loops.

These insights are vital to us because real world forces influencing system dynamics change over time, so our models must be able to do the same. We can test hypotheses about them by deactivating feedback loops we think are the culprits and watch system behavior change (or not). It is especially nice that we can explain such shifts in active or dominant structure by referring to more-or-less simple feedback loops – no mathematics required – perfect for helping even young people include feedback loops realistically in their thinking.

[3] Stocks are accumulations, but not all accumulations are modeled as stocks. How come?

There is a simple answer and a not-so-simple answer. (Jay, of course, knew both, but kept his own counsel.) The simple answer is that some accumulations (stocks) are modeled as simple sums, e.g., Population as the sum of the stocks of Children, Adults, and Elderly. Another common example is Cumulative Perceived Progress in a project model: it's an accumulation, but is most easily and insightfully modeled as the sum of Cumulative Real Progress and Undiscovered Rework. We write such accumulations as auxiliaries simply by adding the component stocks.

The not-so-simple insight is that there is a *time dimension* to stocks. Jay never told us there are quick stocks, moderately moving stocks, and slow stocks, but there are. There are some accumulations that change in a week's time, or over a 20-year time frame, or maybe not much for 200 years.

- An accumulation that changes very quickly, relative to the time frame of the model, should be modeled as an auxiliary.
- An accumulation that changes hardly at all over the time frame of the model should be modeled as a constant.
- Accumulations that have significant dynamics over the time horizon of the model should be modeled as stocks.

[4] We can prove the claim in simple nonlinear systems, such as $dX/Dt = aX - bX^2$, but since we do not have definitive ways of formally identifying dominant loops in complex models we must rely on our model-based experiences (Richardson 1984/1995).

The distinctions here involve the *time constants* of the stocks. The time constant of a stock is the *divisor* in the outflow. The smaller the Time Constant, the quicker the stock can change. The larger the Time Constant, the slower the stock changes.

In the extremes, a stock could conceivably change almost every computation interval (DT), or could remain essentially constant for the entire simulation of the model. In such extremes it is a good idea to model those accumulations as either auxiliaries or constants, not as integrals.

An example of a very quick stock could be Average Weekly Rainfall in a regional or global model designed for a time horizon of, say, 200 years. That average is a clear candidate to model as an auxiliary. An example of a very slow stock could be the Quantity of Sea Water in the earth's oceans – potentially changing hardly at all over the time frame of a model like the *World Dynamics* model designed to run for 200 years.[5]

There is a further subtlety that systems modelers should know. It's OK to model a very slow accumulation as a stock with a long time constant; you won't get into much trouble doing that. It's just unnecessary and not very elegant.

But it is not OK to model a *very quick stock* as a stock with a *very short* time constant. Many of us have tried to get away with that by reducing the computation interval (DT) of the model so that DT is at least as small as a fourth to a tenth of the smallest time constant in the model. But it's not a good idea to shrink DT way down in a model with a long time horizon. Not only do such models take a long time to simulate, but more importantly, such a model can show simulation runs that are more influenced by faulty computer arithmetic than real-world structure.[6]

For example, in a little model of the structure underlying global climate dynamics, I wanted the water cycle to appear as in Figure 2.

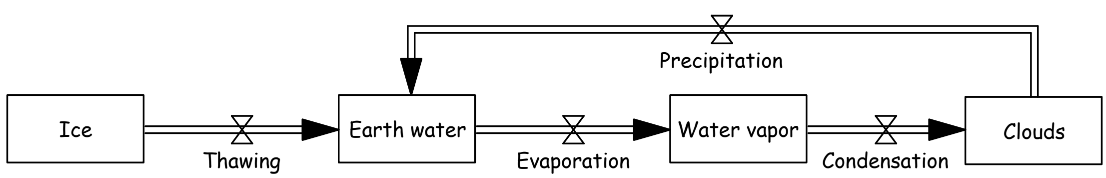

Figure 2: An excerpt from a simple model of global climate dynamics, showing a very quick stock (water vapor).[7]

The problem here is that the time constant for water vapor (in Condensation) is much shorter than the time constants of the other stocks. That suggests we ought to formulate water vapor as an auxiliary. But water vapor is our most important greenhouse gas – it's what made us a livable planet to begin with – so keeping it visually as a stock was important to me and my audience.

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[5] Unfortunately, global heating could change that.

[6] See discussions of "stiff systems" e.g., https://en.wikipedia.org/wiki/Stiff_equation

[7] For simplicity, the picture omits Freezing, to focus only on the outflows shown, where the time constants appear.

The important feedback loop it sits in can shift between reinforcing and balancing depending on its inflow and outflow.[8] So I showed the diagram with water vapor as a stock, and argued the potential shift in loop polarity from the flows of Evaporation and Condensation the picture, but I computed the value of Water Vapor as an auxiliary using the method shown in Richardson & Pugh (1981, 186-189).

[4] Think endogenously.[9]

I don't believe that Jay used the word "endogenous" in any of his early publications (Richardson 1991, 2011). Yet it was a crucial cornerstone of his thinking all the time. He signaled it as early as 1968 in various publications where he listed his most mature view of the components of the system dynamics approach:

- Closed boundary around the system
    - Feedback loops as the basic structural elements within the boundary
        - Level (state) variables representing accumulations within the feedback loops
        - Rate (flow) variables representing activity within the feedback loops
            - Goal
            - Observed condition
            - Detection of discrepancy

It's a familiar list, but in our haste to focus on feedback loops and stocks-and-flows we tend to skip over the first one: the "closed boundary around the system." That's Jay's *endogenous point of view*.

Jay phrased it this way:

> Formulating a model of a system should start from the question "Where is the boundary, that encompasses the smallest number of components, within which the dynamic behavior under study is generated?" (Forrester 1968a, 83)
>
> The closed-boundary concept implies that the system behavior of interest is not imposed from the outside but created within the boundary (Forrester 1969, 12).

His examples around 1968-69 were vivid. In *Urban Dynamics* (Forrester 1969) he set the city in a limitless environment, with no suburbs to interact with the city, steal its resources, or attract its wealthy residents The perspective he took, and the model he built, viewed an archetypical city in a large and dynamically uninteresting environment. The dynamics of interest were internal urban dynamics relative to the environment outside the city. They were to be insistently, undeniably endogenous dynamics generated by the city itself.

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[8] When rising global heat energy causes the inflow to Water Vapor (Evaporation) to be greater than Condensation, Water Vapor rises and a powerful reinforcing warming loop (not shown in the figure) is created. But if rising heat causes Evaporation to be less than Condensation, Water Vapor declines and the loop becomes balancing, a potential counter to global heating.

[9] Parts of this section appeared previously in Richardson (2011).

Jay's urban work was seriously criticized and in some cases rejected for leaving out suburbs because it was the common perception that suburbs contained the causes of urban decay.[10] Yet over a 150-year period, the simulated city, without suburbs, grew, stagnated, and eventually fell into urban decay all by itself. Its changes over time came from the internal stock-and-flow/feedback structure of the city itself.

That endogenous view enabled Jay to uncover policies *under the control of the city* that could reverse inner city urban decay. The possibility that urban growth, stagnation, and decay have sources that trace to perceptions, interactions, and forces inside the city itself would never have emerged had he started with a system boundary that included suburbs, national urban policy, or national economic dynamics. The endogenous point of view was crucial for the insights of the study. In fact, the choice of system boundary narrower than most would have taken proved to be the key to important urban dynamics insights.

Jay's other remarkable example of endogenous thinking appeared in his article "Market Growth as Influenced by Capital" (Forrester 1968a). He developed this model to illustrate a potential source of corporate poor performance: the internal operating policies of the company itself. To make the story most vivid, he set the company represented by the model in a potentially infinite market: there is no external market cap in the model that might limit corporate growth, production capacity, the size of the salesforce, or the amount of orders booked per month.

Yet in the base run, the model corporation gradually goes out of business in an infinite market! Jay then showed internal operating policies that could lead the company out of decline and to successful growth. In spite of the title, making it appear that the focus was corporate growth, Jay built that model to show vividly the power and importance an endogenous point of view in the dynamics of corporate systems.

The deep habit of endogenous thinking also pops up in Jay's reactions to the work of others. In the decade following the publication of *World Dynamics* and the *Limits to Growth*, many scholarly centers around the world worked to contribute model-based insights to the "global problématique" made famous by the Club of Rome. In a retrospective on those efforts (Forester 1982), Jay was forced to note critically that some of them held population exogenous, fed into the models as time series data, using the best estimates available for population data from sectors all around the world. He wrote:

> Many recent world models, by letting population be exogenous, lose feedback from other variables back to population, and thus leave out the central dynamic factor driving world growth.

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[10] The System Dynamics Group at MIT responded to such critiques, not by abstract scholarly arguments, but appropriately by creating a *structural sensitivity test*, revising the model to include the structure and influences of a suburb (Schroeder (1975). The conclusions in Forrester (1969) remained robust. Schroeder (1975, p. 249) concluded "The dominant feedback loops affecting urban behavior lie within cities themselves, as shown by the policy tests in the city-suburb model. For the most part, city-suburb feedback merely compounds urban difficulties."

For example, improving health conditions on a global scale would lower infant mortality and extend average lifespans, eventually increasing the population growth rate again, resulting in a larger global population to feed and sustain materially. He continued:

> ...Perhaps it is time to reintroduce system dynamics into world modeling: it lends itself to communicating with the public, dealing with long time horizons, choosing the appropriate level of aggregation, emphasizing policy choices, making all the variables endogenous,[11] joining the arena of political controversy, and drawing on the rich and diversified mental database (Forrester 1982).

It's possible Jay never told us to "think endogenously" in just those words before 1982, but he practiced it in all his work and undoubtedly expected us to practice it as well. Furthermore, this last example tells us he believed that thinking about *policy* in complex systems required thinking endogenously. No matter what the approach, without endogenous thinking we'd likely be just plain wrong.

[5] Be bold. Push toward insights.

Jay interrupted the narrative in *Urban Dynamics* with a surprising list of generalities (Forrester 1969, Chapter 6). He asserted that complex dynamic systems exhibited:

- Counterintuitive behavior
- Insensitivity to parameter changes.
- Resistance to policy changes
- Control through influence points
- Corrective programs counteracted by the system
- Long-term versus short-term response

Over time, he repeatedly returned to these ideas. Some in the original list have become linked to other phrases, or generalized even further:

- Jay noted that "Goal conflicts" underly a lot of policy resistance and counteractions by the system (Forrester 1971)
- He introduced the notion of "leverage" to help with the idea of influence points. We now have the easy caution that "if we manage to find a leverage point, we usually push the lever in the wrong direction."
- We now often use terms like "compensating feedback" or "counteracting feedback" when talking about "resistance to policy changes."
- And later he expanded the last one in the list to say that policies that appear to work in the short-run often fail in the long-run, and policies that will work in the long-run seem to make the short-term worse. "Worse before better behavior" has become a commonly quoted characteristic of complex dynamic systems.

[11] To my knowledge, this is the first time (1982) Forrester used the word explicitly in print, but it is clear he thought this way all along, as a *condicio sine qua non* of the system dynamics approach, and, in his view, probably of all well-framed policy analysis in dynamic. systems.

Where did these heroic generalities come from? Jay had developed and explored a number of system dynamics models by the time *Urban Dynamics* appeared: the models in *Industrial Dynamics*, the Corporate Growth Model he never published, *World Dynamics*, "Market Growth" and *Urban Dynamics*. These must have been the sources of these courageous insights.

The most recent, *Urban Dynamics*, would have been uppermost in his mind in 1968. Indeed, it contains examples of all six of the original list. For example, Jay found that incentives for building construction had almost no effect in the depressed city, demonstrating both insensitivity to parameter changes and corrective programs counteracted by the system. (We now often lump these with policy resistance.) Further, the urban model showed that building low-cost housing had different effects in the short term and long term; in the long run the policy made unemployment worse by making it harder to build a strong economic jobs base in the crowded city. Knocking down some small fraction of underemployed housing proved to be a surprisingly strong policy to improve the economic health of the inner city when coupled with other internal policies.

World Dynamics has examples of all six characteristics as well. Zero-population-growth initiated in 1970 does indeed halt growth for about a generation, but then population growth resumes and looks much like the base run – a corrective action counteracted by the system. Investing more in corporate growth produces a crushing pollution crisis – an example you can probably link to several of the original list.

But perhaps the most remarkable example of Jay appearing to go boldly going beyond his data appears in "Counterintuitive Behavior of Social Systems" (Forrester 1971), a paper published and republished many times, but originally testimony before a subcommittee of the House of Representatives. With severe editing here to shrink it, but otherwise actual quotes, Jay argued for the following generalities:

1. Industrialization may be a more destabilizing force in world ecology than population....
2. Within the next century, man may be facing choices from a four-pronged dilemma – ... a natural resource shortage, collapse of world population wrought by pollution, population limited by food shortage, or ... controlled by war, disease, and social stresses...
3. We may now be living in a 'golden age' where the quality of life is higher than ever before, ... and higher now than the future offers.
4. Efforts at population control may be inherently self-defeating. ... Improvements can generate forces to trigger a resurgence of population growth.
5. The high standard of living in modern industrial societies seems to result from a production of food and material goods that has been able to outrun rising population. But as agriculture reaches a space limit, and industrialization reaches a natural resource limit, and both reach a pollution limit, population tends to catch up. ...
6. A society with a high level of industrialization may be unsustainable.
7. From the long view of a hundred years hence, the present efforts of underdeveloped nations to industrialize along Western patterns may be unwise. They may now be closer to the ultimate equilibrium with the environment than are the industrialized nations.

Each of these suggestions, presented as likely future scenarios (Jay said each "may" happen), comes from Jay's previous model-based work. We can recognize where. There is no doubt that Jay was a serious scholar and careful thinker. But we see he pushed for bold, generalizable insights that actually went beyond his data. In various places, I think he hinted that he wanted us do that too, with Jay-like care and caution. So, with deep thought, and a magic mix of humility, insight, and bravado, be bold, press for insights.

[6] Never use causal-loop diagrams for conceptualization. Always include obvious stocks.

A counterexample to the title of this article: Jay did tells us that, over and over. There is no example of Jay ever using used CLD's for conceptualization. Instead he always began with stocks (as Richmond guaranteed in STELLA and iThink). Whenever he wrote for people new to the field, he reminded us of the conceptual weaknesses in CLDs. He could not have been more insistent.

But we ignored him, and on this issue many still do.

Why was he so insistent? There are at least five reasons:

- Accumulations are real parts of real system structure: Populations, reputations, inventories, trust, corporate culture, infected people, contagious people, natural resources, herbivores, carnivores, books in libraries, plastic in the oceans, wisdom in people's heads, confidence, alcohol in a person's bloodstream. Ignore them and you miss crucial aspects of real systems. A causal map without stocks is a pale shadow of what it needs to be.
- Even pictures of stocks are important for understanding. Look at what a conserved flow of stocks becomes when you leave the stocks out of the picture (Figure 3). Each pipe becomes two arrows, one adding and one subtracting. Not all users of CLDs know that, and fewer think like that. But Jay knew that, and tried to tell us.

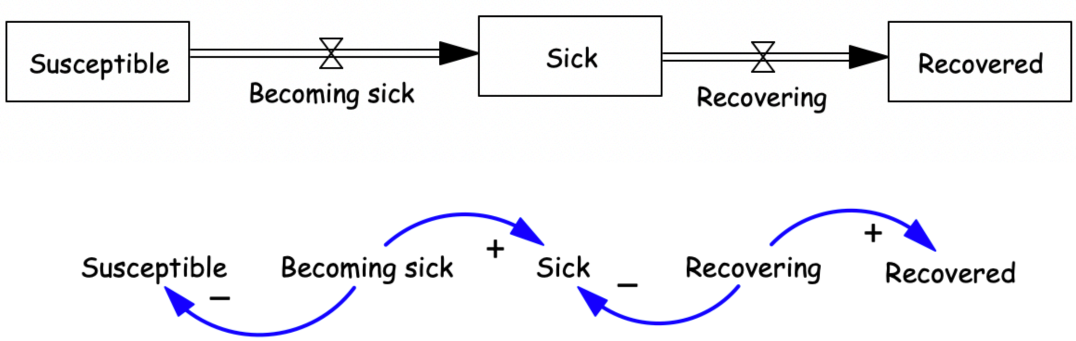

Figure 3: Comparing a stock-and-flow chain with its word-and-arrow (CLD) equivalent.

- Many of us know that stocks are crucial for the dynamics we are trying to learn about. For example, students in the first semester learn that it takes at least two stocks for a system to oscillate, like Position and Momentum, or Inventory and Workforce. So if your purpose is understanding the dynamics of a complex system, or even a simple system, stocks are necessary.

- Here's a strange one: There are goal-seeking reinforcing loops, and you can't understand that unless you see the stocks. For example, the Salesmen loop in Jay's famous Market Growth model is such a loop. If you sketch that loop as a CLD, you will probably miss that Salesmen is a stock whose rate-of-change is a simple goal/gap formulation. That goal-gap structure includes a tiny balancing loop that always has a strength (gain) of 1 (or -1 if you prefer). When the company can't afford the Salesmen it already has, the gain of the reinforcing loop falls below 1, so the negative loop with gain of -1 dominates the reinforcing loop and together they are goal-seeking. Note that in a CLD we'd probably draw it as one reinforcing loop.
- So now it may not be too surprising that there are reinforcing loops that can oscillate, and the reason they can is they contain multiple stocks jarred out of equilibrium.

But we're way beyond where we need to be here. Suffice to say, you need to know about stocks to really understand some aspects of system dynamics behavior. So you need stocks in conceptualization. Jay knew that, and he told us. All of us should stop ignoring that advice.

[7] Stocks are the sources of dynamics.

A surprise? Right now, I know some are saying to themselves, "Of course, Jay didn't tell us that -- it isn't true!"

Why are we skeptical? Many of us (all of us?) are accustomed to telling dynamic stories from loop diagrams that show no stocks at all, such as the classic reinforcing loop in Figure 4 that seems to capture the essence of prejudice and discrimination.

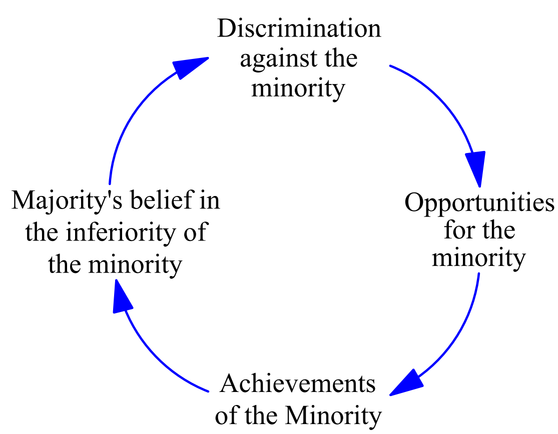

Figure 4: The reinforcing loop underlying the dynamics of prejudice and discrimination, first described (without the picture) by Gunnar Mydahl (1944) and Robert King Merton (1948)

We say "If discrimination against the minority increases, then opportunities for the minority to excel will decrease and so will their achievements, thus reinforcing the majority's belief in the 'inferiority' of the minority." We put the dynamics in the text, in what we say, in the thinking. Who needs a stock?

Yet a stock can create new dynamic behavior endogenously, all by itself, as in Figure 5a, where a constant flow of Articles Produced creates a rising stock of Publications Total. A string of auxiliaries, e.g., links in a CLD, can not produce such a change, as illustrated in Figure 5b.

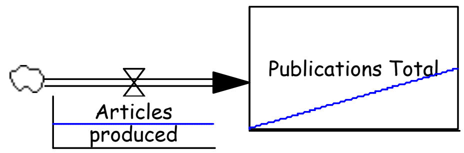

Figure 5a: Illustration of a stock changing the behavior exhibited by its inflow – a constant producing growth over time.

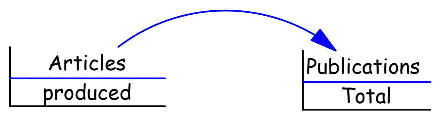

Figure 5b: Illustration showing that an endogenous causal chain without a stock, beginning with a constant, must result in subsequent variables in the chain that are also constant over time.[12]

The inferences should be clear:

- Stocks (accumulations) are necessary to generate dynamics by themselves in simulation models.
- Causal chains with no accumulations can show change over time only if some variable in the chain is disturbed by some exogenous input.
- Mathematically we could say integrals can generate endogenous dynamics, but endogenous algebraic sequences, no matter how complicated, can not.

There's another way to say what we are talking about. Stocks can *transform behavior*; stocks can change the "time shape" of a input (Richardson & Pugh 1981, 178). Figure 6 shows the case of a stock endogenously changing the "cup-down" behavior of the inflow into "S-shaped stock behavior" simply by accumulating the flow.

[12] In Figure 5b, there is no stock, so the bit of model structure says Publications must be algebraically related to Articles Produced. As long as Articles Produced is constant, Publications Total must be constant. Even if there is a string of auxiliaries all tracing back endogenously by some arithmetic to the constant at the beginning, the quantity at the end of the string must be constant also. The only way it could change would be if some quantity in the string were disturbed exogenously.

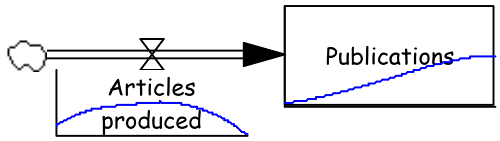

Figure 6: Illustration showing that the accumulation process represented by a stock can transform the time-shape of the inflow behavior into a completely different time shape of the stock.

Indeed, accumulations in complex systems are the endogenous sources of dynamic behavior. To understand the endogenous sources, the origins, and the subtleties of behavior in our mental and formal models, we must include stocks in our thinking.

- In CLDs without stocks, I'm afraid we are doing "systems imagining", not systems modeling. I think it can deserve to be called "systems "thinking" if we include accumulations in our thoughts.
- CLDs without stocks can not generate dynamics on their own. If we have the sense they can, we must be implicitly, unconsciously, adding accumulations to the picture and to our thinking.

Many may find the claim that "accumulations are the sources of system dynamics" disturbing, feeling more comfortable thinking that reinforcing and balancing feedback loops are the real sources of dynamic behavior.

Yet it would be impossible to prove the opposite, that feedback loops are sources of dynamic behavior. We are well aware that complexity defeats mere thought, which we could characterize as the mental manipulation of mental models. We know our mental simulations often fool us in complex systems. But sadly, we can't turn to computer simulation for help because computer simulation of feedback loops in continuous systems without stocks is not possible. Most of our simulation environments will not even allow a loop to be drawn without a stock, and the only one that lets us draw such causal loops (Vensim) will tell you it can not be simulated.

It need not be disturbing. It should be enlightening. All we have to do is include accumulations in all our systems thinking, systems mapping, and systems modeling, and we capture for ourselves and our audiences more of what is essential to understand dynamic systems.

[8] "Systems" are imaginary. We don't "find" them, we "conjure" them.

People have been captivated by "systems" for centuries. Yet they do not exist in the same sense that a waterfall, a highway system, an illness, players at a poker table, or a conference exists. They are not "out there" waiting for us to discover them. A good, confusing example is the national electrical grid. It's really a huge bunch of wires, capacitors, generators, resistors, and similar stuff. Without thought, it's just "stuff". No designer thought of it as a single whole over the decades it took to bring it to what we have today. It is a "system" only when we think of it holistically. As such, it is a "system" only in our heads, in our imaginations. Systems are fictions – usually useful, but fictional nonetheless. We impose "systemicity" on them to create "systems" in our minds.

Like all but one of the items in this Note, Jay didn't tell us that. Adam Smith did, around 1750. In the following lovely quote, Smith said they exist only "in the fancy":

> Systems in many respects resemble machines.
>
> A machine is a little system, created to perform, as well as connect together, in reality, those different movements and effects which the artist has occasion for.
>
> A system is an imaginary machine invented to connect together in the fancy those different movements and effects which are already in reality performed (Smith c.1750)

Smith is saying something almost circular: We don't have a "system" until we think of it that way. The question for this Note is: Is this yet another thing Jay knew but didn't tell us? Did Jay believe that systems are constructs of the imagination, that we have to "think systemically" before we see a system?

I have written [8] as if it belongs in this Note, as something Jay knew but didn't tell us. But the evidence is scant. It is undoubtedly more honest for me to admit that I, the author of this Note, have slipped in a personal bias: Personally, I think Smith was undeniably correct, and I'm unwilling to suggest Jay thought differently. I base my belief partly on the first page of *Industrial Dynamics,* in which Jay begins the ten-step description of his approach with "Identify a problem". He never would have said "Identify a system" – at that beginning moment, there isn't one.

Epilog

We have seen a number of important aspects of our field we think Jay never told us explicitly, or if he did we missed it. We have these nuggets by reflecting on what Jay did, and in some cases by pushing on things he wrote to see what he really meant. It was a valuable thing to do for my own understandings in the field, and I commend the exercise to readers as well.

But imagine what we might find if we did this sort of reflection on all of the great work in our field. Many practitioners have done truly superb work in the field, applications never considered before by others, investigations of some of our thorniest methodological problems, extraordinary exemplary thinking and writing.

What might we learn from, say, the forty Forrester Award winners from what they did, even if they didn't exactly tell us how they got their deepest insights? What might we learn from our most gifted colleagues if we did the sort of deep reflection illustrated in this paper? Let's find out.

Consider our most honored work[13]:

- Winners of the Jay Wright Forrester Award
- Winners of of the Application Award
- Winners of the Dana Meadows Award
- Winners of the Lupina Young Researchers Award

Perhaps my most important insight from thinking about "What Jay Didn't Tell Us" is that he never thought to tell us to do investigations like this. Consider yourself so advised.

How would we do it? Reflecting on the rather haphazard process I followed over the years to produce this note, I came to realize that insights like these in this note tend to come from *surprises*.

An example: One day I was chatting with Jay about *Urban Dynamics,* mainly about the urban renewal efforts in the U.S. in the 1960s. We talked a bit about the efforts cities help revive the inner city by knocking down decayed slums and replacing them with attractive low cost housing. Jay happened to mention that he spent maybe two weeks with the *Urban Dynamics* model investigating variations of that policy, seeing it repeatedly fail in the long run. It was only after that, he said, that he decided to try the opposite, to knock down the worst of slum housing and not replace it. I think he was surprised that that variation made the inner city actually better in the long run. Yes, housing was more crowded, but unemployment was lower, more businesses were staying in the inner city or moving in, and surprisingly, more underemployed people were moving into the city than before in spite of the more crowded housing conditions.

Did Jay know "worse before better" before this experience? Did he know "resistance to policy changes" before that two weeks? Or "compensating feedback"? I love to think he learned from this experience that "if we manage to find a leverage point, we usually push the lever in the wrong direction." Furthermore, did Jay know that leaving out suburbs from the urban model would produce insights that would stand up to Schroeder's structural sensitivity test ([4], note 9)? Or did he just want to see endogenous urban behavior without the outside-the-city complexities of suburbs?

Whether he did or not, in order for Jay to be learning these things, he had to be reflecting deeply on his own work and, I think, to be ever on the alert for surprises.

- Jay had to see the unexpected as sources of potential insights – the more unexpected, the greater the potential significance.
- We have to do the same, in our own work, and in our reflections on the work of our most gifted practitioners.

[13] For thought-provoking examples, see the System Dynamics Society web site describing the work of all the more-than-fifty award winners over the years.

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