Cause&Effect Thinking is Not Enough:

Using System Thinking to Conceptualize Sustainability

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Welcome!

My goals for this Workshop:

1. To identify problems in the public's understanding of sustainability
2. To explain system dynamics and explore its usefulness in enhancing the public's ability to think about sustainable systems
3. To identify leading efforts to teach and help people use system dynamics
4. To begin a discussion on how this approach might be applied (and may already be applied) in the development and implementation of sustainable systems.

My Interest:

1. **Developing students' thinking skills**:

   from my first year teaching physics: most college students and adults don't think as Piaget expected, using "formal operations": identifying variables, asking "what if…?", taking various points of view, finding all combinations, thinking proportionally

2. **Sustainability**

   from the first Earth Day, and now climate change, resource depletion, etc

3. **System dynamics**

   from engineering and then roommates, *Urban Dynamics, Limits to Growth,* etc

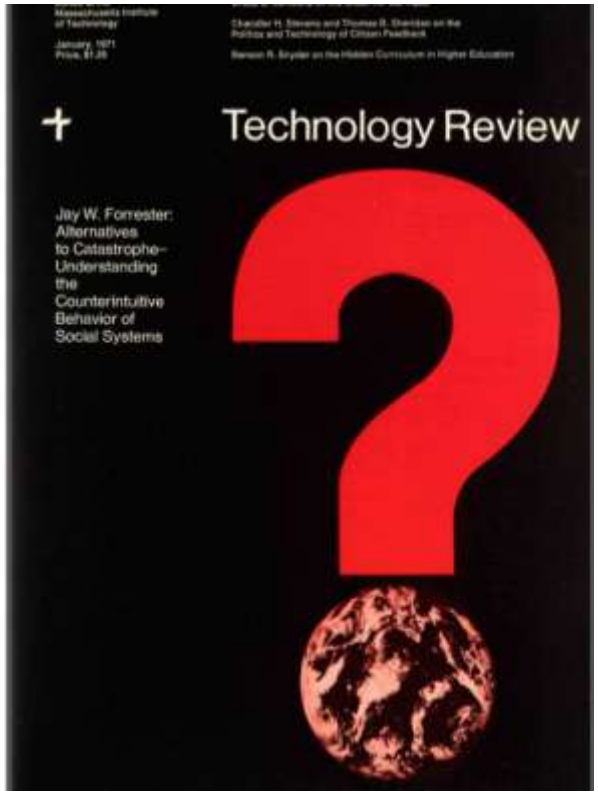
Thinking about sustainable systems requires more than the Piagetian framework, but learning systems thinking will help students learn formal operations, and vice versa.

A bit of my connections to system dynamics (1966 – 1970)

Tutoring Plus

Forging relationships th

1970, 1971…


Technology Review
Jay W. Forrester: Alternatives to Catastrophe–Understanding the Counterintuitive Behavior of Social Systems

"The Counterintuitive Behavior of Social Systems", first paragraph

The human mind is not adapted to interpreting how social systems behave.

… In the long history of evolution it has not been necessary, until very recent historical times, for people to understand complex feedback systems.

Evolutionary processes have not given us the mental ability to interpret properly the dynamic behavior of those complex systems in which we are now embedded.

Jay Forrester, *Technology Review*, January 1971, p52
available online from *www.constitution.org/ps/cbss.htm* and other sources

“The Counterintuitive Behavior of Social Systems”, last two paragraphs

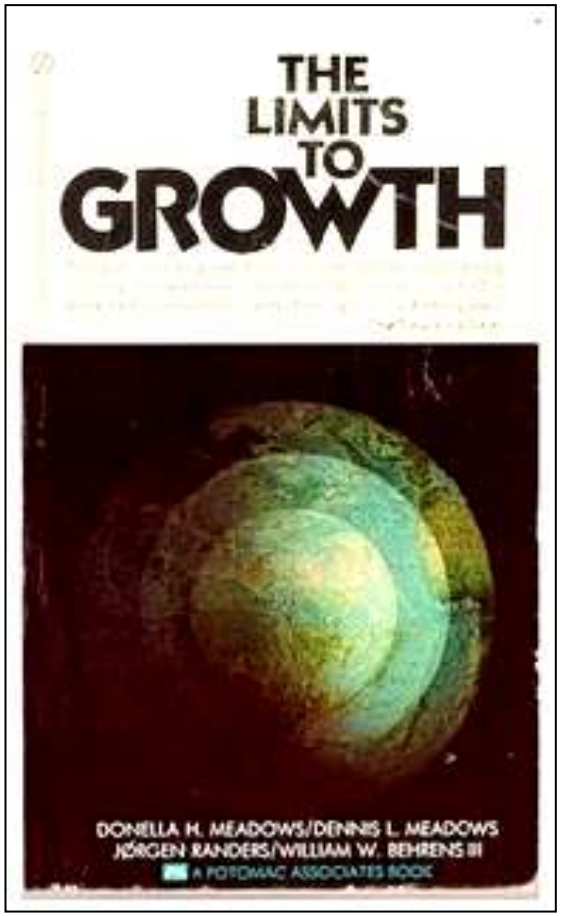
…complex systems mislead people because intuition has been formed by experience from simple systems, from which we expect behavior very different from that actually possessed by complex systems. …

But there is hope. It is now possible to gain a better understanding of dynamic behavior in social systems.

Progress will be slow. There are many cross-currents in the social sciences which will cause confusion and delay. … If we proceed expeditiously but thoughtfully, there is a basis for optimism.

…ibid, p68

…1972…


THE
LIMITS
TO
GROWTH
DONELLA H. MEADOWS/DENNIS L. MEADOWS
JØRGEN RANDERS/WILLIAM W. BEHRENS III
A POTOMAC ASSOCIATES BOOK

Have people learned how to think about complex systems since 1971?

Linda Booth Sweeney and John Sterman, 'Bathtub Dynamics', *System Dynamics Review*, Sept 2000:

- "students at MIT's Sloan School of Management are highly educated and possess unusually strong background in mathematics and the sciences compared to the public at large",

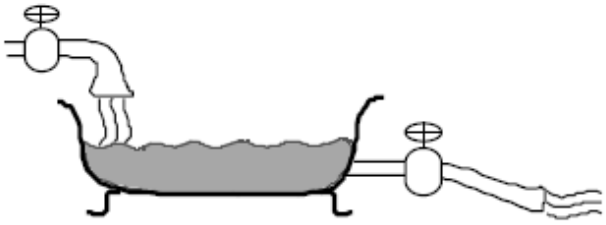
and yet

  - "the students exhibited persistent, systematic errors in their understanding of the basic building blocks of complex systems."

Figure 1 from 'Bathtub Dynamics', ibid, p31

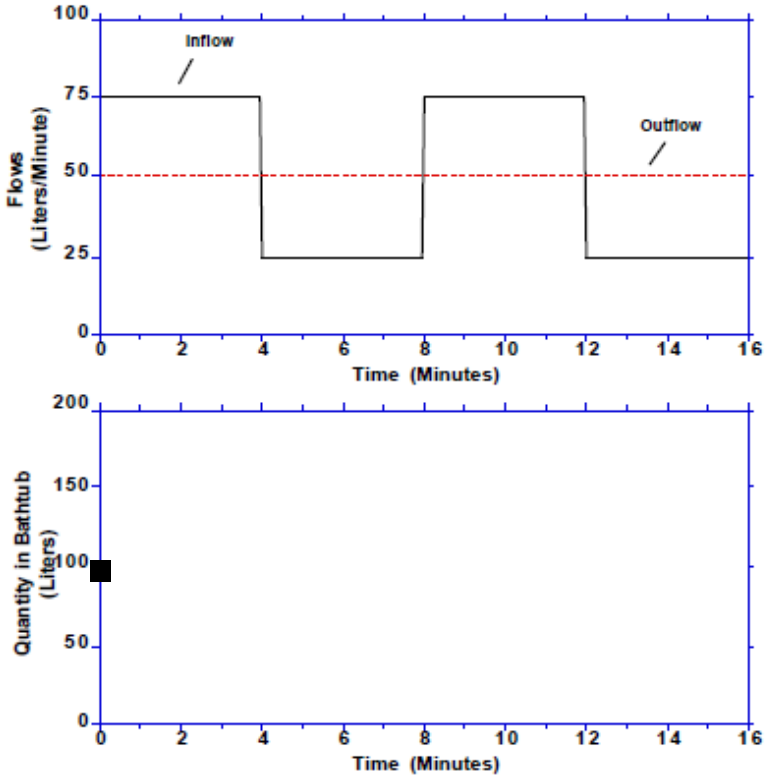
(Subjects in this study were given two additional tasks: one about the cash balance in a store, the other about product inventory in a factory.)

Consider the bathtub shown below. Water flows in at a certain rate, and exits through the drain at another rate:

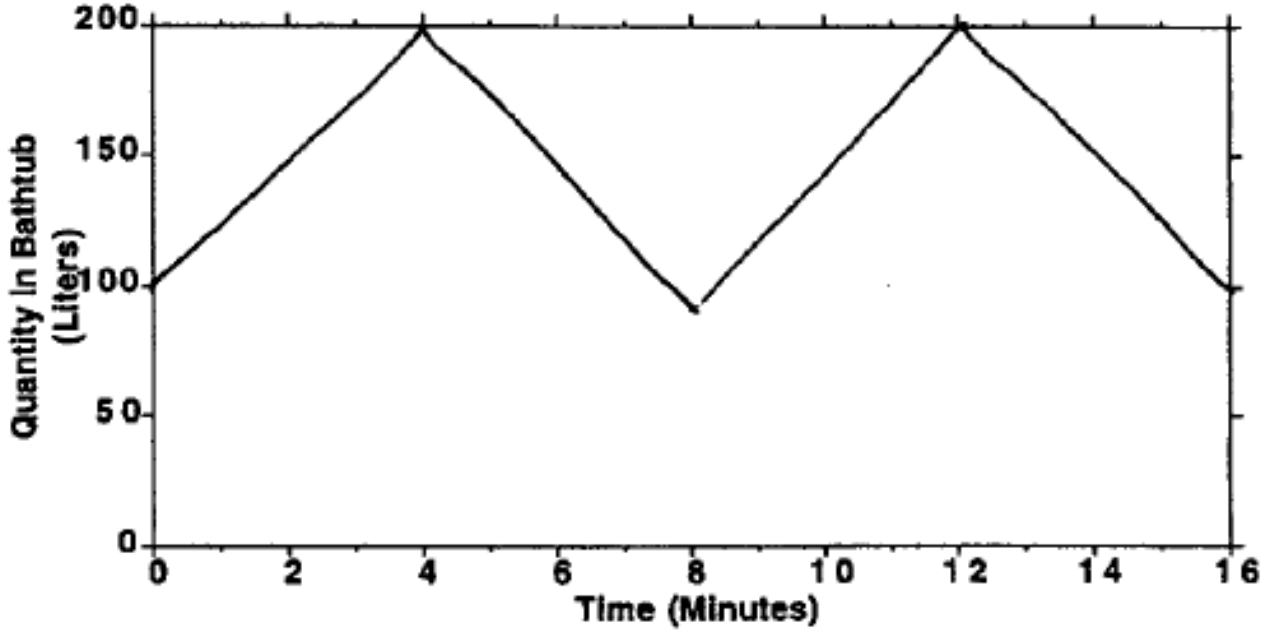


The graph below shows the hypothetical behavior of the inflow and outflow rates for the bathtub. From that information, draw the behavior of the quantity of water in the tub on the second graph below.

Assume the initial quantity in the tub (at time zero) is 100 liters.

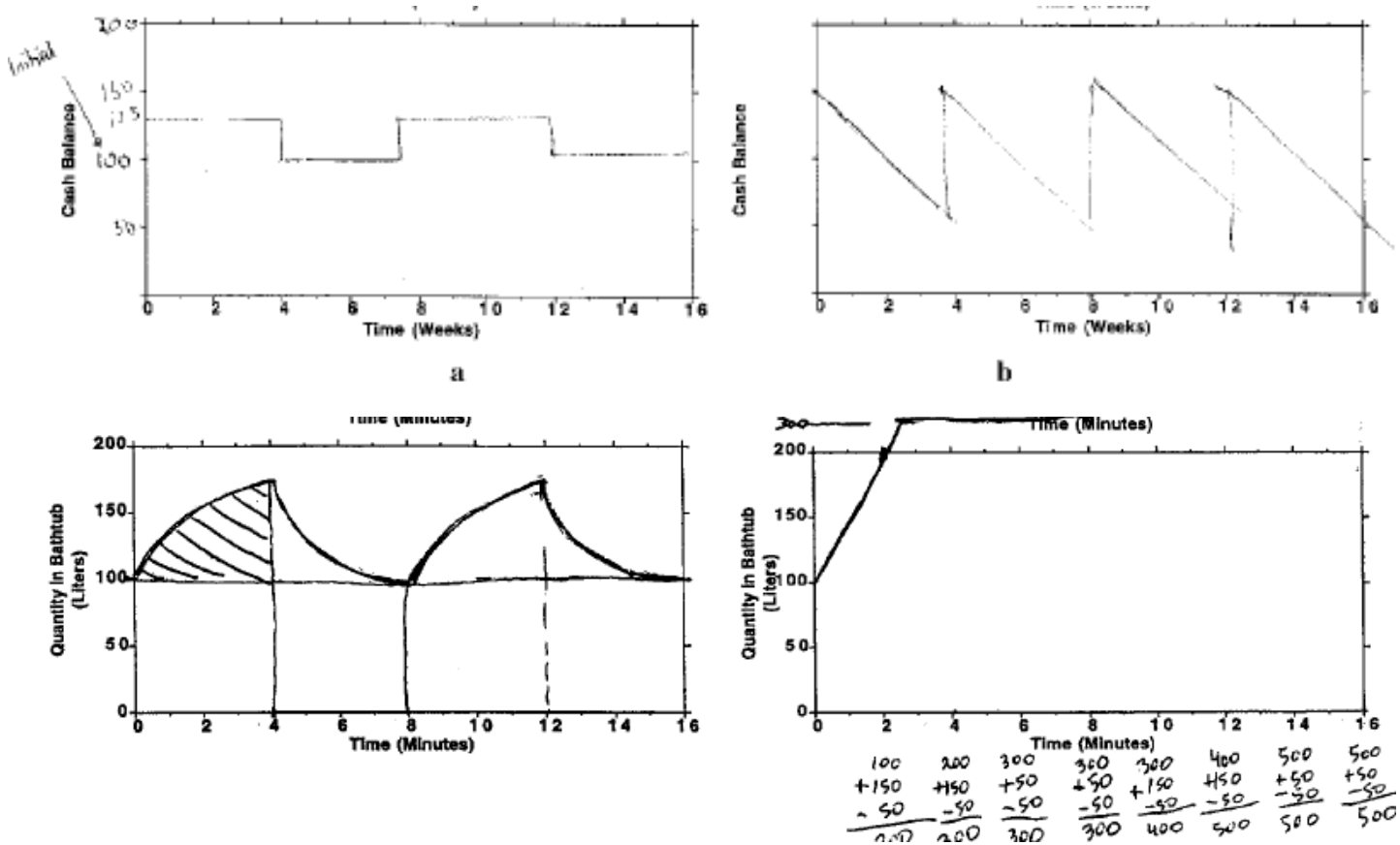


The answer: here's how the level of water in the bath changes:



(from Sweeney and Sterman, "Bathtub Dynamics: Intial Results of a System Thinking Inventory", *System Dynamics Review*, September 2000.)

Typical erroneous responses:



… and in 2002:

further research by Sterman & Sweeney ("Cloudy Skies", *System Dynamics Review*, May 2002) extended the study to include grad students at Harvard and the University of Chicago as well as at MIT

- confirmed the results

- Let's try to do one of the tasks that they gave to these grad students:

Sweeney & Sterman's conclusion?

- "The results strongly suggest that highly educated subjects with extensive training in math and science have poor understanding of some of the most basic concepts of system dynamics, specifically, stocks and flows, time delays and feedback"
- "There is abundant evidence that sophisticated policymakers suffer from the same errors in understanding stocks and flows that we observe in our experiments."
- **But…** subjects who had a small introduction to system dynamics did much better.
    - These concepts are crucial for an understanding of climate change, resource depletion, supply chain management, etc. So we'd better help our students (and our governments!) learn them…

What's behind the mistakes?

The kind of thinking that makes people believe that

- if we lower the rate at which CO2 is put into the atmosphere, that will reduce global warming;
- to decrease the national debt, we only need to lower the the government's yearly deficit;
- the level of water in the bathtub will drop if we lower the rate at which water flows into it

  - We often mix up the amount of something (the **stock** or level) with the rate at which it changes (the **flow** or rate)

So - what is System Dynamics?

(part 1)

- **system:** A collection of parts that interact to function as a whole.
  - A system is almost always defined with respect to a specific purpose.
  - Systems often contain circular patterns of cause and effect called *feedback loops*.

- **dynamic:** Varies with time; not static.

What is System Dynamics? (part 2)

- **System dynamics** is an approach to understanding the behaviour, over time, of complex systems.
- It deals with **feedback loops** and **time delays** involving the system's **stocks** and **flows** that affect the behaviour of the entire system.
- Models using these elements help describe how even seemingly simple systems display baffling nonlinearity.

(from Wikipedia, May 25th, 2011)

Peter Senge's definition (1984)

- System dynamics is a **general-purpose tool** for understanding complex systems… especially complex social systems.
- The tool is unique in its **broad applicability** to biological, [mechanical,] ecological, family, group, corporate, urban, and larger societal systems.
- It is powerful in its ability to integrate traditional points of view and reveal previously unseen innovative approaches to problems.
  - It is clarifying both as an analytic and educational tool, often providing the basis for broadening public understanding of important social issues…
    - [a powerful **paradigm**]

What are the strengths of this paradigm?

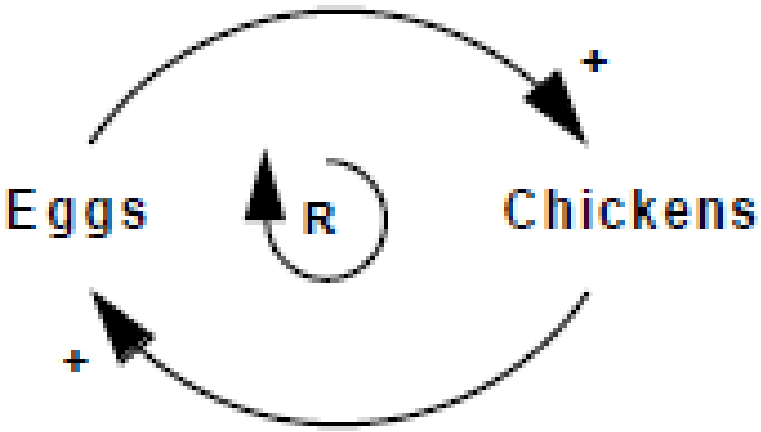
- Its models are **graphic** and **intuitive** to build and discuss (even tho' their outputs may not match our intuition)
- Its archetypes are **broadly applicable**
- Even if a computer-based model is never constructed, the steps involved in building the graphical mental model are themselves powerful and insightful, and help the group make its assumptions about the system explicit

Compared with other approaches:

- Many system relationships can be modelled using Excel, but Excel's models aren't as easy and graphical to build, revise, or review
- Differential equations can model mechanical systems, but most social systems are too complex.

to illustrate "graphic", "intuitive" and "broadly applicable", we'll model a couple of historically important questions:

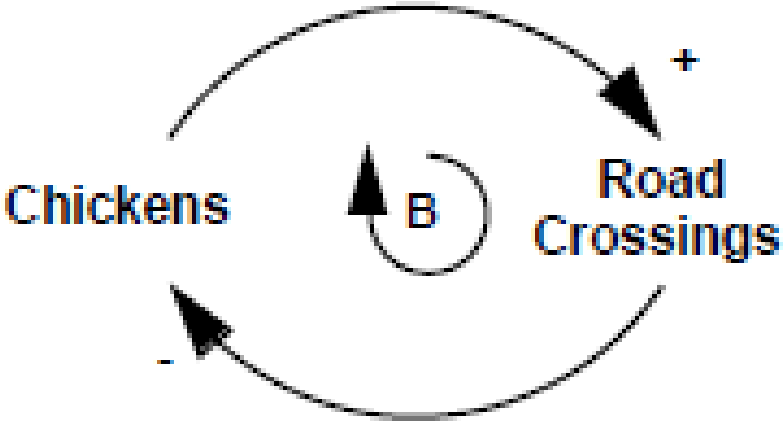
- Which comes first, the chicken or the egg?



a **reinforcing feedback** loop, from Sterman, *Business Dynamics*, 2000. p13

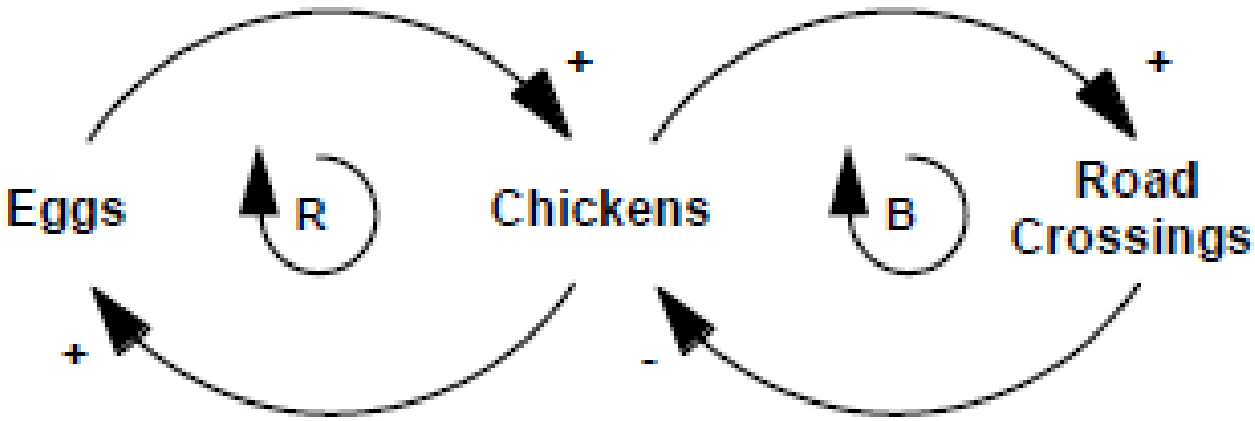
second question:

- Why did the chickens cross the road?



a **balancing feedback** loop, from Sterman, *Business Dynamics*, 2000. p14

But let's not view these in isolation:



… a causal-loop diagram of a dynamic system

- Causal loop diagrams are great for preliminary discussions.
- System dynamics software helps us to go beyond these diagrams, graphically and quantitatively, to build testable simulation models.
    - But now let me introduce you to some of the developers of the field.

Who invented system dynamics?

Jay Forrester

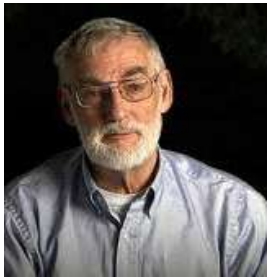
- born July 14, 1918
- farm boy: grew up on Nebraska cattle ranch
- undergrad engineering degree at U Nebraska
- research assistant at MIT; mentored by **Gordon Brown** (pioneer of feedback control systems, later Dean of Engineering and then, after retirement in 1968, instigated teaching of system dynamics in public schools in Arizona)
- oversaw development of NORAD's SAGE radar missile-tracking air defense systems
- invented magnetic core memory
- moved to MIT's new Sloan School of Management in 1956

...

Jay Forrester, continued

- at Sloan, worked on applying engineering systems ideas to management; led development of DYNAMO
- wrote *Industrial Dynamics* (1961) and *Principles of Systems* (1968)
- met John Collins (retired mayor of Boston) at Sloan, wrote *Urban Dynamics* (1969); also "Counter-Intuitive Behavior of Social Systems" (1968)
- met Aurelio Peccei (Club of Rome founder) which led to his *World Dynamics* (1971) and his team to *Limits to Growth* (1972)
- helped found the **System Dynamics Society** and the **Creative Learning Exchange**
  - and he's still at it…

Other leaders in the field:



Donella (Dana) Meadows

- lead author of ***Limits to Growth*** (1972) and its follow-up editions (*Beyond the Limits* and *Limits to Growth: The 30-year Update*)
- PhD in biophysics, Harvard, 1968
- joined husband **Dennis Meadows** at MIT as part of team to develop World 3 model with Jay Forrester
- founded The Sustainability Institute and co-founded The Balaton Institute
- wrote weekly "The Global Citizen" column and many other articles and books
- wrote ***Thinking in Systems*** (2008)
- Pew Scholar, MacArthur Fellow
  - posthumously received the John H. Chafee Excellence in Environmental Affairs Award for 2001 presented by the Conservation Law Foundation.

Other leaders in the field:

Peter Senge

- author or lead author of *The Fifth Discipline* (1990), *The Dance of Change* (1999), *Schools that Learn* (2000), *Presence* (2004), ***The Necessary Revolution*** (2008), etc
- MS in social systems modelling, MIT, 1972
- founded Society for Organizational Learning, 1997

Andrew Ford

- professor of environmental science at Washington State U; teaches computer simulation modeling of energy and environmental problems
  - author, ***Modeling the Environment*** (1999, 2009)

more leaders in the field

Barry Richmond

- developed iThink and STELLA software so that PCs could run system dynamics models; founded iSee Systems

Daniel Kim

- systems author, founder of Pegasus Communications

Dennis Meadows (not just Donella Meadow's husband)

- 2009 Japan Prize (awarded to key individuals "who have contributed to the progress of science and technology and the advancement of world peace and prosperity"), for work on and after *Limits to Growth*

a few more…

Linda Booth Sweeney

- promotes Systems Literacy, wrote *The Systems Thinking Playbook* (for K-12 system dynamics lessons), great website

John Sterman

- *Business Dynamics: Systems Thinking and Modeling for a Complex World* (McGrawHill, 2000)

Juan Martin Garcia

- *Theory and Practical Exercises of System Dynamics*

Louis Edward Alfeld

- *Introduction to Urban Dynamics* (1976); "Urban dynamics – the first fifty years" (1995)

Ugo Bardi

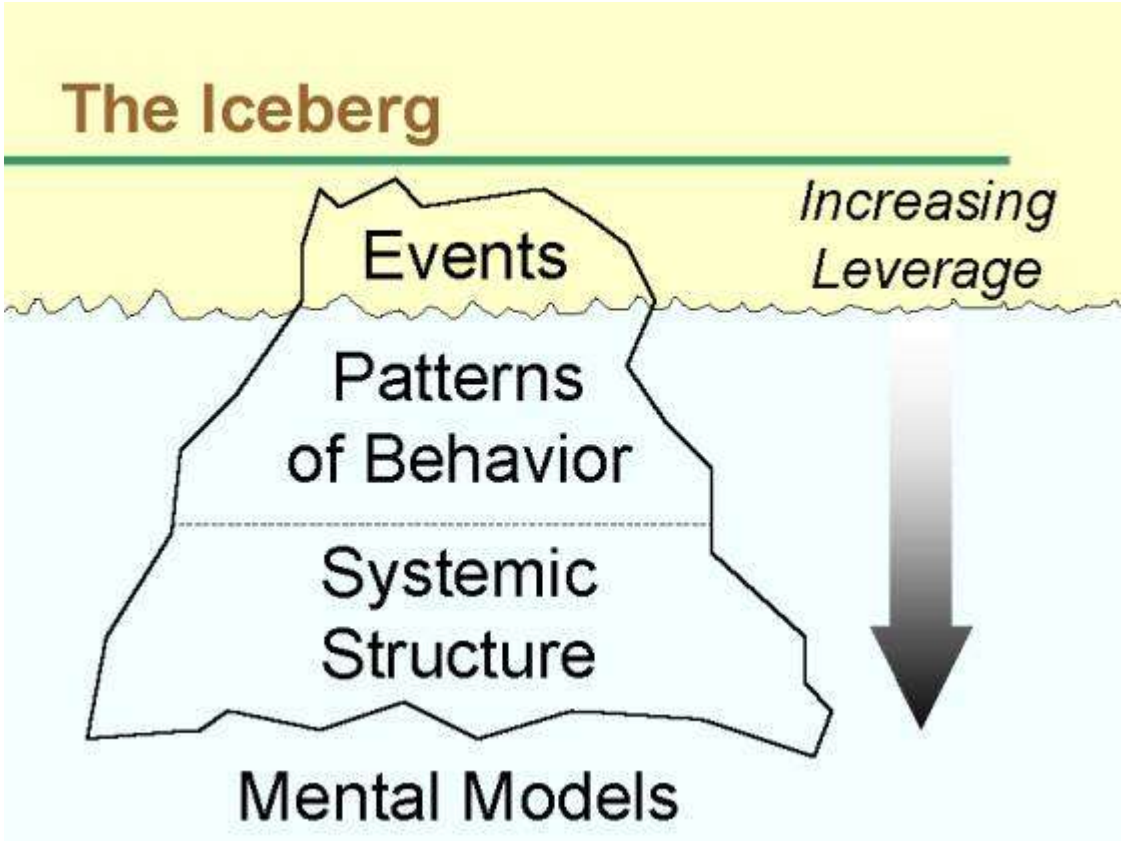
- *The Limits to Growth Revisited* (Springer, 2011)

Jac Vennix

- *Group Model Building: Facilitating Team Learning Using System Dynamics* (Wiley, 1996)

System dynamics helps us look beyond the surface to the system's structure…

To achieve sustainability, we've got to look beyond **events** and **patterns** to the **system's structure**, so we can improve our **mental models** and adjust the system



Let's look at systems from your fields of interest:

- **system:** A collection of parts that interact to function as a whole, for a specific purpose.

Task:

- Get together in groups of three or four.
- Each person think of an important problem in your field.
- Identify a system that's related to that problem, and tell the others about the problem and the system.
- Discuss these systems a bit; see if you see any similarities.
- Then each report back to the whole group.

now that you've identified some systems...

Task, continued:

1. Identify several variables that are part of the system and relevant to the problem
2. Classify each variable as either
   - a **stock**, or
   - a **flow**

- Let's illustrate these terms first ...

What are Stocks and Flows?

from an earlier slide: "System dynamics deals with feedback loops and time delays involving the system's **stocks** and **flows** that affect the behaviour of the entire system."

- **Stock**: how much of something is there?
  - also called a **level**
- **Flow**: how fast is the stock changing?
  - also called a **rate**
- Stocks are increased and decreased by flows – *input* and *output* flows
- **Feedback** about the level of a stock may affect a flow, immediately or after a **time delay**

Stocks

(from iSee Systems)

- Stocks are **Nouns**. They represent a current state, magnitude, or condition. They tell how things are. Freeze the action, and the current condition of the stock persists.
- Stocks accumulate. Items on Balance Sheets are stocks. Think of them as bathtubs.
- Use upper case first letters for stocks:
  - Cash, Population, Water Reserves, Debt, Greenhouse Gases, Trust, Commitment, Anger, Corruption, Frustration, Self Esteem.

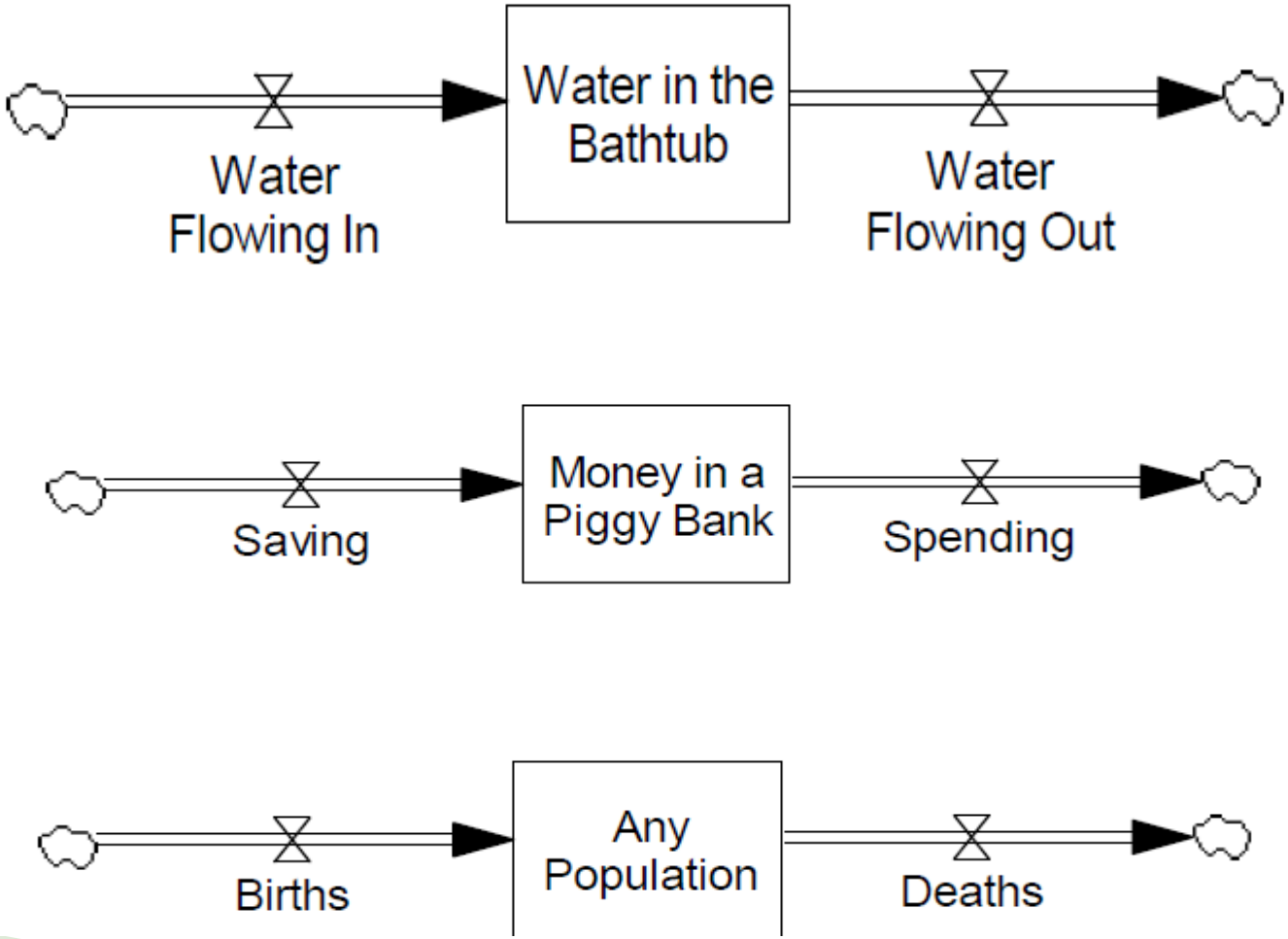
Flows

(from iSee Systems)

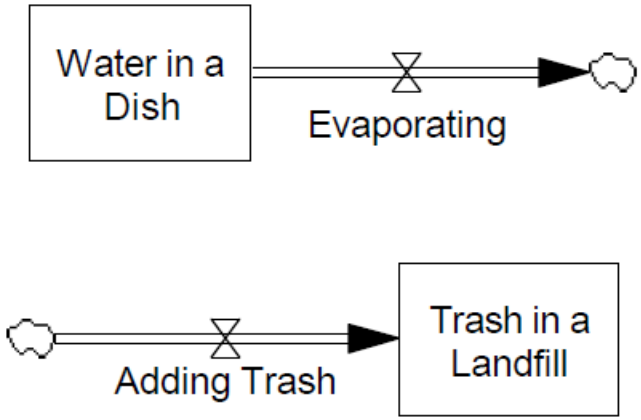
- Flows are **Verbs**. They represent actions or activities. They tell how things are going. Freeze the action and flow volumes go to zero.
- Items in an Income Statement are flows Think of flows as faucets or drains.
- Use “ing” ending whenever possible. Use lower case first letters:
  - spending, quitting, eating, scolding, lecturing, learning, selling, thinking, talking, praising, walking.

stocks and flows, in pictures

(from *The Shape of Change – Stocks and Flows*, Quaden, Totsky and Lyneis, Creative Learning Exchange, 2006)



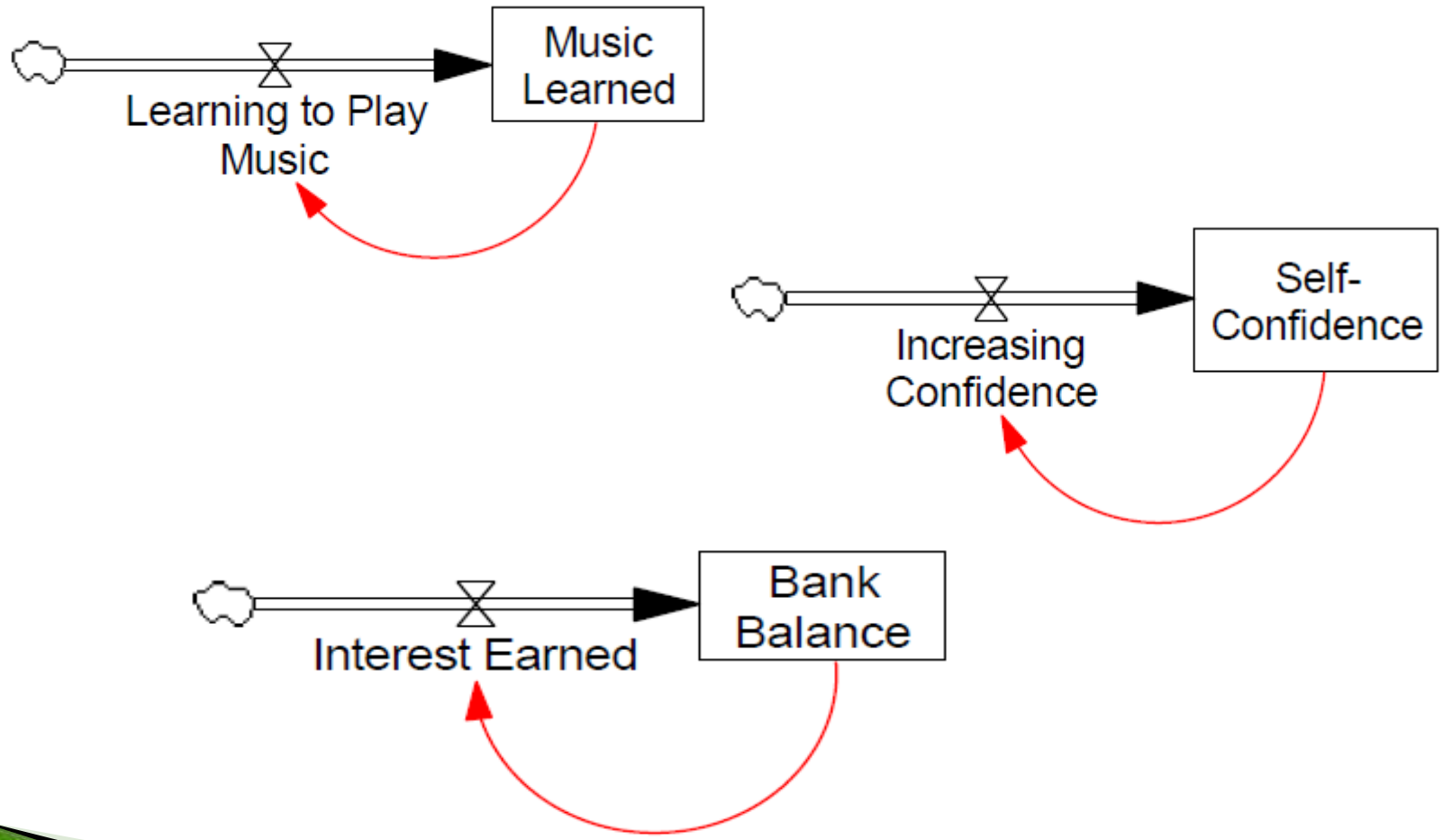
single flows in or out are OK



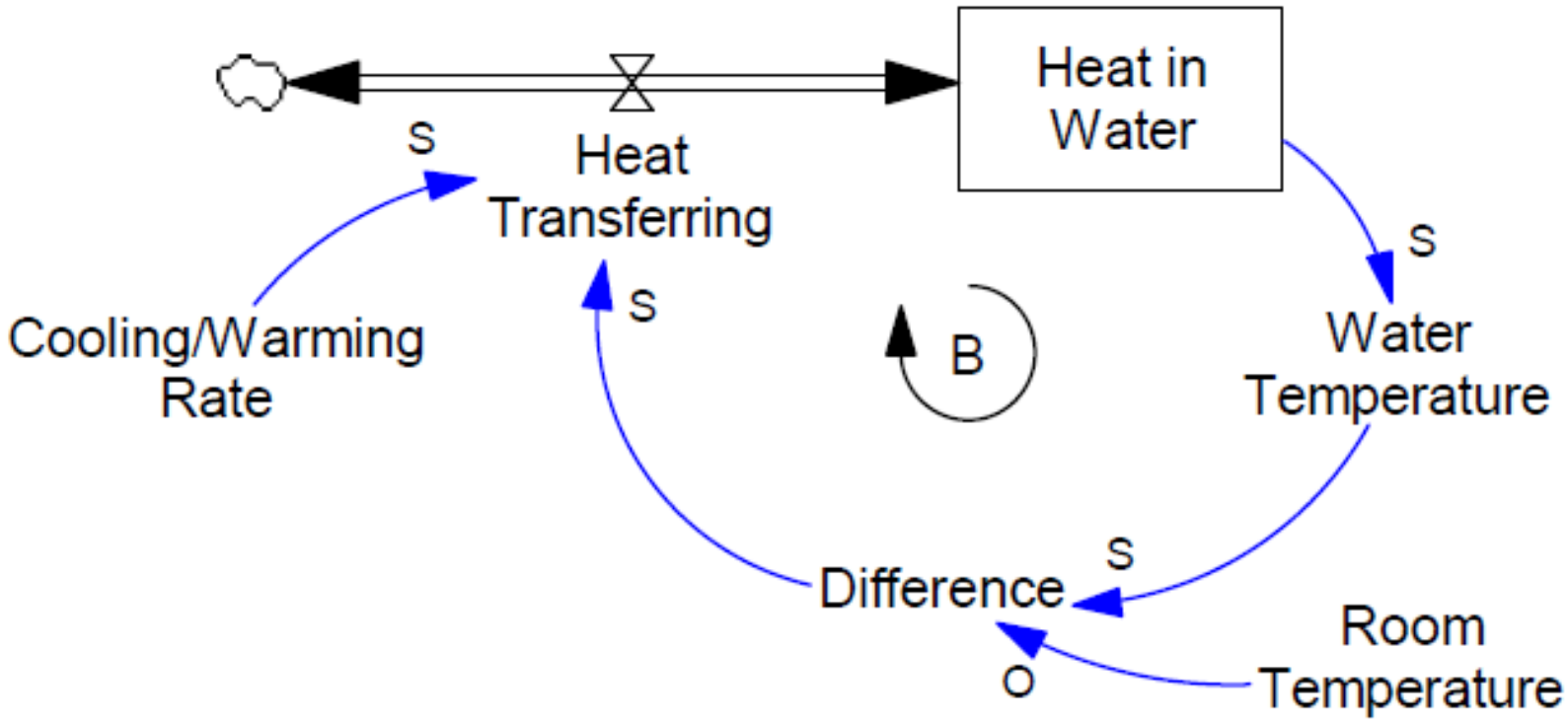
now back to **Task**, part 2:

- Classify your variables as stocks or flows
- Tell your group members how you see it; ask if they see your system's variables the same way.

stocks and flows & feedback



another stock & flow diagram



Task, part 3:

- Work in a your group
- Choose one of your group members' systems to work on
- Discuss the connections between the system's variables; if you discover another necessary variable, add it
- Draw a stock & flow diagram of the system

a population model...

(from Andy Ford's *Modeling the Environment*, 2009)

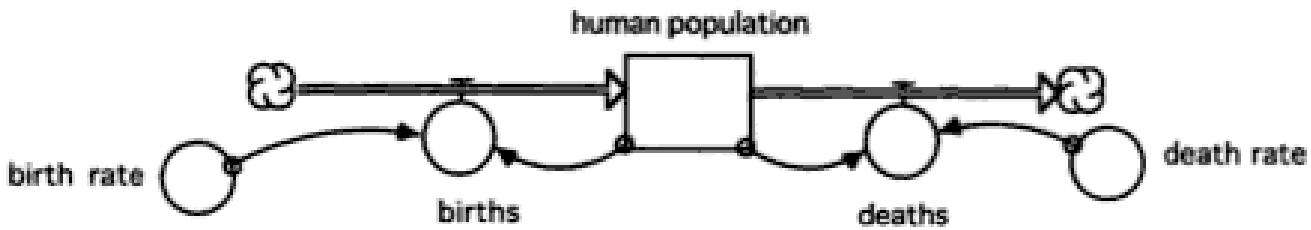


Figure 2.4. Model of population with two flows.

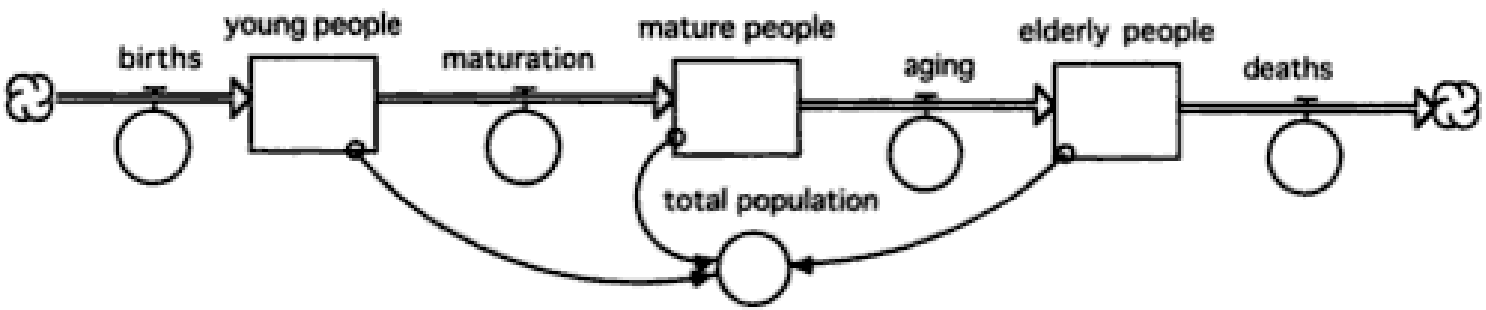
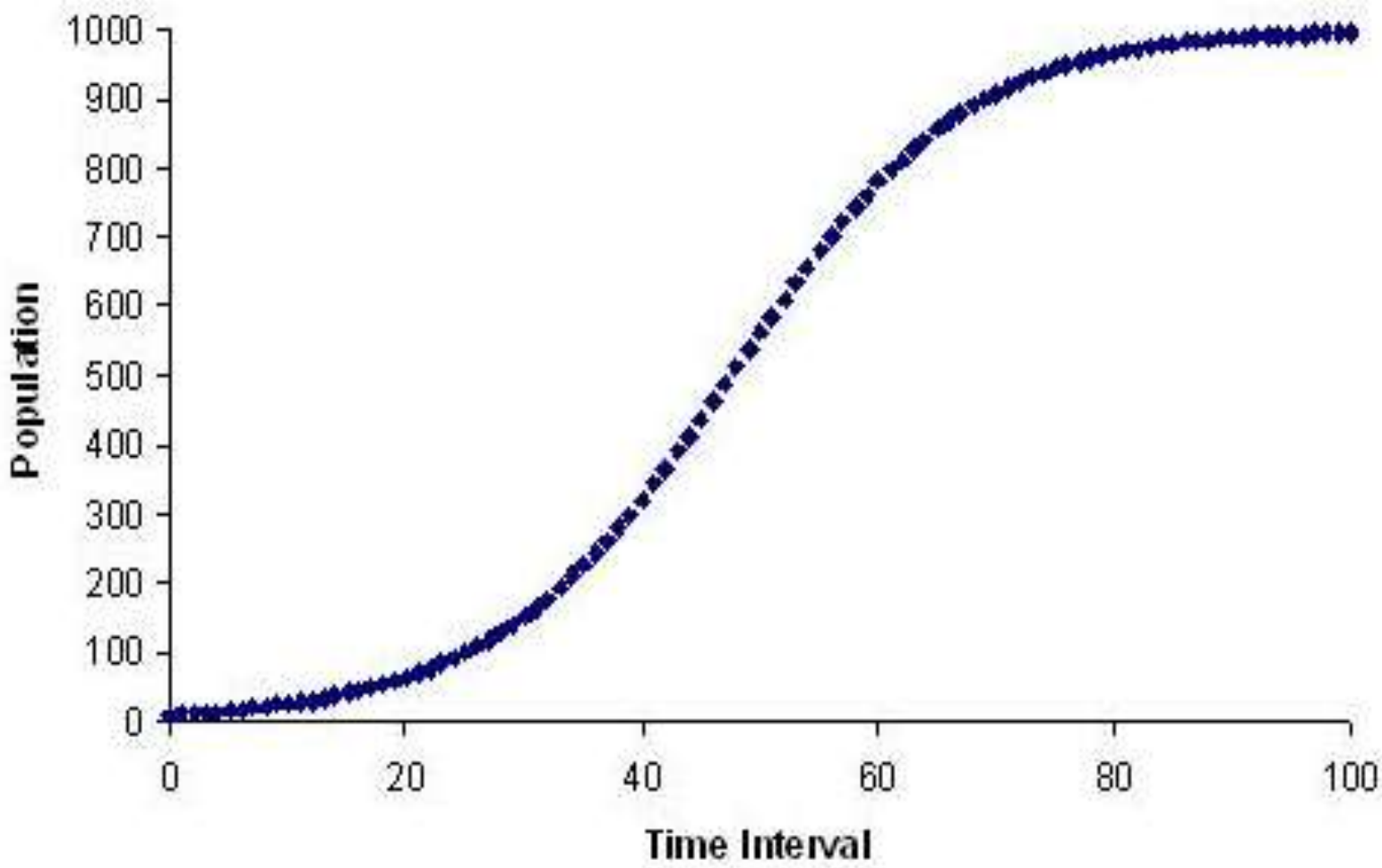
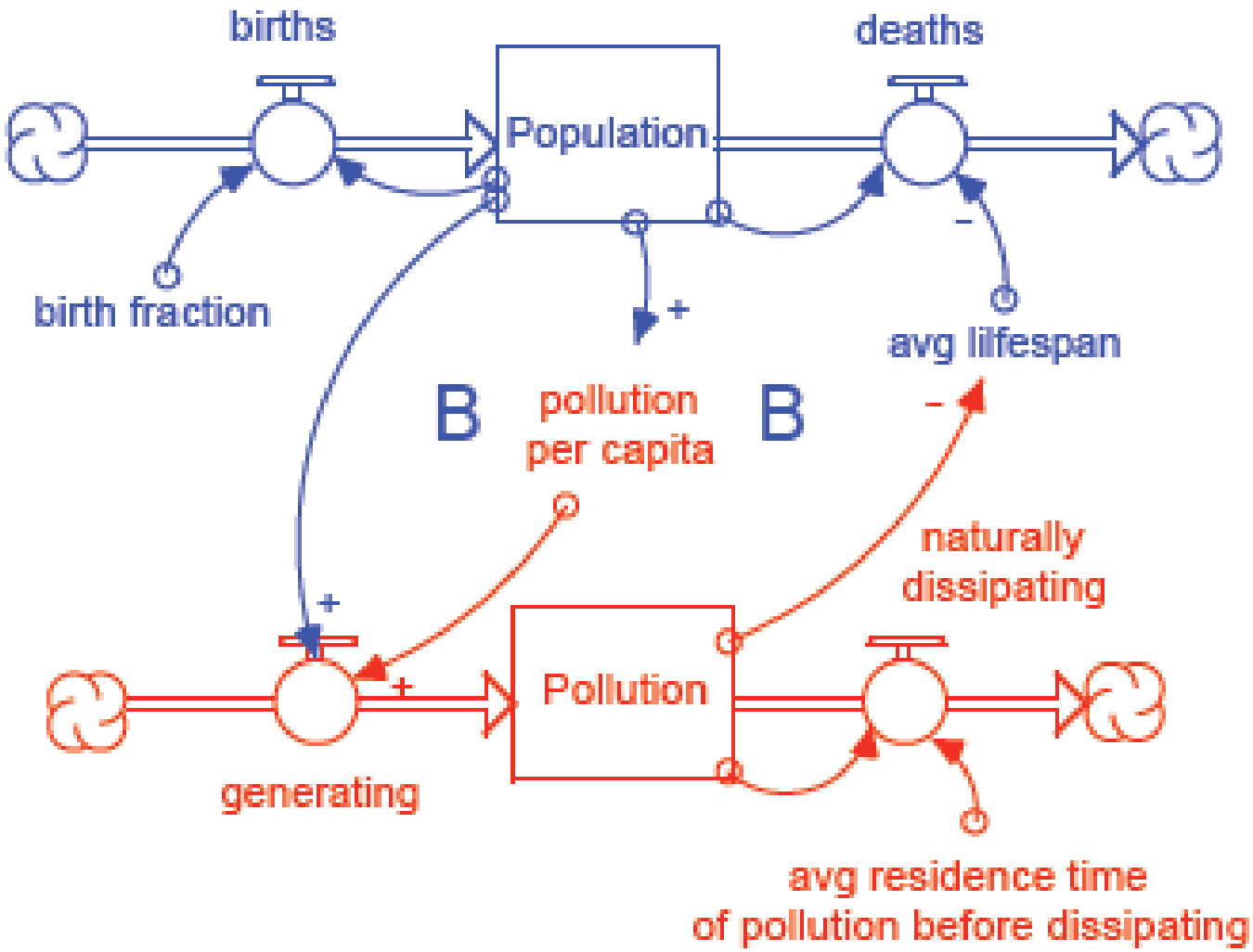


Figure 2.5. Model of population to keep track of maturation and aging.


1000
900
800
700
600
500
400
300
200
100
0
Population
0
20
40
60
80
100
Time Interval

adding some other factors...

(from iSee Systems)



the World3 model...

(from *World Dynamics*, 1972; also used in *Limits to Growth*)

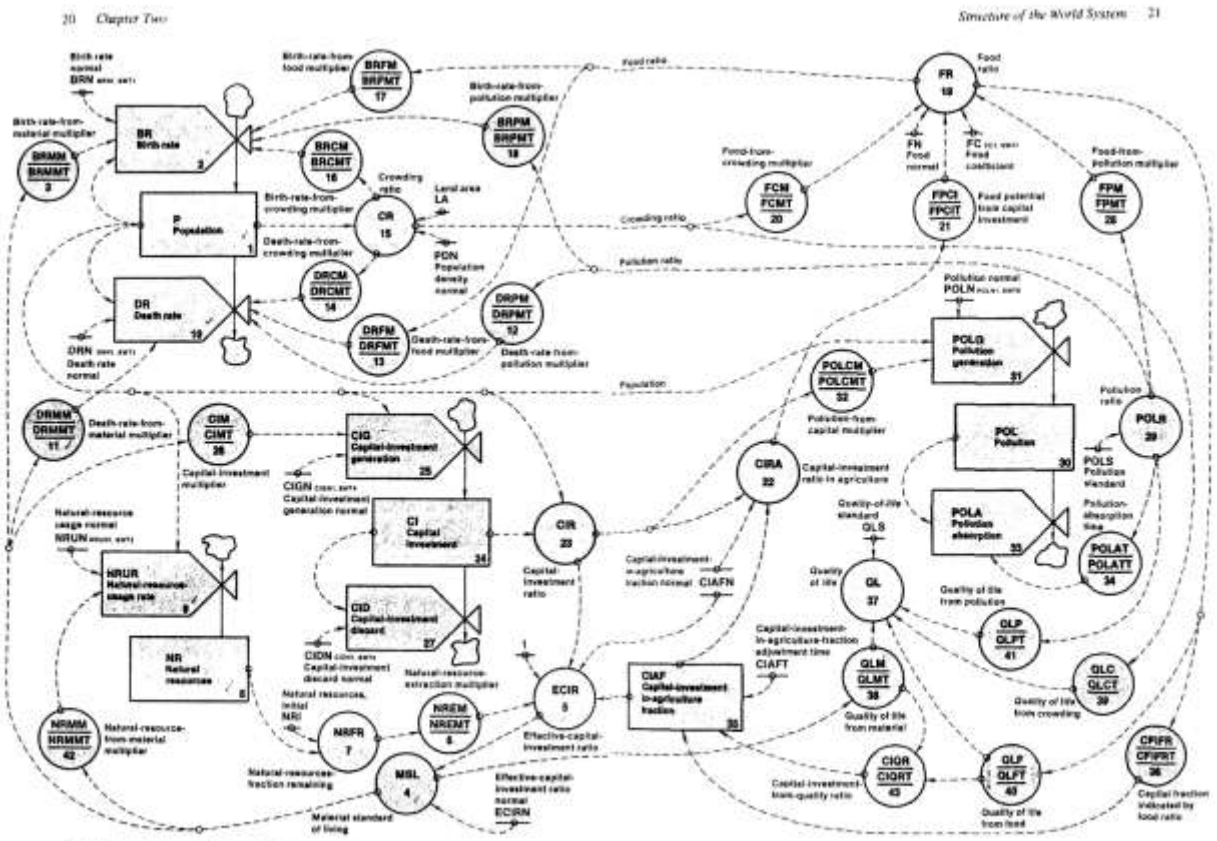
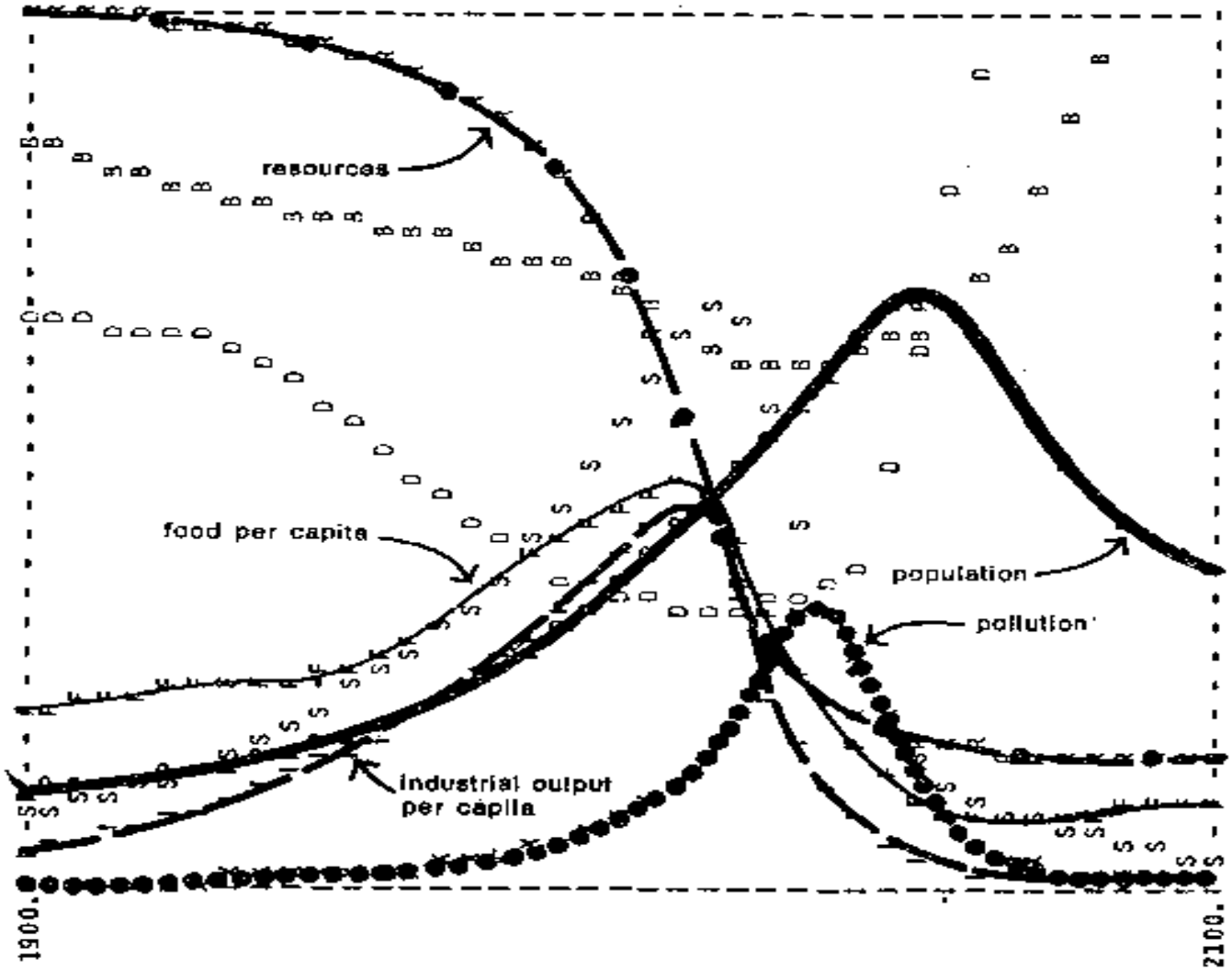


Figure 2-1 Complete diagram of the world model interrelating the five level variables — population, natural resources, capital investment, capital-investment-in-agriculture fraction, and pollution.

Figure 35 WORLD MODEL STANDARD RUN



How might this approach be useful in your field?

Task:

- In small groups, discuss this, and then report back to the whole group

Where is system dynamics being taught?

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The Social Science and Policy Studies department offers an extensive graduate curriculum in system dynamics, which can be pursued independently as well combined with a WPI undergraduate degree program for work towards a 5-year bachelors/masters degree. Our graduate courses are also offered on line for those who may wish to pursue them either individually or as a part of a graduate degree or certificate.

- Graduate Courses in System Dynamics
- Graduate Certificate in System Dynamics
- Master of Science in System Dynamics
- Interdisciplinary Master of Science in Systems Modeling
- Interdisciplinary Doctorate in Social Science
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Where Can I Study System Dynamics?

The field of system dynamics can be studied around the world at both the undergraduate and graduate levels, as well as in executive education programs (non-degree). We hope this page will give you some ideas about where to study. If you are teaching using system dynamics and your course description is not here, please fill the survey form and send it to office@systemdynamics.org. We would especially like to link to your local home page so be sure to include the URL.

Please send suggestions of any kind via Feedback above.

System Dynamics degree courses around the world

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- Australia and New Zealand
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CSDNet is supported by the Boorstein Fund for System Dynamics, a gift to Cornell from alumnus Allen Boorstein (ENGR '46)

Welcome to CSDNet

The last half-century has witnessed tremendous growth in the number of advocates of "systems thinking" as a more appropriate way to address social, economic and environmental problems System Dynamics (SD) is a broadly applicable approach to problem solving that underlies "systems thinking". Using SD, a real-life problem can be expressed as a feedback model that can help to facilitate understanding of how a problem developed over time, and to suggest lasting solutions to the problem.

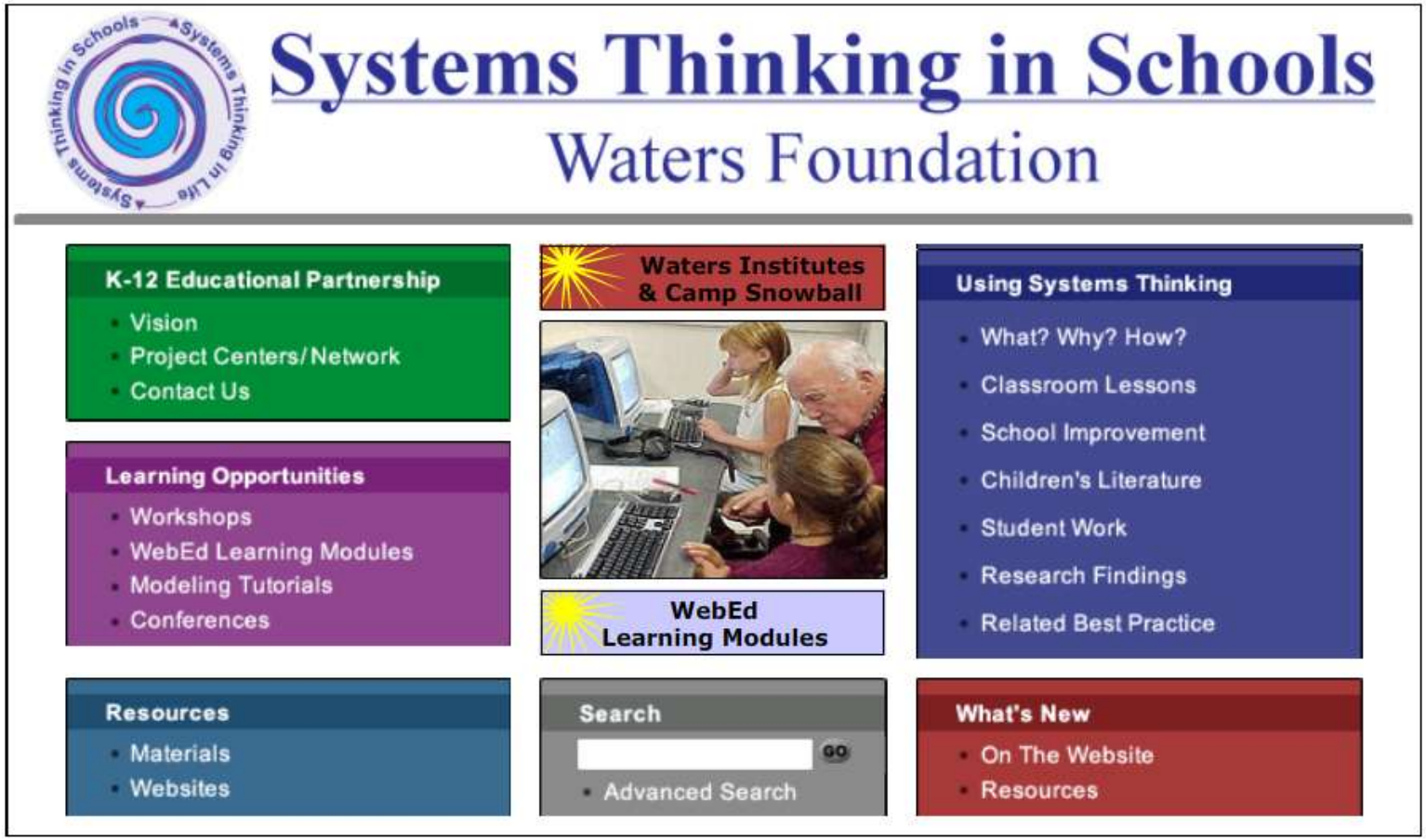
The Cornell System Dynamics Network (CSDNet) is a group of faculty, students and staff from various departments with an interest in the application of systems modeling and systems thinking in research, instruction, outreach and administration. Current CSDNet activities emphasize the application of system dynamics in research. CSDNet undertakes the following activities:

- SD Seminar Series (usually Friday afternoons): invited speakers present seminars on applications of SD to diverse research and policy questions.
- SD Course Development: An introductory course in System Dynamics was offered and Fall 2004 through the Department of Applied Economics and Management. CSDNet has also facilitated access to the courses offered through the well-regarded distance education program offered through Worcester Polytechnic Institute (WPI) in Worcester, MA.

Barriers to the development of a System Dynamics program at Cornell:

- *Limited awareness of SD Methods.*
- *Lack of a community of SD practicioners.*
- *Limited opportunities to learn about SD.*
- *Lack of incentives for faculty, students, staff and administrators to learn and apply SD.*
- *Disciplinary and administrative barriers to funding for SD projects.*

How about in K-12?



from www.watersfoundation.org

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To develop Systems Citizens in K-12 education who use systems thinking, system dynamics, and an active, learner-centered approach to meet the interconnected challenges that face them at personal, community, and global levels

Spotlight

10th Biennial Systems Thinking and Dynamic Modeling Conference - Registration is open!

The CLE is pleased to announce that we will be hosting our 10th biennial ST/DM conference at the Babson Center in Wellesley, MA from June 30 to July 2, 2012. The theme for the conference this year will be ***Critical Thinking: Using Systems Thinking and System Dynamics to address the State Common Core Standards and STEM standards***.

We will explore best practices for using ST and SD in the classroom and in school systems, using the wealth of ST/SD tools and approaches that can help our students (and adults) think critically about the systems around us and how they change over time. The conversation will include the synergy with **Common Core Standards** and the **STEM** process as well as the attitudes and beliefs of systems citizens gained through ST/SD study. **Register** now! **Or learn more...**

Teacher receives System Dynamics Society Lifetime Achievement Award

Diana Fisher, a high school mathematics teacher from Portland, Oregon, was recently bestowed a pretigous Lifetime Achievement Award by the **System Dynamics Society**. It is only the second time, in the 35-year history of the society, this award has been bestowed.

Ms. Fisher has worked over the last 20 years to bring system dynamics into high school mathematics (algebra, pre-calculus, and calculus), and created a year-long system dynamics modeling course for students age 15 to 18 years, using the visual nature of

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Getting Started: Learn System Dynamics

- Introduction to System Dynamics
- Instructional Materials for Modeling

CLE Products

- CLE CD of materials
- *Dollars and Sense* book
- *Healthy Chickens, Healthy Pastures* Playkit
- *Shape of Change* book
- *...that School in Tucson* book and DVD
- *Tracing Connections: Voices of Systems Thinkers* book

Register with CLE

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CREATIVE LEARNING Exchange

System Dynamics & Systems Thinking in K–12 Education

CURRICULUM TRAINING NEWS PRODUCTS ABO

CLE DVD: ....that School in Tucson DVD

..that School in Tucson

A longitudinal study of systems thinking in K-12 Education

View samples from the video

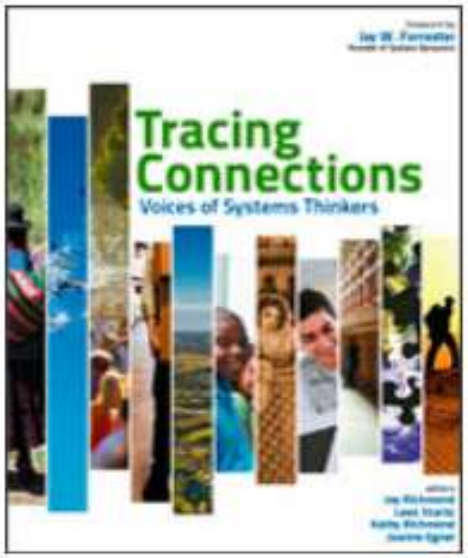
Thirteen years ago, middle school students and their faculty in Tucson, AZ, pioneered a revolutionary new approach to learning—using systems thinking tools to engage in collaborative, real-world problem solving that honed their critical thinking skills. We have the rare opportunity to revisit some of them thirteen years later and hear how this learner-centered approach transformed their lives. The excitement they felt, the confidence they developed, and the fostered habits of mind are all still evident in their maturation into young adults with the skills and motivation to be leaders in today's complex world.

Tracing Connections: Voices of Systems Thinkers

with a foreword by Jay W. Forrester

"This extraordinary book could not come at a better time..."

Peter Senge



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Tracing Connections is for anyone who's ever wondered how Systems Thinking can be effectively used to significantly and successfully transform education, business, public policy, and research.

In ten chapters, teachers, World Bank Executives, corporate consultants, researchers and college professors lead the reader through an amazing spectrum of applied System Thinking that leads to unexpected realizations and critical understanding.

Inspired by Barry Richmond, Systems Thinking pioneer, isee systems founder, and creator of STELLA and *iThink*, **Tracing Connections** reveals how a new way of thinking can radically improve your ability to work through complex issues and uncover elegant solutions.

Sustainability Institute

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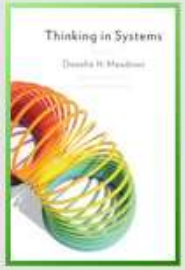
THINKING IN SYSTEMS – A PRIMER



"*Thinking in Systems* is required reading for anyone hoping to run a successful company, community, or country. Learning how to think in systems is now part of change-agent literacy. And this is the best book of its kind."—**Hunter Lovins**, founder and President of Natural Capital Solutions and coauthor of *Natural Capitalism: Creating the Next Industrial Revolution*

In the years following her role as the lead author of the international bestseller, *Limits to Growth*—the first book to show the consequences of unchecked growth on a finite planet— Donella Meadows remained a pioneer of environmental and social analysis until her untimely death in 2001.

DONATE NOW (+)

DONELLA MEADOWS LEADERSHIP FELLOWS PROGRAM

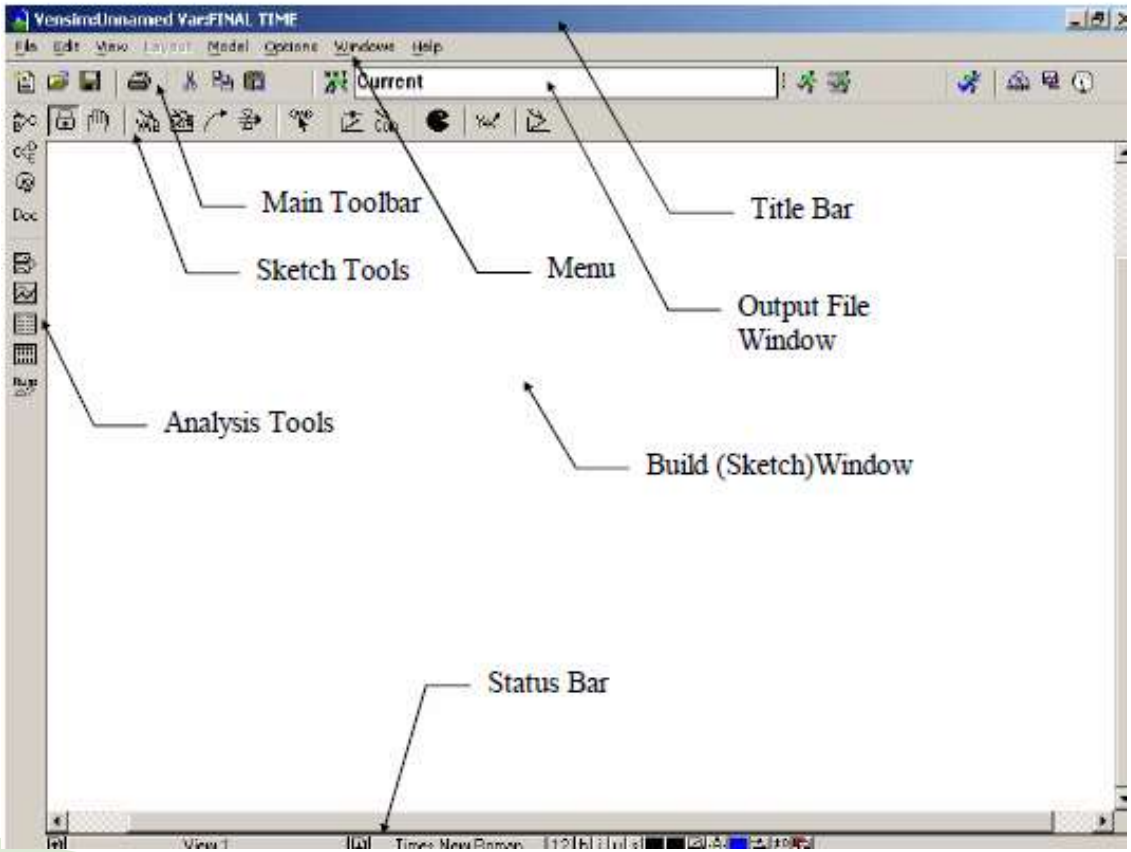
The mission of SI's Fellowship Program is to accelerate the shift to global sustainability by increasing the effectiveness of well-positioned sustainability leaders. Fellows learn to address social, economic and environmental issues at their root causes while benefiting from a national and international network of talented and supportive colleagues. More (+)

System dynamics in use: IPCC's 'Climate Interactive' modeling

Software for modelling

Vensim PLE

- free for educational use: www.vensim.com/software.html
- quick tutorial at: www.public.asu.edu/~kirkwood/sysdyn/SDRes.htm

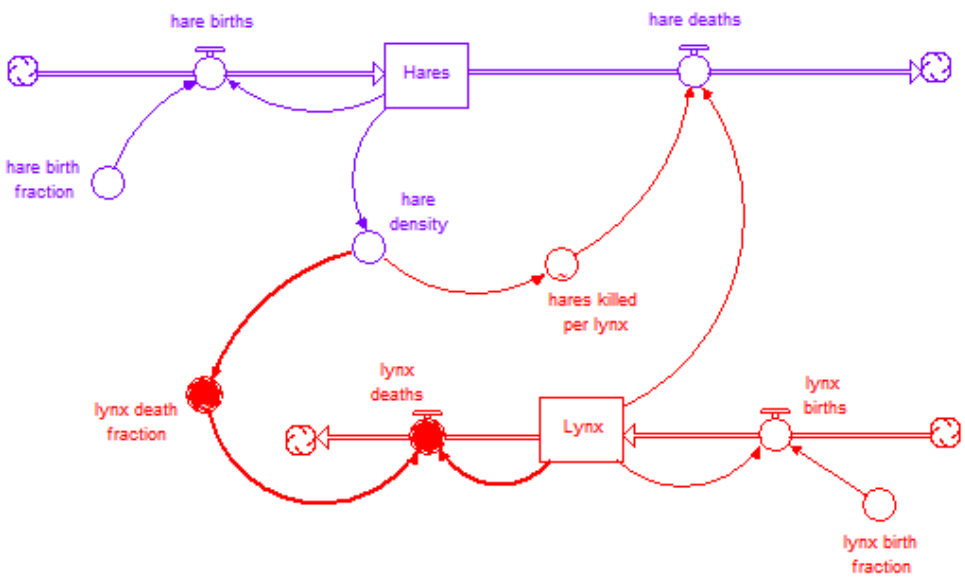


Software for modelling

iThink or STELLA

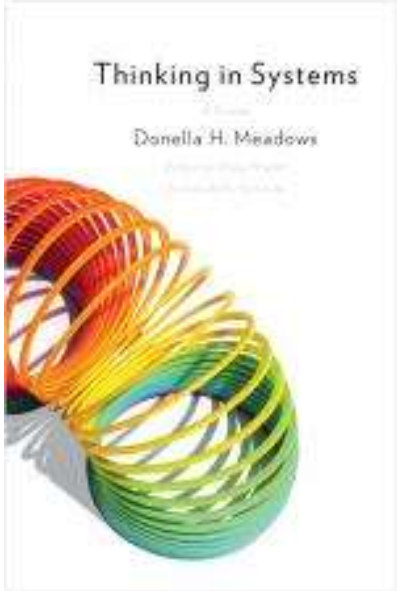
- www.iseesystems.com/

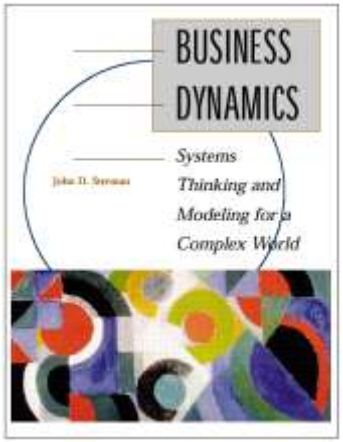
Simple Predator-Prey Dynamics
Core Model Structure



Texts and other resources

- *Thinking in Systems*, by Donella Meadows
- *Business Dynamics*, by John Sterman
- *Modeling the Environment*, by Andrew Ford
- *Principles of Systems*, by Jay Forrester
- *Modeling Dynamic Systems,* by Diana Fisher
- *The Global Citizen*, by Donella Meadows (book and web archive)
- many articles on-line…





… System Dynamics Websites

1. www.sustainer.org/
2. www.clexchange.org/
3. www.watersfoundation.org/
4. www.systemdynamics.org/
5. www.pegasuscom.com/aboutsd.html
6. thesystemsthinker.com/systemsthinkinglearn.html
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9. www.lindaboothsweeney.net/
10. www.ccmodelingsystems.com/
11. www.wpi.edu/academics/Depts/SSPS/Graduate/certificate.html
12. www.uib.no/rg/dynamics
13. www.europeansystemdynamics.eu/
14. www.iseesystems.com/community/downloads/NetsimModels.aspx
15. www.vensim.com/software.html
16. climateinteractive.org/

What next?

- Discuss the possibilities:
  - new, introductory courses?
  - integrating SD into existing courses? what support would be useful?
  - new elective courses?
  - in which Faculty or Faculties and Department(s)?
  - in Faculty of Education, to train teachers?
  - other comments and ideas?

Thank you!

(next page for activists only…
if you want to change the system)

Places to Intervene in a System

(From *Thinking in Systems*, Donella Meadows, 2008)

In order of increasing effectiveness:

12. Constants, parameters, numbers (such as subsidies, taxes, standards)

11. The sizes of buffers and other stabilizing stocks, relative to their flows

10. The structure of material stocks and flows (such as transport networks, population age structures)

9. The length of delays, relative to the rate of system change

8. The strength of negative feedback loops, relative to the impacts they are trying to correct against

7. The gain around driving positive feedback loops

Places to Intervene in a System,

continued

in order of increasing effectiveness

6. The structure of information flows (who does and does not have access to what kinds of information)

5. The rules of the system (such as incentives, punishments, constraints)

4. The power to add, change, evolve, or self-organize system structure

3. The goals of the system

2. The mindset or paradigm out of which the system - its goals, structure, rules, delays, parameters - arises

1. The power to transcend paradigms