Using systems thinking to attract more kids (and teachers!) to math and the scientific method

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Systems Thinking and Dynamic Modeling Conference for K-12 Education
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What is the systems lens?

Hint: Structure and behavior

Agenda

• What is system dynamics?
• Change over time by grade & subject
• K-3 Example
• Potential grade-staging of system dynamics artifacts
• Description of a few of the artifacts
• Using system dynamics to think about drug-related crime
• Modeling Process: Connections to the scientific method
• Barry Richmond’s systems thinking skills
• Really important outcomes of practicing systems thinking
• Connections to math
• Next steps
What is System Dynamics?

System dynamics \([\textit{systems thinking}]\) deals with how things \textit{change through time}, which includes most of what most people find important.

It uses \textit{computer simulation} \([\textit{systems thinking uses mental simulation instead}]\) to take the knowledge we already have about details in the world around us to show why our social and physical systems behave the way they do.

System dynamics demonstrates how most of our own decision-making policies are the cause of the problems that we usually blame on others, and how to identify policies we can follow to improve our situation.

System dynamics gets a lot of its power from a 'feedback' perspective -- the realization that tough dynamic problems arise in situations with lots of pressures and perceptions that interact to form loops of circular causality, rather than simple one-way causal chains.

See Reference 1 for an interesting article by Jay Forrester, entitled “Learning Through System Dynamics as Preparation for the 21st Century.”

(above from 1997 system dynamics email list postings by Jay W. Forrester and George Richardson)
Change through time examples by age & subject (except math & science)

<table>
<thead>
<tr>
<th>Subject</th>
<th>Age Group</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>K-3</td>
</tr>
<tr>
<td>Personal Life</td>
<td>Plant system</td>
</tr>
<tr>
<td>News</td>
<td></td>
</tr>
<tr>
<td>Literature</td>
<td></td>
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<tr>
<td>History</td>
<td></td>
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<tr>
<td>Civics</td>
<td></td>
</tr>
<tr>
<td>Economics</td>
<td></td>
</tr>
<tr>
<td>Health &amp; PE</td>
<td>Tired at bedtime – hours of sleep</td>
</tr>
</tbody>
</table>

Using system dynamics to attract more kids (and teachers!) to math and the scientific method
Integrating Model-Building Concepts in the Primary Grades Curriculum

“Using as a guide the Report of the National Council for the Social Studies Task Force on Scope and Sequence (Social Education 1984), the subject matter recommended for the primary grades focuses on the home, family, and local community. Three key system dynamics concepts may be introduced at the primary grade level in conjunction with these topics:

1. **Causation and Feedback** – a change in one element in a system will cause a change in another, eventually affecting the original element again
2. **Change** – focusing on behavior as it changes over time
3. **System** – encouraging the student to understand how all the parts of a system fit together (synthesis-level thinking). This way of thinking is quite natural for younger students but seems to disappear from the curriculum in the upper grades.”

“Using these two pictures, a teacher can begin generating a “circle” story, such as:

**Being tired at bedtime causes you to sleep.** When you’ve had a good night’s sleep, and you go to bed the next night, you probably feel less tired, **causing** you to stay up late and play. Staying up late playing will probably cause you to get less sleep and be tired again the next night at bedtime.
A second K-3 example from Nancy Roberts\textsuperscript{2}

This series of pictures suggests that when a child leaves a room messy, it might cause the child’s mother to be angry. An angry mother might cause the child to straighten up his or her room. When the mother notices the clean room, it might cause her to be happy and relaxed, perhaps causing the child, the next time at play, to forget and leave the room somewhat messy again.
A third K-3 Example from Nancy Roberts

Seed-plant cycle: The more seeds there are, the more plants there will be, producing even more seeds and plants.

Self-regulating cycle: The more plants there are, the more crowded they are, causing an increase in the number of deaths, eventually resulting in fewer plants and less crowding.
An educated guess for grade-staging of a few systems thinking concepts & artifacts*

K-3

4-6

7-9

10-12

Causation & feedback, change & system via simple causal loop diagrams (SCLDs)

Playing physical group games that introduce system concepts (Group Games)

Drawing simple stock and flow diagrams (SFDs)

Using simple pre-built simple simulation models & games (SIM Games)

Graphing simple behaviors-over-time (BOTGs)

Adding link & loop polarities to make complete CLDs

Building simple no-feedback simulation models (NFSIMs)

Building simple feedback SIMs (SFSIMs)

Building feedback SIMs (FSIMs)

* Based on curriculum units at http://clexchange.org/ & http://watersfoundation.org/

“It is amazing how far one can get in this world using a little first year algebra along with computer simulation!”

Paul Newton
4 systems thinking artifacts we illustrate

• BOTG (Behavior-over-time graph)
• CLD (Causal loop diagram)
• SFD (Stock-flow diagram)
• SIM (Simulation)
Systems Thinking Artifacts: BOTGs & CLDs

- **Tiredness during day**
  - Dynamic hypothesis: 
    - Hours of sleep
    - Tired at bedtime
    - Can't catch up

- **Happiness of mother**
  - Dynamic hypothesis: 
    - Messiness of room
    - Happiness of mother
    - I'm sorry Mama!

- **Number of plants**
  - Dynamic hypothesis: 
    - Number of seeds
    - Number of plants
    - Natural limit
    - Anything is possible
    - Amount of crowding
    - Number of deaths

Graphical representations show the relationships and dynamic hypotheses between these variables.
Systems Thinking Artifacts: SFD & SIM

Number of Plants

Number of Growing Plants

Number of Plants

plant death rate

normal mature plant lifetime

average plant lifetime

effect of crowding

fraction of total area occupied

gEographical area available

total area occupied by plants

area required per plant

Number of Plants : Current

Number of seeds

Anything is Possible

Natural Limit

number of plants

number of deaths

Natural Limit

number of seeds

Anything is Possible

number of plants

amount of crowding

number of seeds

Anything is Possible

Natural Limit

number of deaths

20100801b_AddDeathRate_SimOfFigure5pt9APlantSystem.mdl
Creating Model Equations:

First draw sketch elements. Then use mouse to “click in” the equations. Equations are best kept simple as shown below...

Number of Plants = INTEG ( maturing - plant death rate , initial number of plants )
Units: plant

total area occupied by plants = Number of Plants * area required per plant
Units: feet * feet

Sprouting = Number of Plants * germinating seeds per year per plant
Units: plant / Year

average plant lifetime = normal mature plant lifetime * effect of crowding ( fraction of total area occupied )
Units: Year

This section of the equation is like “f(x)” where the function “f” is “effect of crowding.” Although “effect of crowding” is a function, you don’t have to write an equation; instead you just “click in” the function shape you want!
What is the systems lens?

Number of Plants germinating seeds per year per plant

Number of Growing Plants sprouting

time to mature

Number of Plants maturing

Number of Growing Plants

Total area occupied by plants

fraction of total area occupied

area required per plant

Natural Limit

normal mature plant lifetime

average plant lifetime

effect of crowding

generig area available

Number of Plants : Current

Structure and Behavior

System dynamics’ iterative modeling process

1. State Problem (Reference Modes)
2. Hypothesize Structure (SFDs or CLDs)
3. Develop Equations
4. Test Model (Simulate To Try To Replicate Reference Modes)
5. Compare Strategies (Decision Rules, Policies)

Results of any step can yield insights that lead to revisions in any earlier step (indicated by the links in the center of the diagram).

Connections to the Scientific Method

Does this look familiar?

How would you compare or contrast this with the scientific method?

Using systems thinking to attract more kids (and teachers!) to math and the scientific method!
The Modeling Process

“Systems Thinking” vs. “System Dynamics”

1) Problem articulation
   – Theme selection
   – Key variables
   – Time horizon
   – Dynamic problem definition (reference modes)

2) Formulation of dynamic hypothesis
   – Initial hypothesis generation
   – Endogenous focus
   – Mapping (CLDs, SFDs, HDs)

3) Formulation of a simulation model
   – Specification
   – Estimation
   – Tests

4) Testing
   – Comparison to reference modes
   – Robustness under extreme conditions
   – Sensitivity
   – Many other tests… (see chap 21)

5) Policy design and evaluation
   – Scenario specification
   – Policy design
   – “What if…” analysis.
   – Sensitivity analysis
   – Interactions of policies

[Chapter 3 of Sterman (2000)]

**Systems Thinking**

- Everyone agrees that “systems thinking” includes these.
- Some people say system thinking encompasses these too, Policy design is best with the aid of simulation, but, in the absence of simulation, is certainly better with the feedback-rich systems thinking view than without.
Systems thinking & dynamic modeling of a social problem: Drug-related Crime

"Drugs are a big worry for me, not least because of the crimes that people commit to fund their dependency. We want the police to bust these rings and destroy the drugs. They say they're doing it and they keep showing us sacks of cocaine that they've seized, but the crime problem seems to be getting worse".

Typical description of the problem by the victims of drug-related crime

Our hunch is that using systems thinking and dynamic modeling on such problems as this will attract more students and teachers to mathematics and the scientific method.

Unintended
Dynamics of Drug-Related Crime

Graph the behavior-over-time described on the previous slide...

Systems thinkers ask: “What feedback structure could explain this puzzling divergence?”

[Morecroft (2007) p 47, Fig 2.10]
Causal Loop Diagram (CLD) for Drug-Related Crime

“What feedback structure could explain this puzzling divergence between reported crime and expected crime? Systems thinkers would say that the persistence of unwanted growth in crime suggests a feedback loop that weaves its way around society, and by doing so it goes unnoticed.”

Stakeholders represented?
- Community
- Police
- Drug users
- Drug dealers

Systems Thinking
- a ‘shift of mind’ from ‘event-oriented’ to ‘feedback systems’ thinking
- expanded thinking boundaries
- tells ‘the rest of the story’
Individual Stakeholder Views

Community
- community sensitivity to crime
- call for police action

World of the Drug Users
- average yield per crime incident
- drug related crime
- funds required to satisfy addiction
- demand for drugs

Street Market
- initial street price
- change in street price
- supply of drugs on the street
- total supply of drugs
- drug supply gap
- pressure for price change
- demand for drugs

Police Department
- indicated allocation of police
- change in allocation of police
- time to move staff
- number of police allocated to drug busting
- drug seizures
- police effectiveness in drug busting
Feedback loop that wends its way around society, and by so doing, goes unnoticed!
1) Problem Articulation

Reference Modes

Drug Related Crime

Dynamic Hypothesis

Model Formulation

Testing

Parameter settings for the three simulation runs

Parameter: "police effectiveness in drug busting"

<table>
<thead>
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</tr>
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Drug Related Crime

Drug seizures

call for police action

crime related crime

supply

Crime Spiral

price

demand

SD Process with BOTG, CLD, SFD & Sim Tools

Drug Related Crime

incident/Month

Time (Month)

0  3  6  9  12  15  18  21  24  27  30  33  36  39  42  45  48

Looks like our Reference Mode!
Behavior on previous slide is like our reference mode...but there's a problem...

Drugs on the street should not go negative!!!

And now they don’t!
Continuing to use the Model to Improve Our Thinking

1. State Problem (Reference Modes)
2. Hypothesize Structure (SFDs or CLDs)
3. Develop Equations (Simulate To Try To Replicate Reference Modes)
4. Test Model
5. Compare Strategies (Decision Rules, Policies)

Price is growing beyond all reason

But now it doesn’t...

Price
Final Model Simulation Behavior

Supply of Drugs on the Street

Drug Related Crime

Price

Number of Police Allocated To Drug Busting
What is the Systems Lens?

Structure & Behavior

Drug Related Crime

reported expected

time

Time (Month)

0 3 6 9 12 15 18 21 24 27 30 33 36 39 42 45 48

drug related crime: 4th Base
drug related crime: 4th Effectiveness 10 to 20
drug related crime: 4th Effectiveness 10 to 0

Parameter settings for the three simulation runs

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Systems Thinking Skills

- 10,000 meter thinking¹
- System as cause thinking¹
- Dynamic thinking¹,²
- Operational thinking¹,²
- Closed-loop thinking¹,²
- Non-linear thinking¹

- Scientific thinking¹,²
- Empathic thinking¹
- Continuum thinking²
- Generic thinking²
- Structural thinking²
- Quantitative Thinking³

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What distinguishes/defines Systems Thinking is a unique collection of thinking skills

10,000 Meters Thinking
System as Cause Thinking
Dynamic Thinking

Operational Thinking
Closed-loop Thinking
Continuum Thinking
Nonlinear Thinking

Quantitative Thinking
Scientific Thinking

Filtering Skills
(what to include, what to omit; and at what level of aggregation?)

Representing Skills
(stocks, flows, converters, feedback loops)

Simulating Skills
(internally-consistent numbers; controlled experiments)

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The REALLY IMPORTANT outcomes of practicing systems thinking

from

http://watersfoundation.org/
Systems thinking connections to math

**Mathematical Thinking**
- Change over time
- Causation
- Continuous vs. discrete time
- Integration & differentiation
- Layers of causation (loops as well as links)
- Aggregation
- Problem formulation: setting time & space boundaries
- Modeling

**Math content & techniques**
- Graphing over time
- Better solve word problems
- Making algebra concrete
- Causation vs. correlation
- Importance of units
- Notion of a limit
- Functions
- Numerical integration
- Nonlinear relationships
- Exponential growth & decay
- Sigmoidal growth
- Oscillations

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Next Steps

• Does it now seem to you that there might be potential for systems thinking to attract more students (& teachers) to math and the scientific method?
  – If so, we need to think together about how to help you learn more about this....

• If we decide systems thinking can attract more students and teachers to math and the scientific method (to STEM), then
  – We need to figure out how to help both in and pre-service teachers gain adequate systems thinking skills, and
  – We need to set up a system of coaching for these teachers, e.g. perhaps retirees & volunteer engineers from Boeing & other companies.

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# Systems thinking curriculum unit examples by age & subject [(#)s are references]

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</table>

|                              | 4-6                                   |
|                              | The Friendship Game (9)               |
|                              | Schoolwork, homework and grades (11) |

|                              | 7-9                                   |
|                              | causes of the Civil War in the U.S. (4) |
|                              | Search & Destroy Policy in Vietnam (10) |
|                              | New Deal - FDR 1932-1940 (7)          |

|                              | 10-12                                 |
|                              | Civil rights: allowed vs perceived (8) |
|                              | bank balance with interest rates (3)  |
|                              | mortgage financing (3)               |
|                              | managing a retail store (6)          |
|                              | drinking and driving (5)             |

Using systems thinking to attract more kids (and teachers!) to math and the scientific method
References numbered on slides

11. http://watersfoundation.org/index.cfm?fuseaction=content.display&id=125
Introductory Books & Software for Teachers

• Books
  – Systems thinking group activities & games
    • Quaden, Rob and Allen Ticotsky (2008) *The Shape of Change*
  – Introduction to systems thinking
    • Richmond, Barry (2010) *An Introduction to Systems Thinking with Stella*. (book is great, even if you don’t buy the Stella software)
  – Introduction to simulation modeling

• Software
  – *Vensim PLE* (Personal Learning Edition - free for educational use, including personal educational use)
  – *STELLA* (most K-12 education models have been built in STELLA)
Introductory Books & Software for Business

• Education
  – IseeSystems Short course
  – Online courses: Worcester Polytechnic Institute
  – Free online self-study courses: Roadmaps or Guided Study Program or Dept of Energy
  – Courses around the world

• Books
  – Business Dynamics: Systems Thinking and Modeling for a Complex World, by John Sterman
  – An Introduction to Systems Thinking, by Barry Richmond and IseeSystems
  – Process Improvement Manual, by IseeSystems

• Software
  – Vensim
  – iThink