

SYSTEM DYNAMICS MODELING IN SCIENCE AND ENGINEERING

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Contents

System Dynamics Modeling is

- **SIMPLE**

Simple tools make the modeling of dynamical systems accessible

- **POWERFUL**

Simple ideas can be combined into models of complex systems and processes

- **USEFUL**

It makes the integration of modeling and experimenting a simple matter

- **NATURAL**

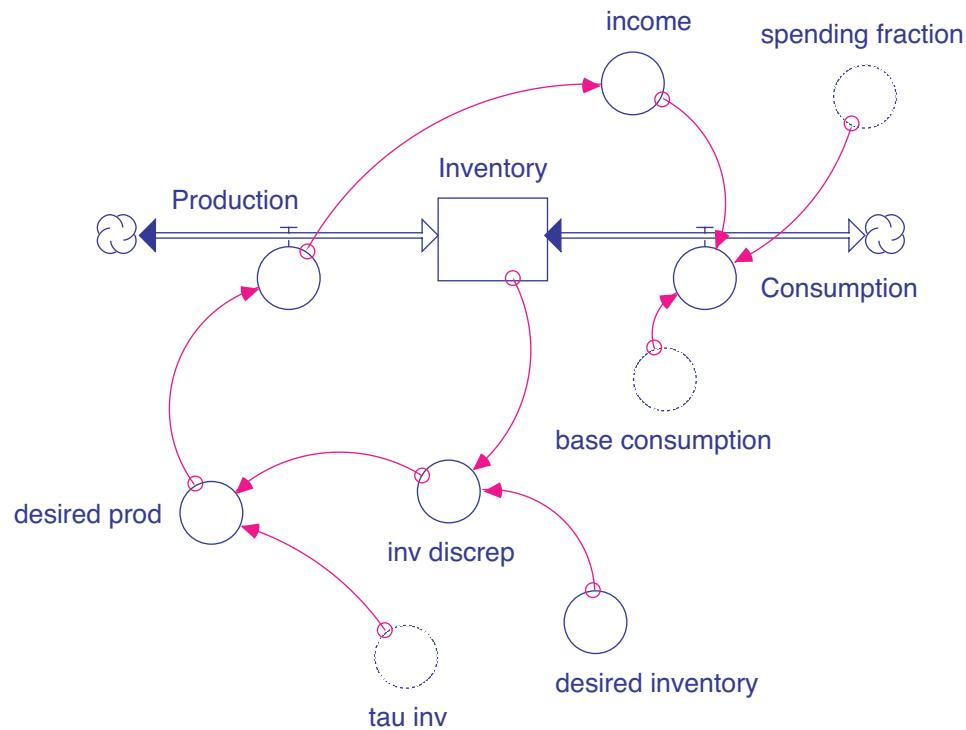
The simple ideas behind SD models correspond to a basic form of human thought

- **FUN...**

...see for yourself...

SD Modeling: An Example

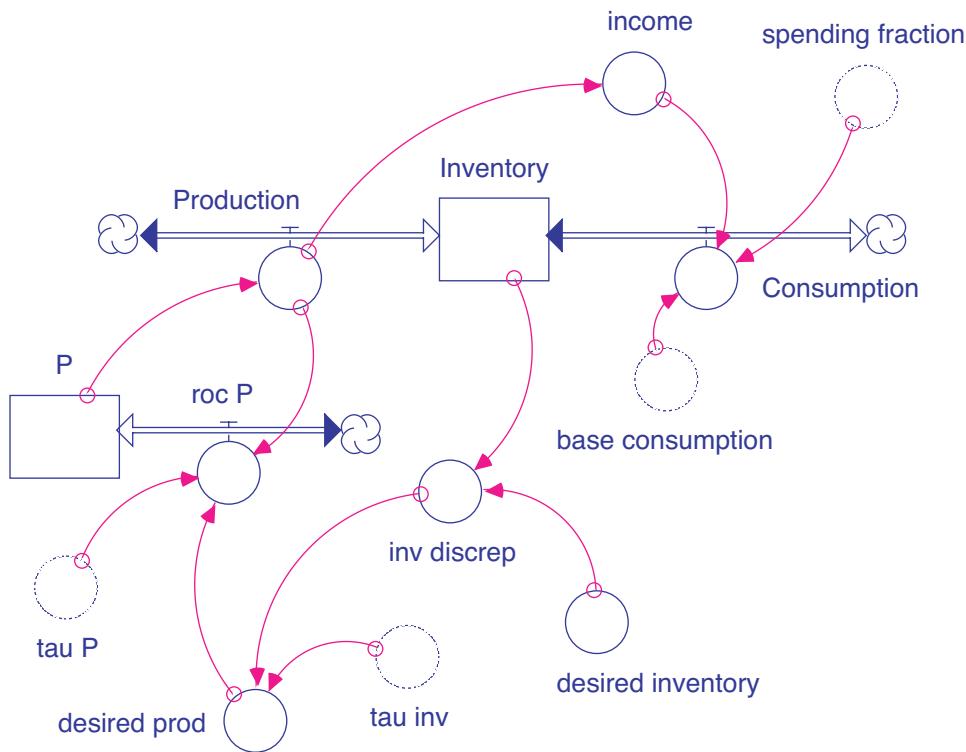
Visual representation



The balance of a substance (Inventory of products in an economy), plus ideas concerning processes changing the quantity of this substance.

SD Modeling: An Example

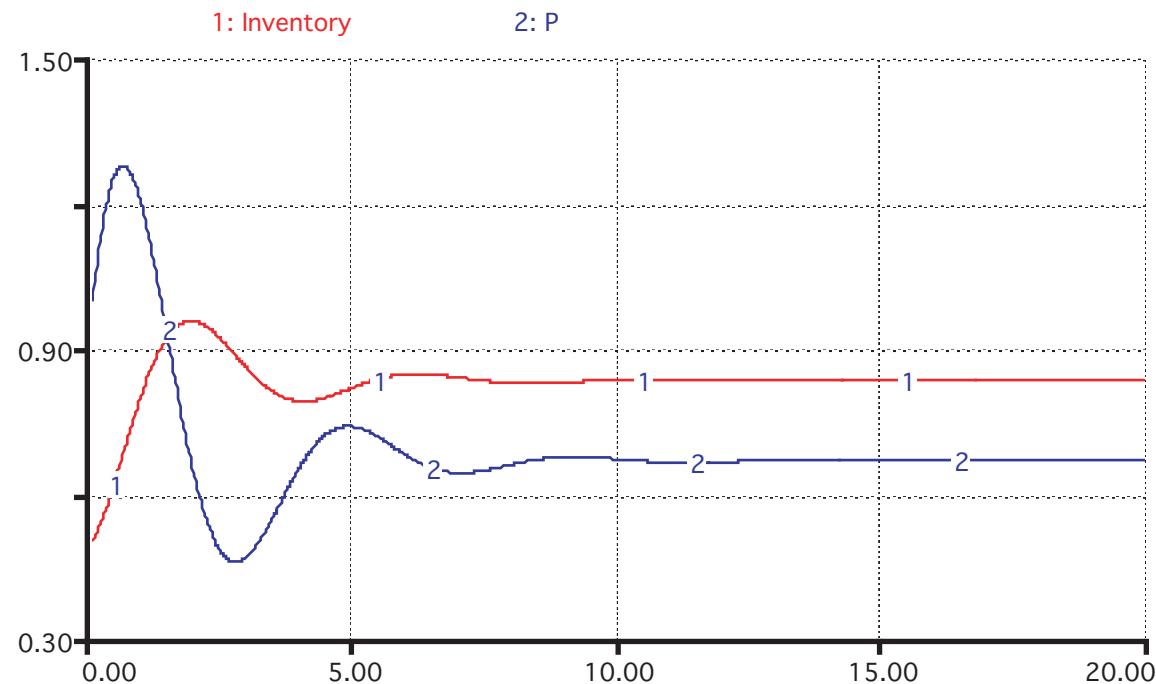
Visual representation



The balance of a substance, plus the law of inertia applied to one of the processes changing the amount of this substance.

SD Modeling: An Example

Simulation results



The combination of a law of balance with a law of inertia makes for an oscillatory system. Here, the oscillation is damped.

SD Modeling: An Example

The formal mathematical level of a Model

Law of Balance: $\text{Inventory}(t) = \text{Inventory}(t - dt) + (\text{Production} - \text{Consumption}) * dt$
INIT Inventory = 0.5
Production = P
Consumption = base_consumption+spending_fraction*income

Law of inertia: $P(t) = P(t - dt) + (\text{roc}_P) * dt$
INIT P = 1
 $\text{roc}_P = (\text{desired_prod}-\text{Production})/\tau_P$

Constitutive laws: desired_prod = inv_discrep/tau_inv
income = Production
inv_discrep = desired_inventory-Inventory

Parameters: base_consumption = 0.4
desired_inventory = 1
spending_fraction = 0.4
tau_inv = 0.25
 $\tau_P = 1$

SD Modeling

A graphical approach to building models of dynamical systems by combining the relations we perceive in such systems. It makes use of a very few structures which are projected onto virtually any type of dynamical system and its processes, i.e., it makes strong use of analogical reasoning.

Mathematically speaking, the models created are initial value problems of spatially uniform elements.

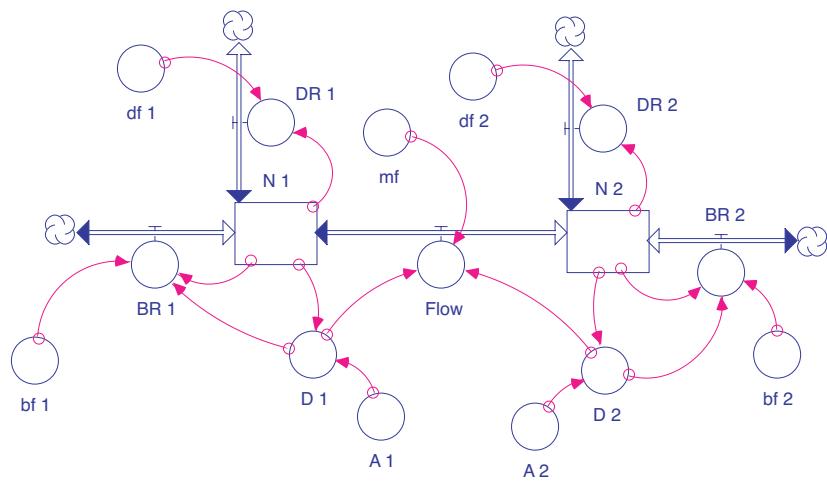
There are several programs available that implement the SD approach.

- Why are physicists and engineers so shy about applying SD modeling?

1 System Dynamics Modeling is Simple

Simple tools make the modeling of dynamical systems accessible...

A model of the growth and the migration of a species will be constructed...



$$N_1(t) = N_1(t - dt) + (BR_1 - DR_1 - Flow) * dt$$

$$INIT N_1 = 0.1$$

$$BR_1 = bf_1 * N_1 * (1 - D_1)$$

$$DR_1 = df_1 * N_1$$

$$Flow = mf * (D_1 - D_2)$$

$$N_2(t) = N_2(t - dt) + (BR_2 + Flow - DR_2) * dt$$

$$INIT N_2 = 0$$

$$BR_2 = bf_2 * N_2 * (1 - D_2)$$

$$DR_2 = df_2 * N_2$$

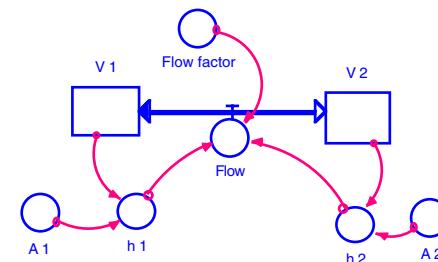
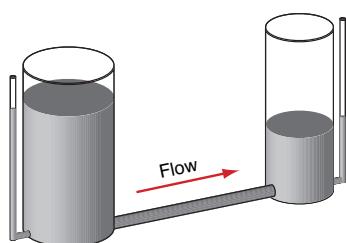
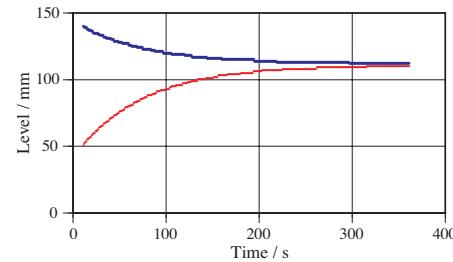
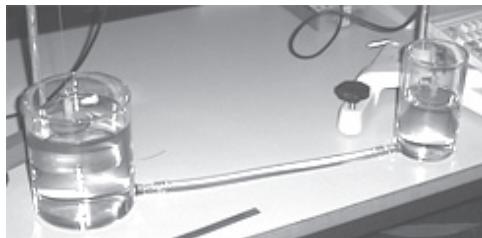
$$D_1 = N_1 / A_1$$

$$D_2 = N_2 / A_2$$

2 System Dynamics Modeling is Powerful

Simple ideas can be combined into models of complex systems and processes...

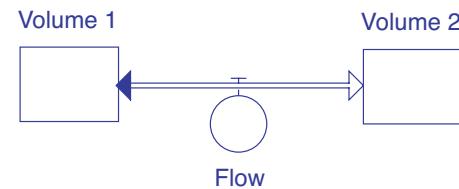
Simple ideas and a simple modeling methodology exemplified by an archetypal example. The example is extended step by step into a more complex model.



Simple ideas and a simple modeling methodology

- There are two tanks connected by a pipe; a fluid is flowing:

Assembling the balance of water



- What quantities does the flow depend upon?

The answer is a (not yet ordered) list of possible candidate quantities

- ...and how?

The list has to be ordered according to

- ...quantities directly responsible for the flow
- ...quantities only indirectly responsible
- ...variable quantities
- ...constant system parameters

...construct an expression...

Variables

Level Difference

Constants

Length of pipe

Radius of pipe

Viscosity of fluid

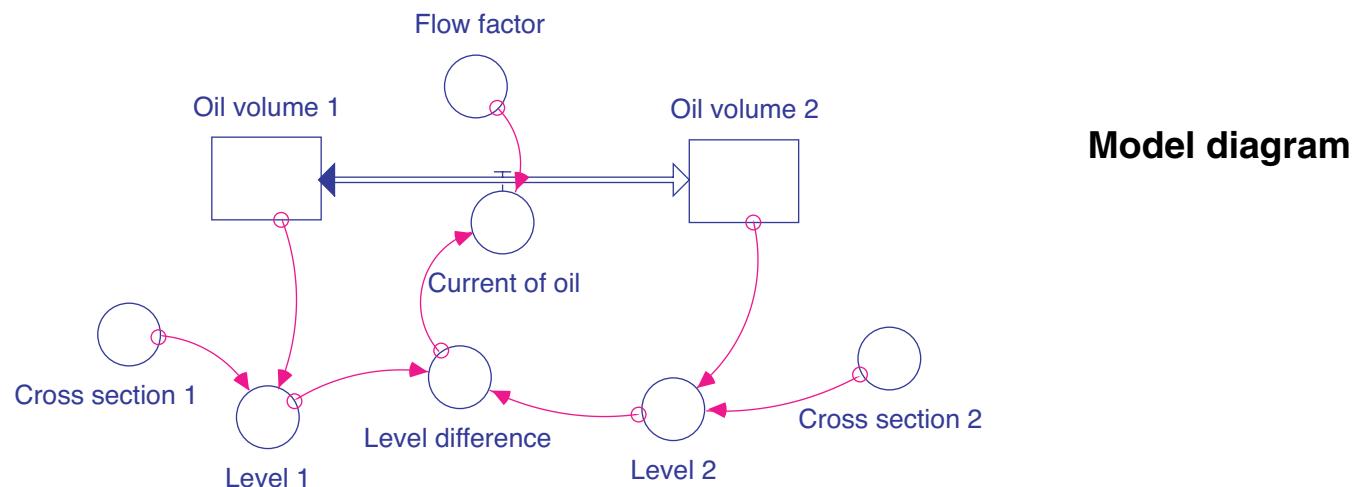
Indirect influence

Volume

Radii of tanks

Temperature...

A possible model...



Model diagram

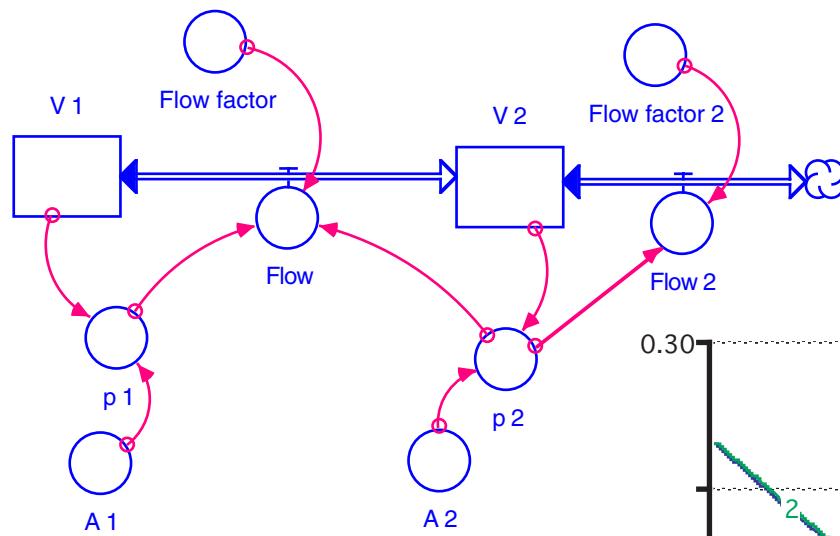
Model equations

```
Oil_volume_1(t) = Oil_volume_1(t - dt) + (- Current_of_oil) * dt  
INIT Oil_volume_1 = Cross_section_1*h1_init  
Current_of_oil = Flow_factor*Level_difference
```

```
Oil_volume_2(t) = Oil_volume_2(t - dt) + (Current_of_oil) * dt  
INIT Oil_volume_2 = Cross_section_2*h2_init
```

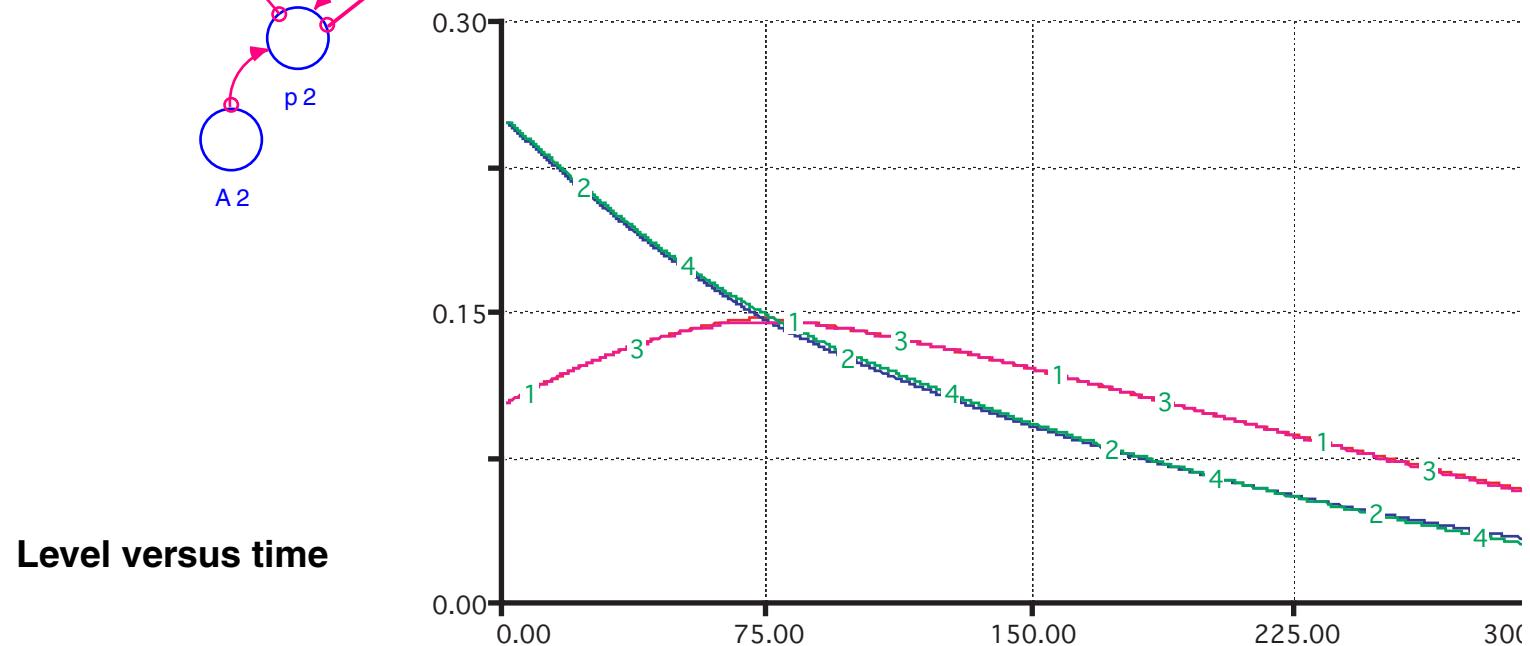
```
Level_1 = Oil_volume_1/Cross_section_1  
Level_2 = Oil_volume_2/Cross_section_2  
Level_difference = Level_1-Level_2
```

Extend 1: Two communicating water containers with outflow

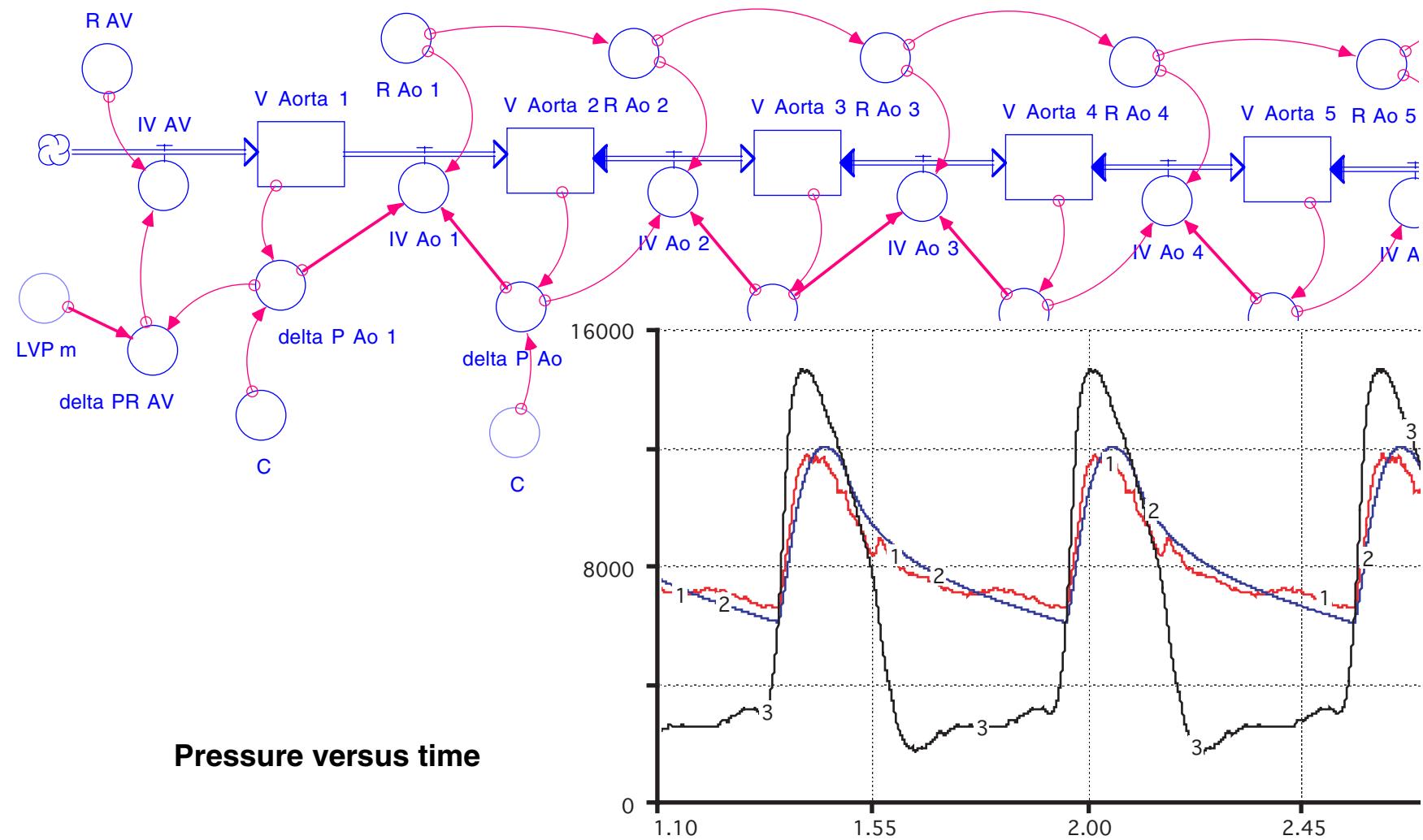


Flow =

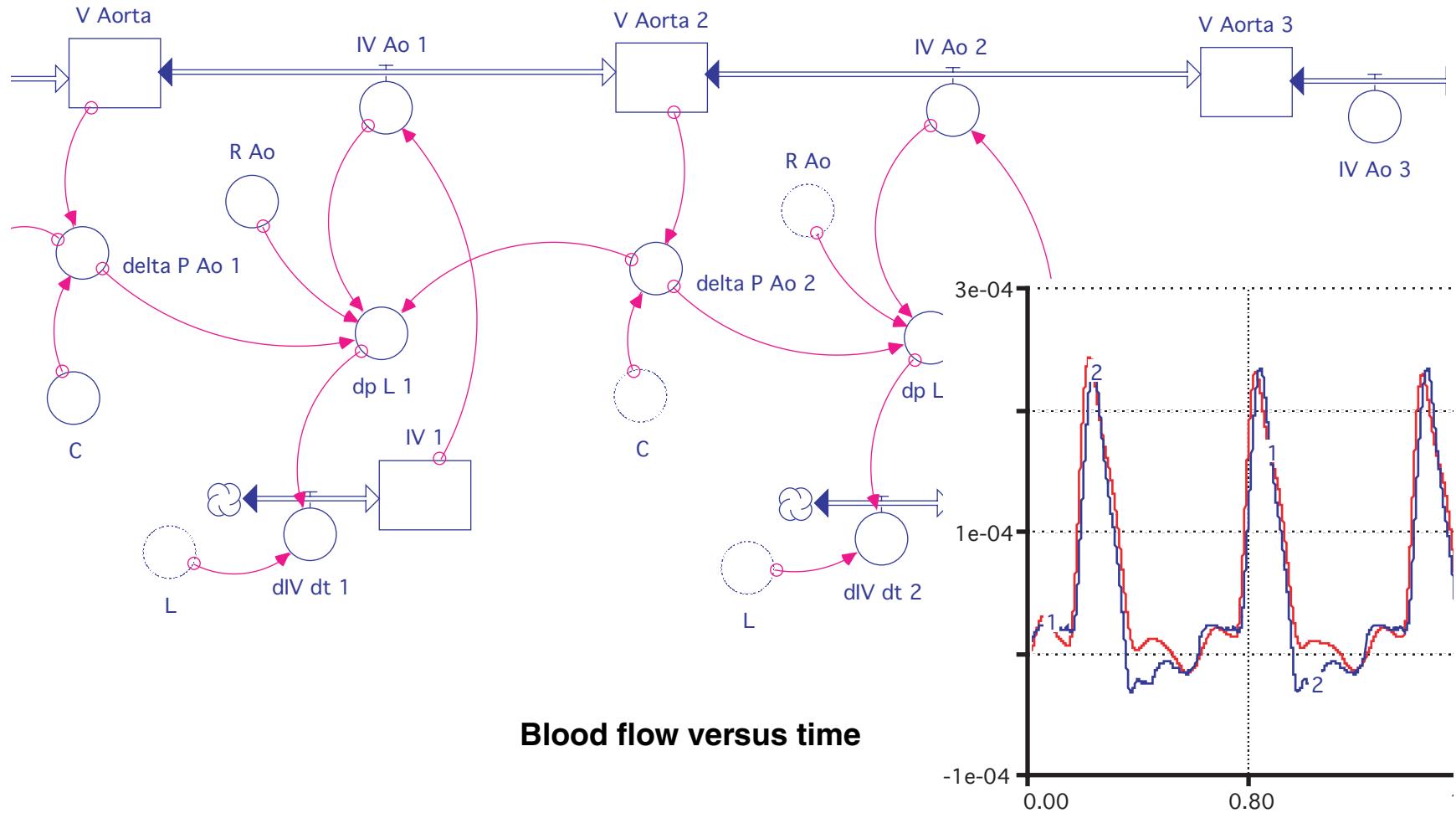
**IF ((P1-P2) > 0) THEN SQRT((P1-P2)/k1)
ELSE -SQRT(-(P1-P2)/k1)**



Extend 2: A model of a sheep's aorta



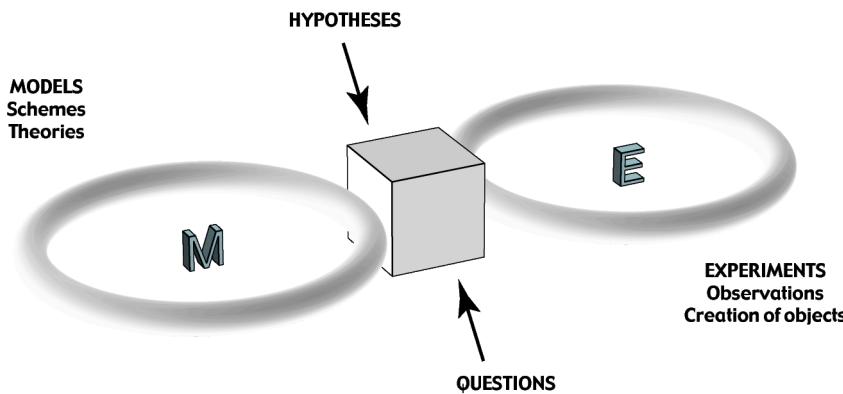
Extend 3: A model of a sheep's aorta with inductive effects



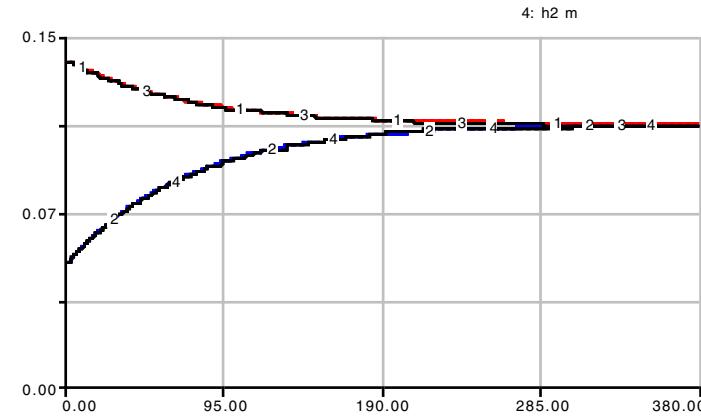
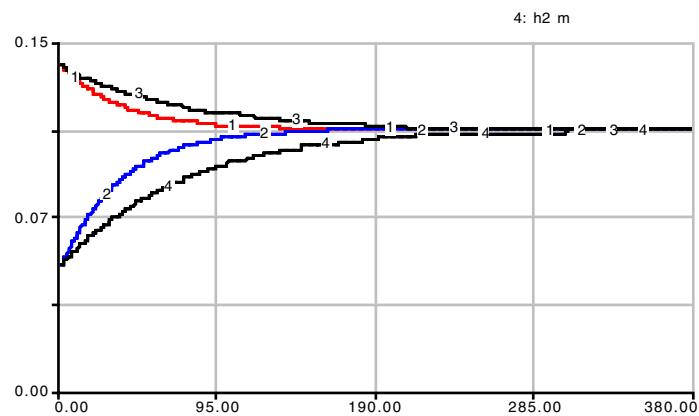
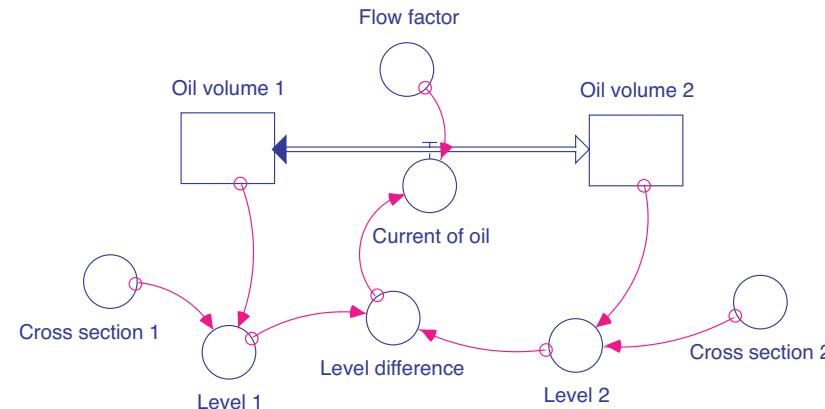
3 System Dynamics Modeling is Useful

It makes the integration of modeling and experimenting a simple matter...

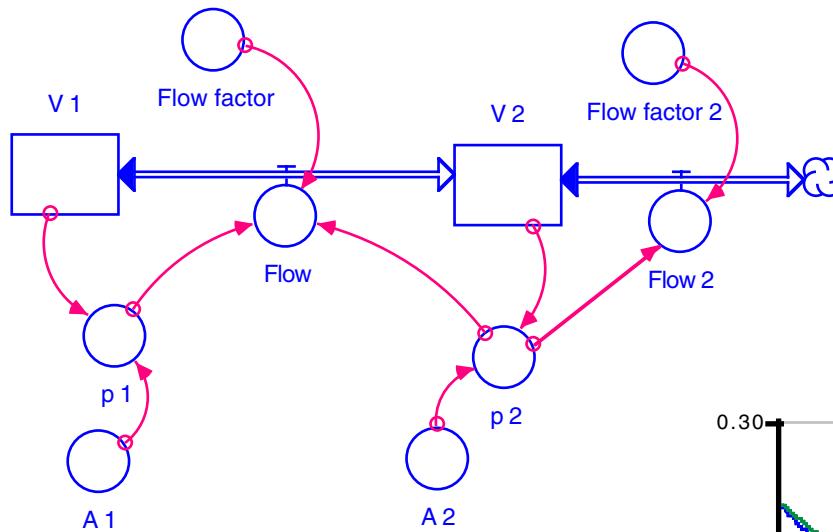
Going back and forth between experiment and model (the science-bi-cycle)



Comparison of the results of ideas (simulations of models) with reality (data)

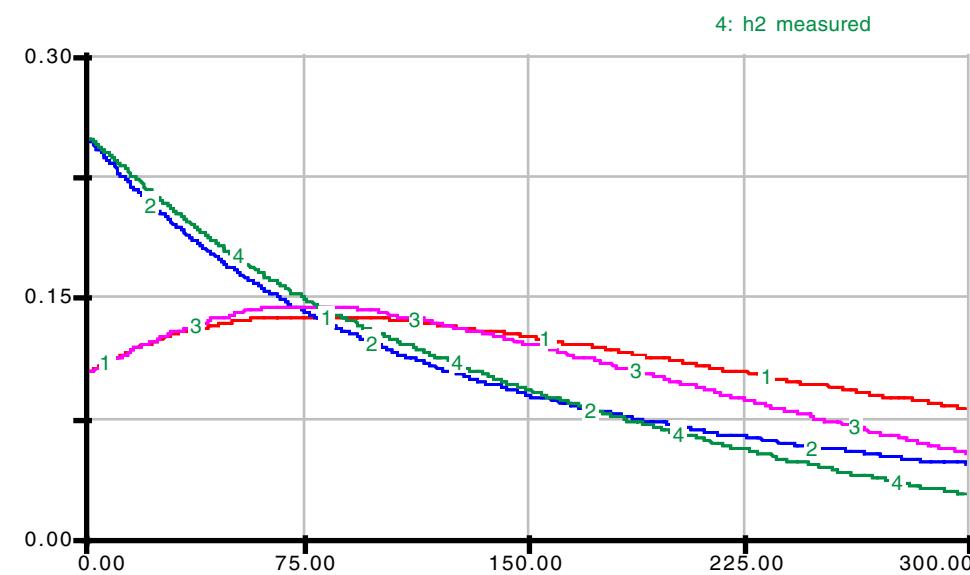


Two communicating water containers with outflow 1

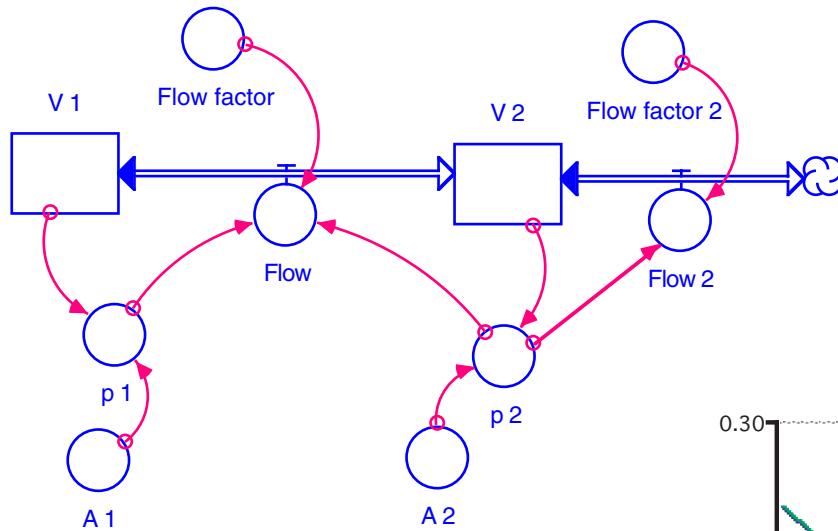


$$\text{Flow} = \text{FF} \cdot (P_1 - P_2)$$

Level versus time



Two communicating water containers with outflow 2

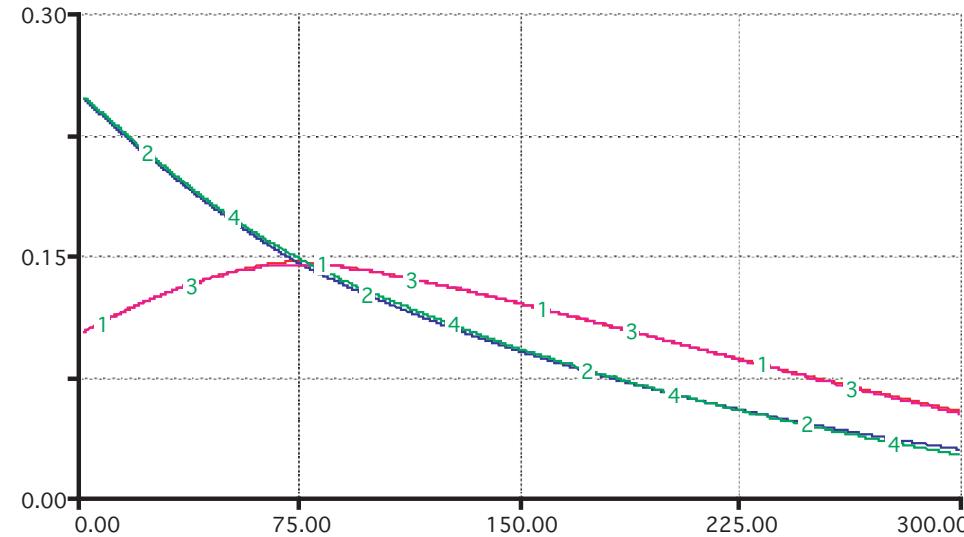


Flow =

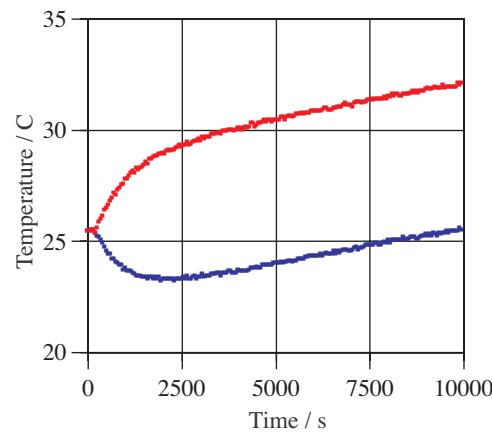
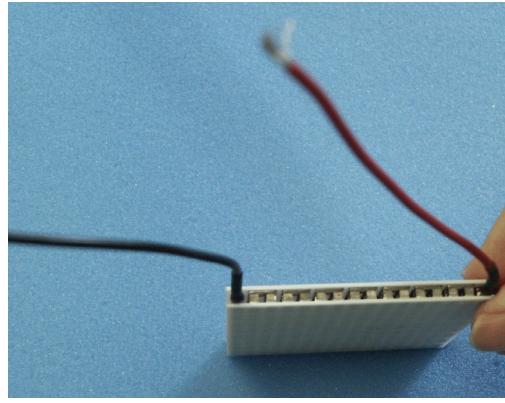
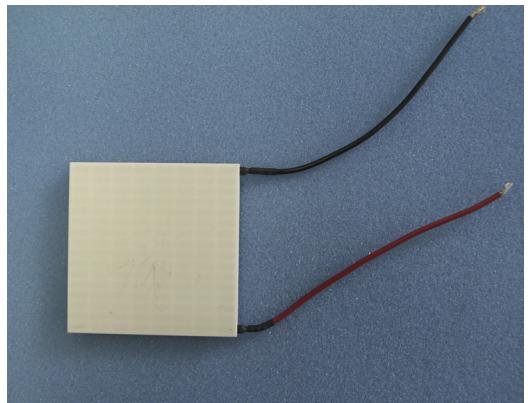
$$\begin{aligned} \text{IF } ((P_1 - P_2) > 0) \text{ THEN } FF \cdot \text{SQRT}(P_1 - P_2) \\ \text{ELSE } -FF \cdot \text{SQRT}(-(P_1 - P_2)) \end{aligned}$$

Automatic parameter estimation, for example with *Berkeley Madonna*

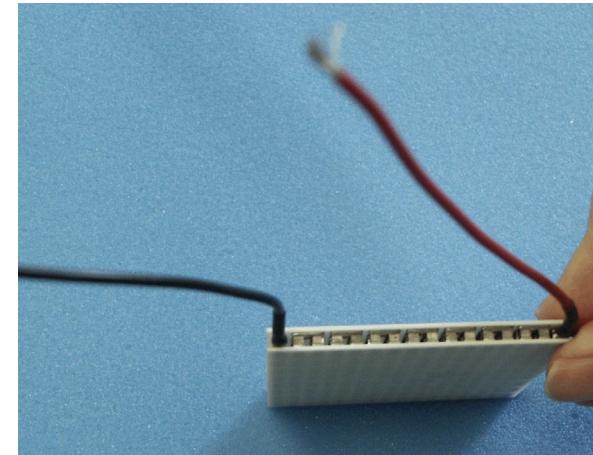
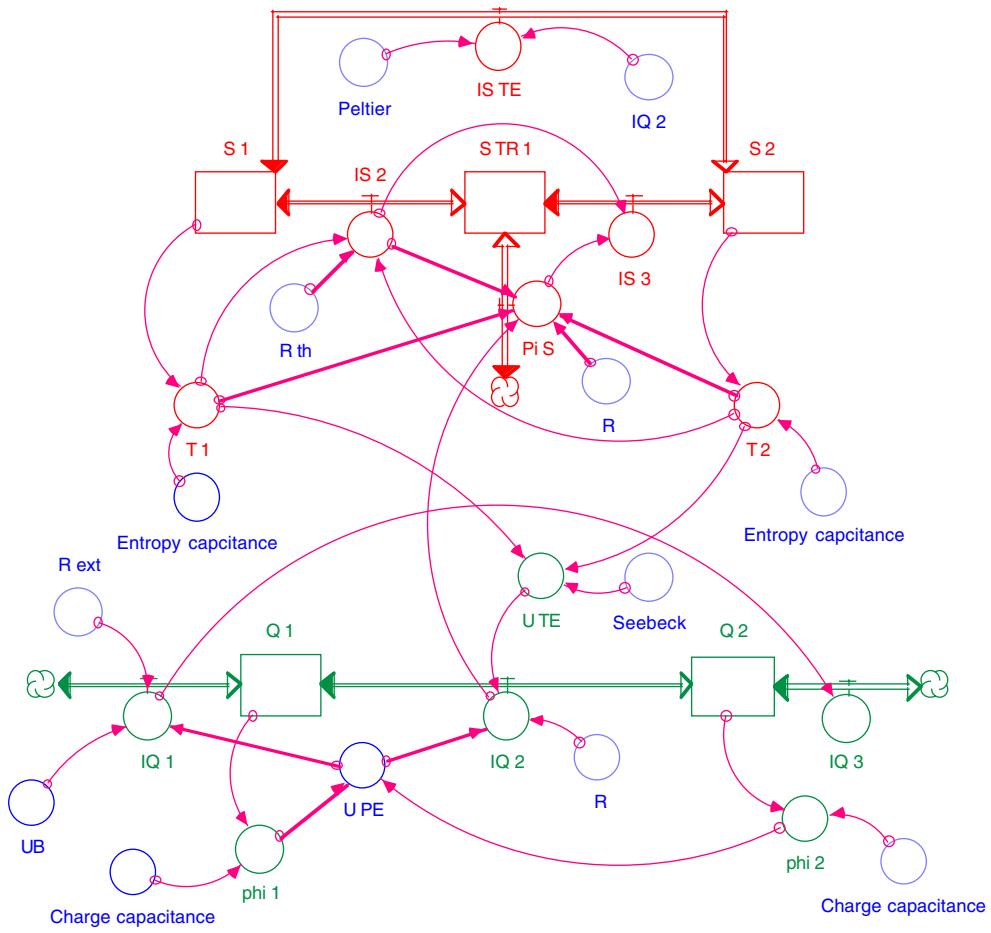
Level versus time



Peltier cooler between two bodies of water



Peltier device: Principle



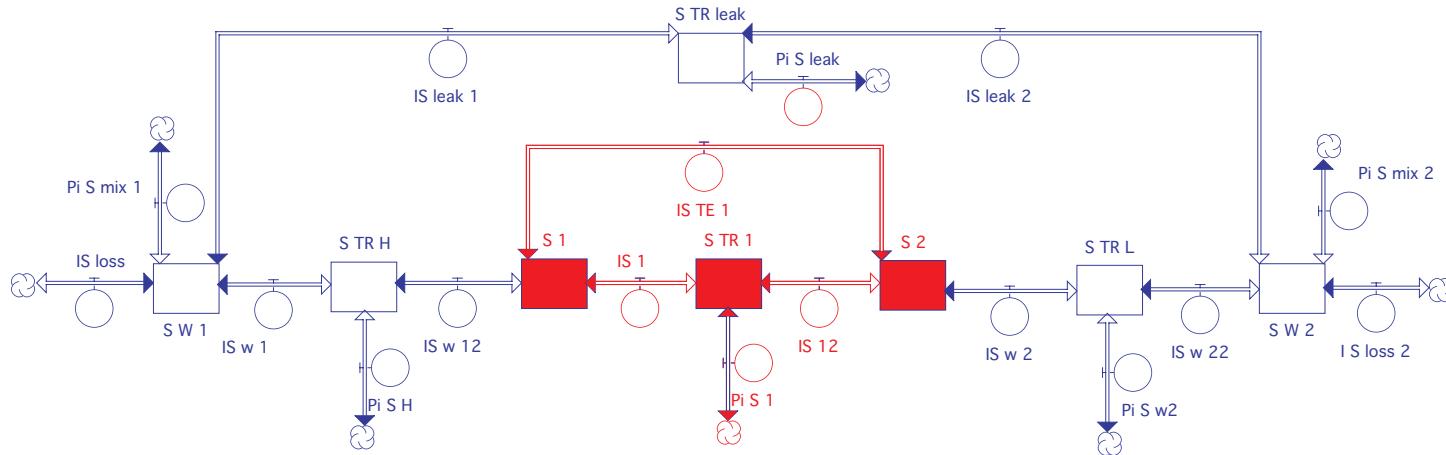
$$U_{TE} = \text{Seebeck}^*(T_2 - T_1)$$

$$IS_{TE} = \text{Peltier}^*IQ_2$$

$$Pi_S = P_{diss}/T_2$$

$$P_{diss} = -IS_2(T_2 - T_1) + R^*IQ_2^2$$

Peltier experiment: Going back and forth between experiment and model



- Original experiment
- First model
- First simulation and comparison: parameters of device (moderately successful...)
- Back to experiment: loss of container to environment (no big change...)
- Back to experiment: hot and cold water—equilibration—heat transfer to PD (much better result...)
- Another look: there is a thermal “bypass” (good results)

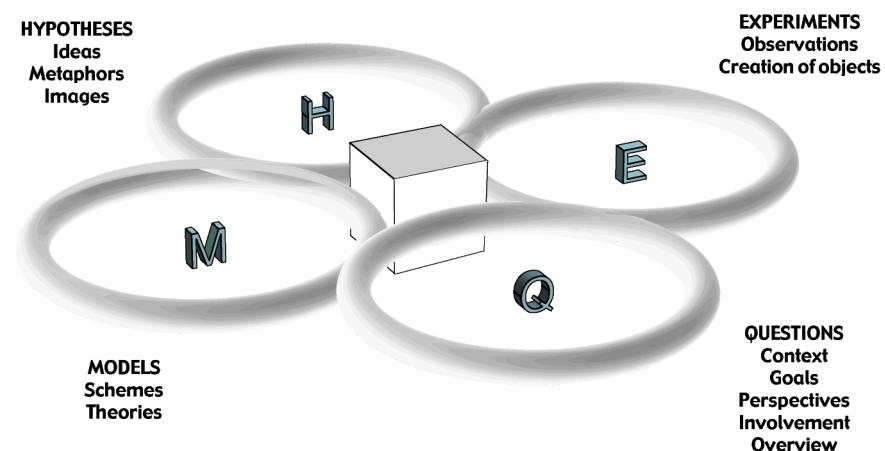
4 System Dynamics Modeling is Natural

The simple ideas behind SD models correspond to a basic form of human thought...

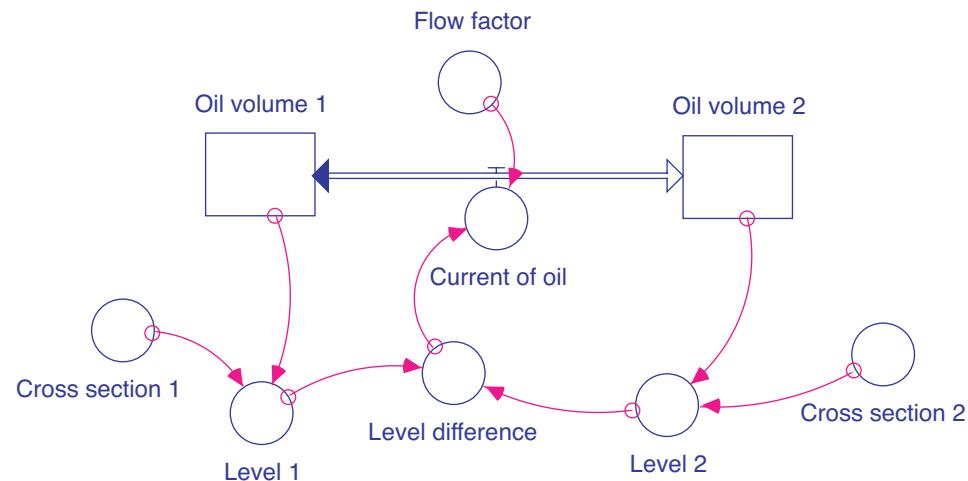
There is a certain natural simplicity or simple naturalness to SD modeling...

Steps leading to the creation of hypotheses and the generation of good questions can be represented as two additional cycles in the bi-cycle.

(See Kieran Egan on cognitive tools.)

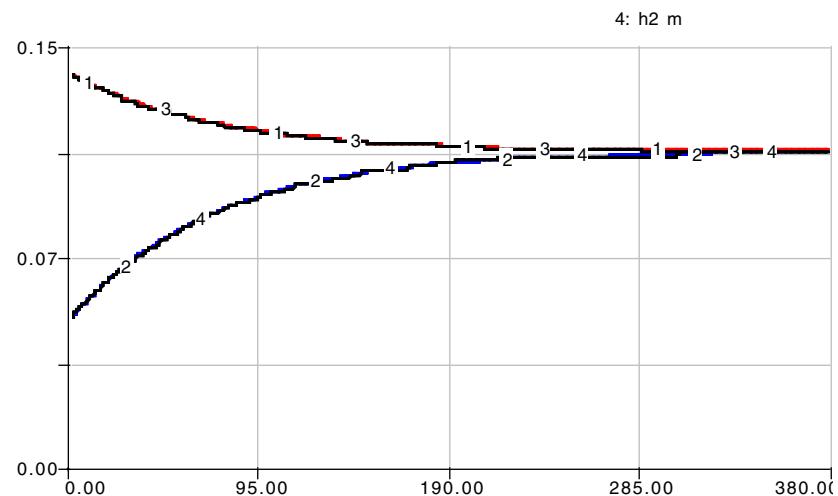


Similarity in models 1: Two tanks

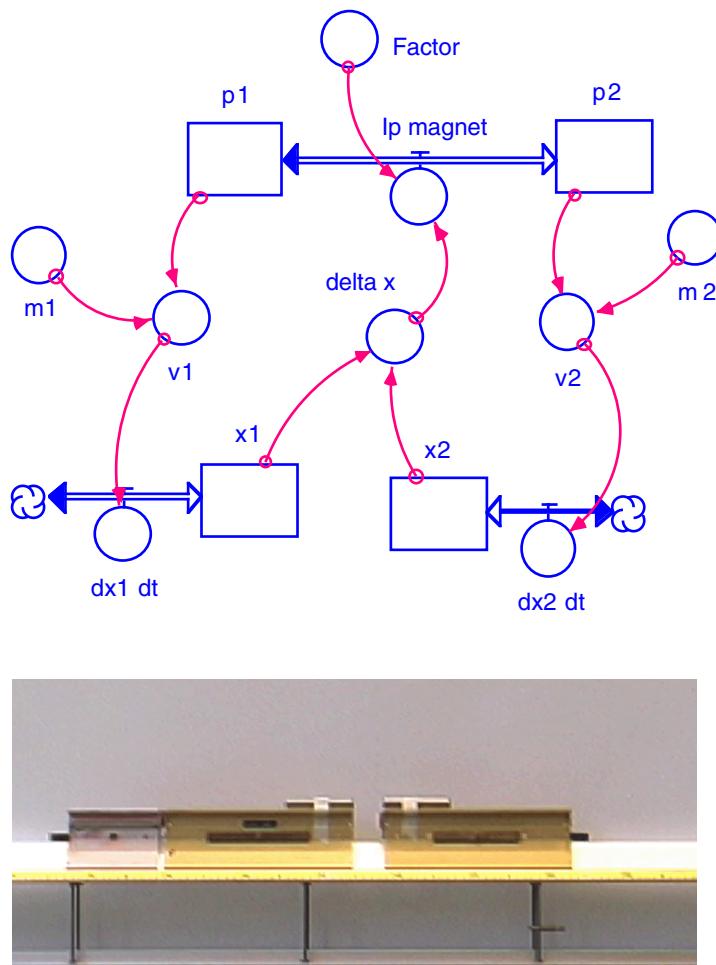


$$\text{Flow} = \text{Flow factor} \cdot \text{Level difference}$$

Level versus time

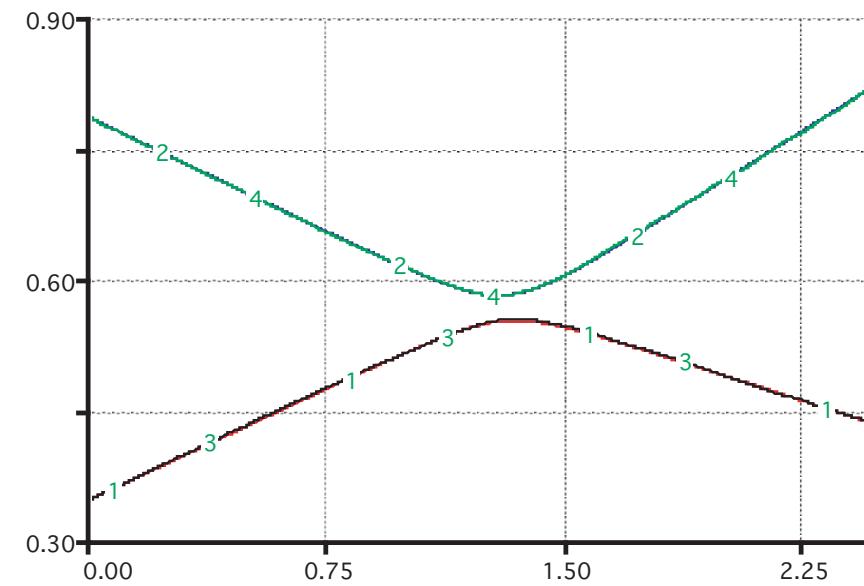


Similarity in models 2: Two gliders with magnets

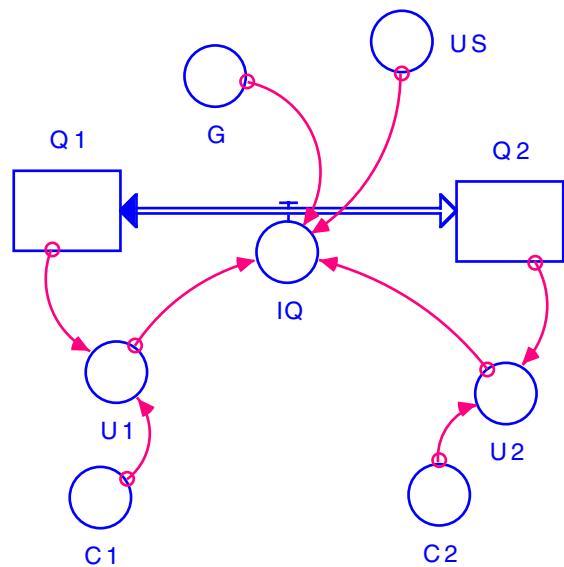


$$I_{p_magnet} = \text{Factor} / \delta x^5$$

Position versus time

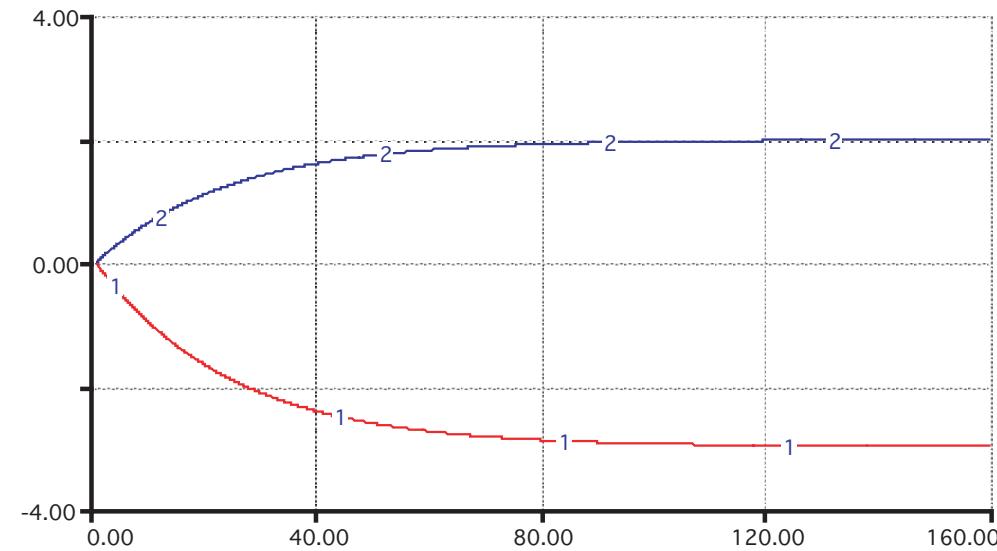


Similarity in models 3: Two capacitors with battery

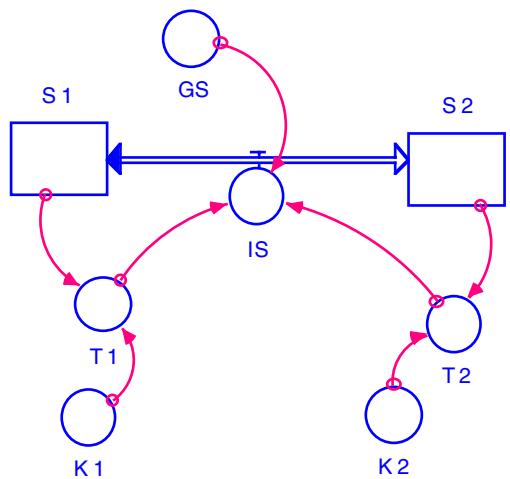


$$I_Q = G \cdot (U_S + U_1 - U_2)$$

Voltage versus time



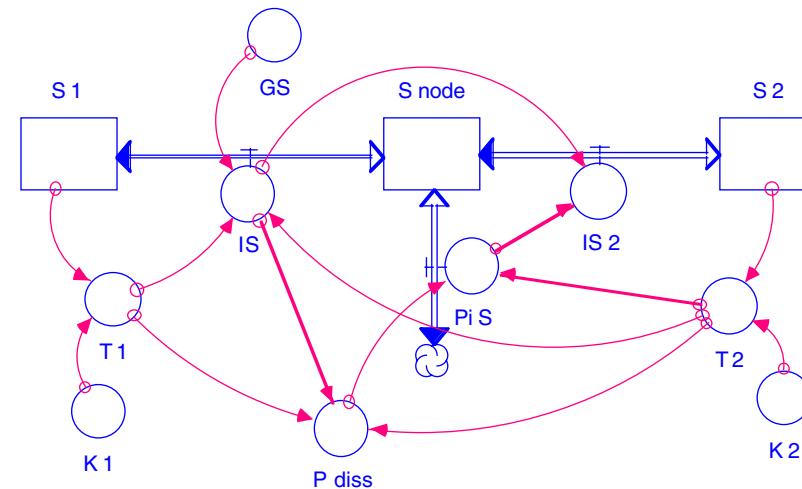
Similarity in models 4: Thermal equilibration



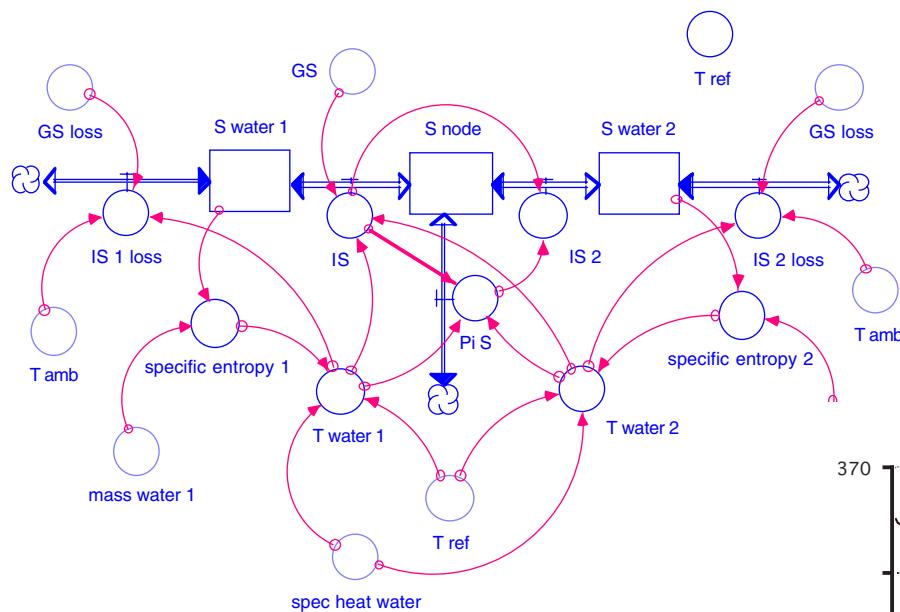
$$IS = GS * (T_1 - T_2)$$

$$P_{Diss} = (T_1 - T_2) * IS$$

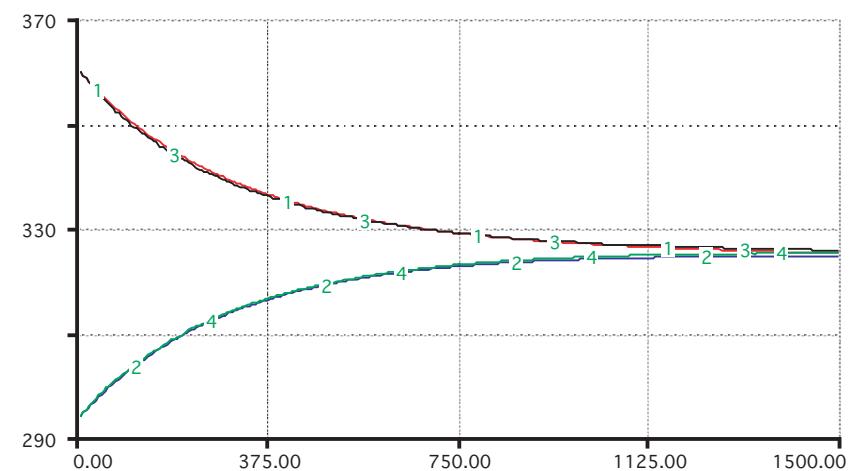
$$Pi_S = P_{diss}/T_2$$



Similarity in models 4: Thermal equilibration



Temperature versus time



Summary: Structure of SD models in physics

Some quantities are stored, they can flow (and sometimes, they are produced). There are differences (of potentials) which lead to

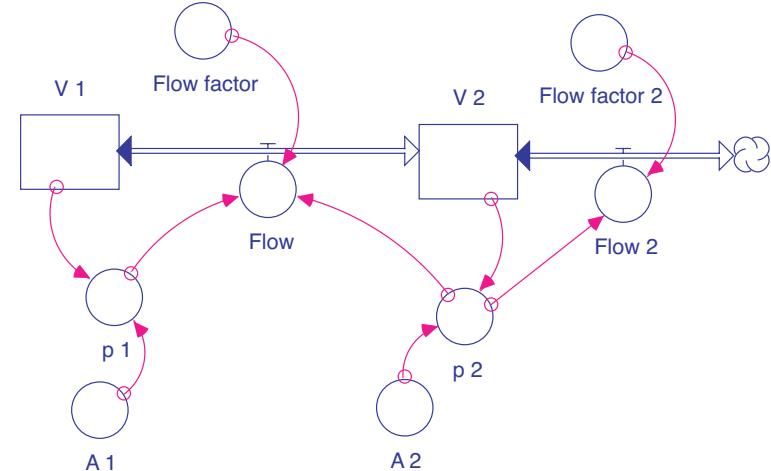
- flows
- changes of flows
- production rates

Differences are produced by

- storage
- pumps (in a generalized sense)

When quantities flow through a difference, energy is released. The energy released is

- used to drive other processes (set up other differences)
- dissipated
- stored or transferred



The gestalt of physical processes

Human perception of phenomena such as fluids, electricity, heat, motion

The concept of “heat,” for example, is abstracted by perception from the sum total of thermal experiences in the form of a **gestalt**: An entity that encompasses more than the sum of its parts. While we do not differentiate a gestalt of a collective of phenomena (such as electricity or heat) consciously, we do notice aspects. The most fundamental **aspects** humans use to talk about such a **gestalt** are

Table 1: The gestalt of collectives of physical phenomena

ASPECT OF GESTALT	METAPHORIC STRUCTURE
Intensity (quality)	Polarity such as light-dark, warm-cold, high-low, fast-slow, strong-weak. The concepts are structured metaphorically by the image schema of verticality (intensity as a level).
Quantity (substance)	Substance-like concepts are metaphorically structured in terms of fluid substances.
Force or power	Prototypical <i>causation</i> as the gestalt of direct manipulation.

Evidence for the gestalt of physical processes 1

Journalism students judging the validity of linguistic expressions using heat and temperature

People are asked if they agree or disagree with certain expressions

- The temperature is high
- Today, the heat is high
- There is lots of heat in this room
- There is lots of temperature in this room
- Heat drives the engine
- Temperature drives the engine

Tabelle 2: Agreement with classes of expressions^a

	as substance	as cause	as level
Heat	0.67 (1)	0.77 (1)	0.14 (0)
Temperature	0.09 (0)	0.09 (0)	0.83 (1)

a. Agreement (1) or disagreement (0) with expressions using heat and temperature. Expected results in parentheses. Results of a questionnaire given to journalism students in Summer of 2004.

Evidence for the gestalt of physical processes 2

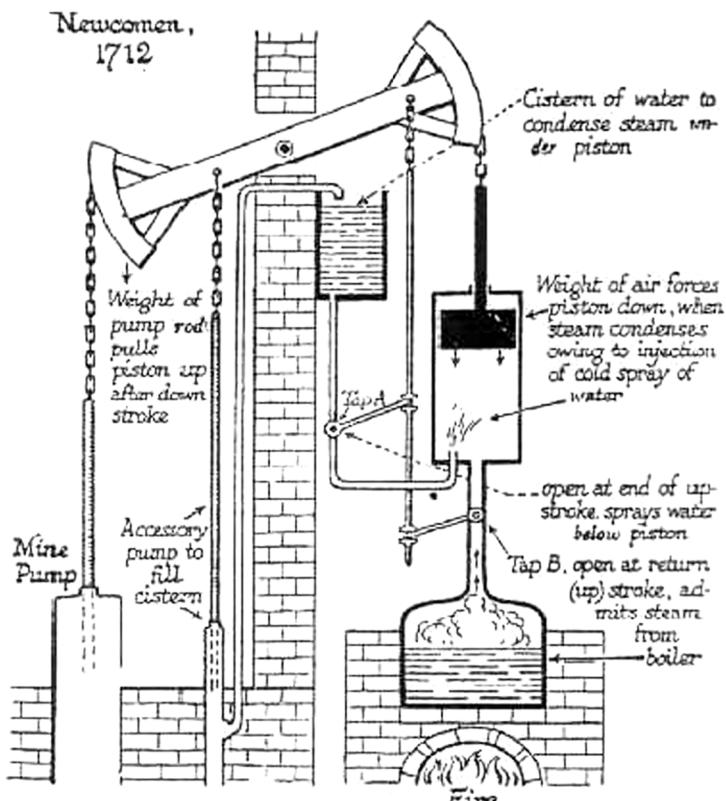
Sadi Carnot's image of the waterfall and its comparison to the power of heat



Sadi Carnot (1796-1832)

Réflexions sur la puissance motrice du feu

D'après les notions établies jusqu'à présent, on peut comparer avec assez de justesse la *puissance motrice de la chaleur* à celle d'une *chute d'eau* [...]. La puissance motrice d'une chute d'eau dépend de sa hauteur et de la quantité du liquide; la puissance motrice de la chaleur dépend aussi de *la quantité de calorique* employé, et de ce qu'on pourrait nommer, de ce que nous appellerons en effet *la hauteur de sa chute*, c'est-à-dire de *la différence de température* des corps entre lesquels se fait l'échange du calorique.



DIAGRAMMATIC VIEW OF NEWCOMEN'S ATMOSPHERIC OR FIRE ENGINE (1712)

Evidence for the gestalt of physical processes 3

The concept of heat in the Accademia del Cimento

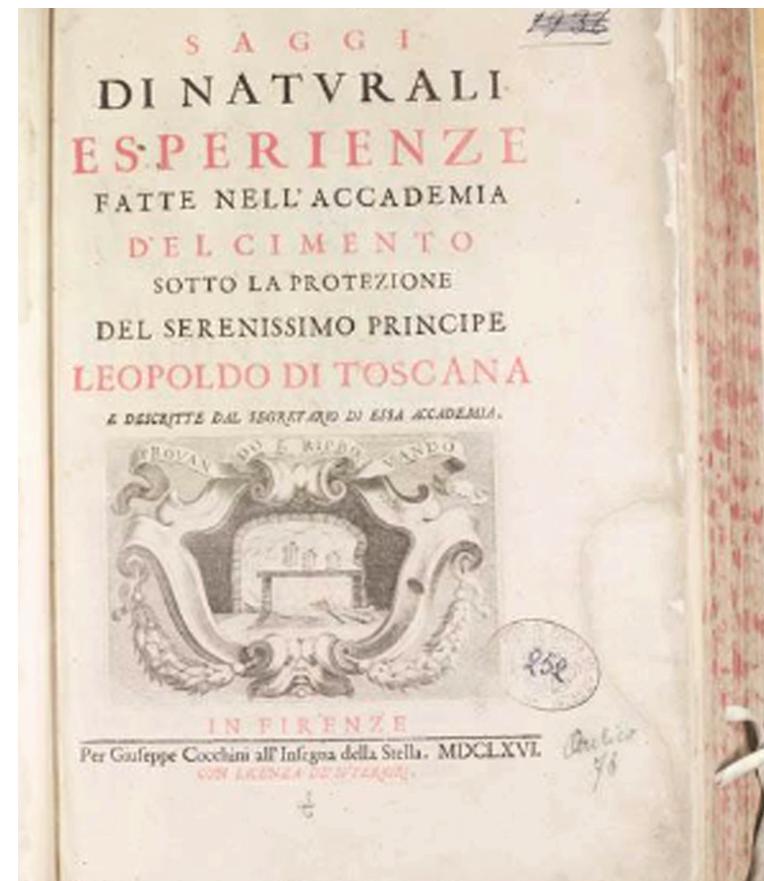
**The concept of heat developed by the members of the Accademia del Cimento:
Saggi di naturali esperienze... (1667)**

M. Wiser and S. Carey (1983): When Heat and Temperature were one.

“The Experimenters’ concept of heat had three aspects: **substance** (particles), **quality** (hotness), and **force**. ”

A weakly differentiated gestalt

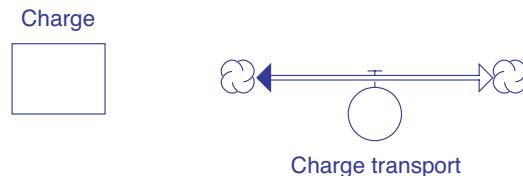
It seems that the Experimenters did not really distinguish between these aspects of the gestalt of heat.



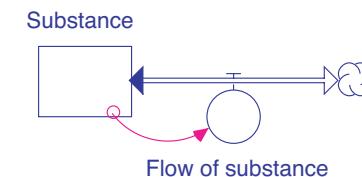
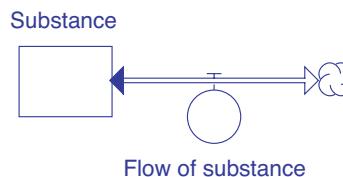
Evidence for the gestalt of physical processes 4

Visual expressions of the metaphors used to structure the aspects of the gestalt

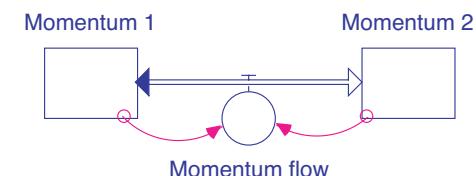
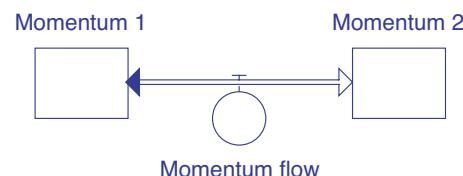
**Substance-based thinking
(storage and flow/production)**



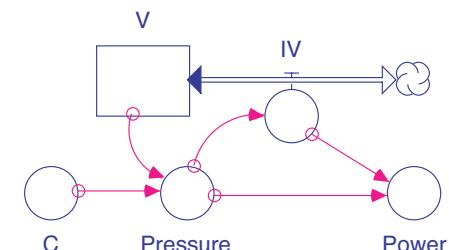
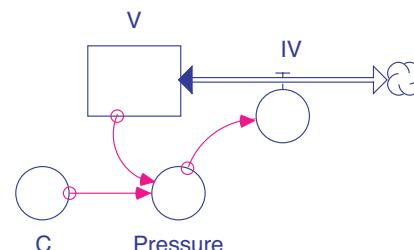
Causative thinking / With feedback-thought



**Causative thinking (interaction) /
With feedback-thought**



**(Level differences)
(Releasing energy)**



Evidence 5: The gestalt of abstract concepts

Concepts such as **pain** or **love** are conceptualized in the same manner as physical concepts such as heat or electricity. They have a similar gestalt with the same aspects of

quantity (substance) / intensity (quality) / force or power

Linguistic expressions

- The pain was too strong
- The level of pain went down
- More and more pain...
- The pain gained control of me
- The aspirin took away my headache
- The headache soured my mood

Entailments of the conceptualization

Two broken teeth means double the pain. More pain means higher intensity. More pain means the pain is more powerful. Higher intensity leads to more power.

Evidence 6: Egyptian cosmology

- Creating and maintaining the tension between Earth and Sky

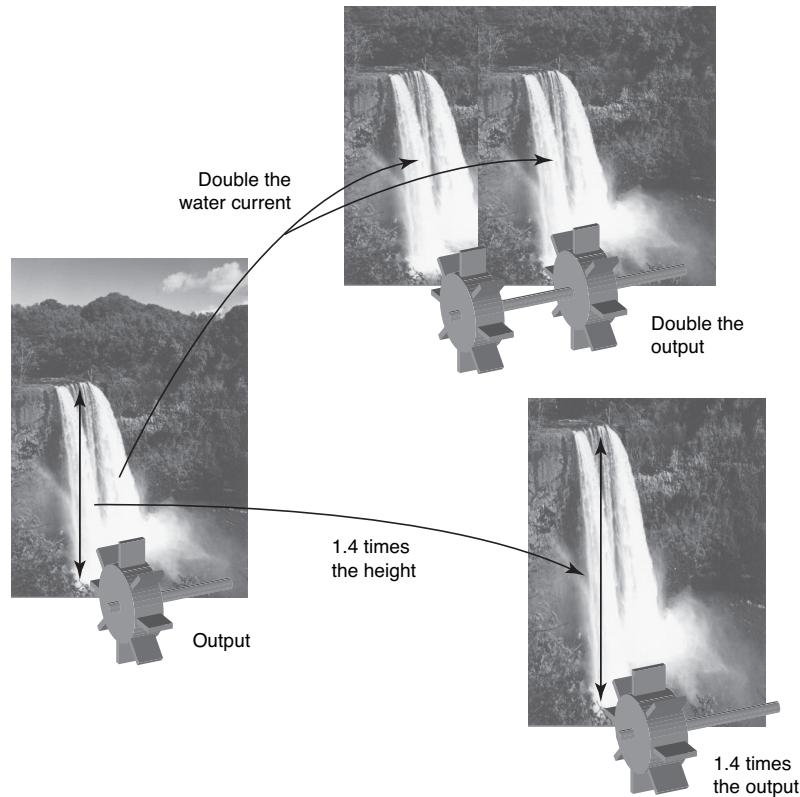


In Egyptian mythology, Shu (air) separates Nut (sky) from Geb (Earth). The sky has to be supported or it collapses. <http://www.civilization.ca/civil/egypt/images/reli28b.jpg>

This mythic view of nature sounds very modern—or modern physics sounds very mythic.

Entailments of the metaphoric structure of physical concepts

An example of entailments that can be brought into quantitative form



$$\text{Power} = \text{Level difference} \cdot \text{Current of substance}$$

Carnot and analogies...

The structure of basic metaphors

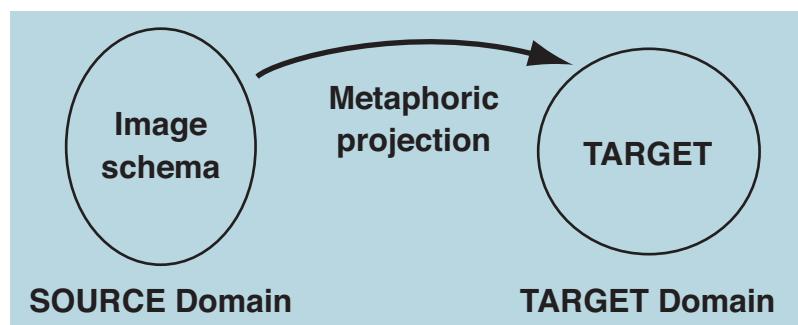
Image schemata as primal source domain

Image schema is a recurring structure of, or within our cognitive processes, which establishes patterns of understanding and reasoning. It emerges from our bodily interactions, linguistic experience and historical context. **[Image schemata are gestalts.**

M. Johnson (1987): *The Body in the Mind*. Chapter 5.]

Examples: up/down, inside/outside, near/far, balance, object, process, path

Image schemata are projected metaphorically onto more abstract domains. (Metaphors are one-sided projections.)

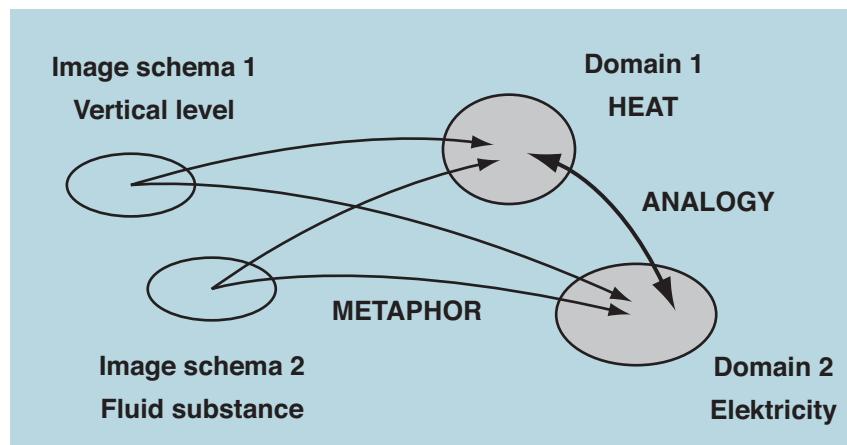


Metaphors and analogical reasoning

Origin and meaning of analogies

When different domains of experience are structured metaphorically by the same source domains (such as by the same image schemata), these domains become comparable (they start to look similar).

This comparison can be applied in the construction of analogies. An analogy is a double-sided mapping (more or less symmetrical).



5 *System Dynamics Modeling is Fun...*

SD modeling can stimulate and enliven many courses.

It is a good tool to implement hands on, inquiry based learning.

Design oriented courses can greatly profit from SD modeling.

LITERATURE

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