System Science

D. L. Hysell
Earth and Atmospheric Sciences
Cornell University

June, 2011

There is no universal definition of “system science.”

People seem to have trouble defining “system science” without using the term “system.”

Is “system science” whatever people say it is? What do we say?

The Department of [redacted] at [redacted] invites applications for an Assistant Professor in the area of extreme weather under climate change. ... The incumbent could take an **Earth system approach to the subject, emphasizing the interactions of atmospheric, oceanic, and land-surface processes** in responding to forcing from the climate system ... [1]

[1] An actual position announcement

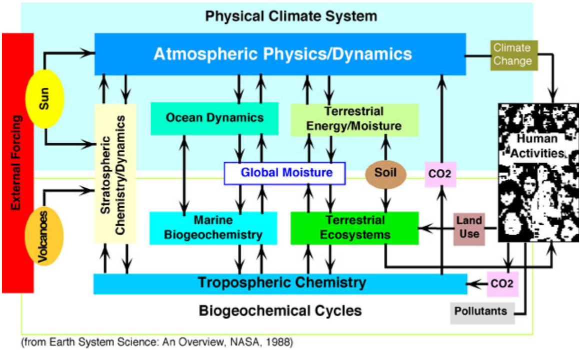
“Given the concerns that humankind is impacting the earth’s physical climate system, a broader concept of the earth as a system is emerging. Within this concept, knowledge from the traditional earth science disciplines of geology, meteorology and oceanography along with biology is being gleaned and integrated to form a physical basis for Earth System Science. The broader concept of Earth System Science has also come to include societal dimensions and the recognition that humanity plays an ever increasing role in global change.”
“The Earth System Science concept fosters synthesis and the development of a **holistic model** in which disciplinary process and action lead to synergistic **interdisciplinary** relevance.” [2]

[2] Johnson, D. R., et al., What is Earth System Science?, Proceedings of the 1997 International Geoscience and Remote Sensing Symposium, Singapore, August 4 - 8, 1997, pp 688 - 691

"The Earth system is often represented by interlinking and interacting "spheres" of processes and phenomena. The atmosphere, hydrosphere, biosphere and geosphere form the simplest collection, though some would add the cryosphere as a special element dealing with polar regions and processes, and others would add the anthroposphere emphasizing human dimensions and impact on the planet. **The difficulty with any representation that divides the system is the danger of continuing a deconstructed perception of the holistic Earth system - in reality no part of the Earth system can be considered in isolation from any other part**." [3]

[3]Teaching Entry Level Geoscience, Science Education Resource Center, Carleton College.

Bretherton diagram



One of many similar diagrams now. [4]

"Scientists had studied the solar system for many years — now it was time to study the earth system."[5]

[4] Earth System Science Committee (1986). Earth System Science: A Program for Global Change. Washington, DC., NASA.

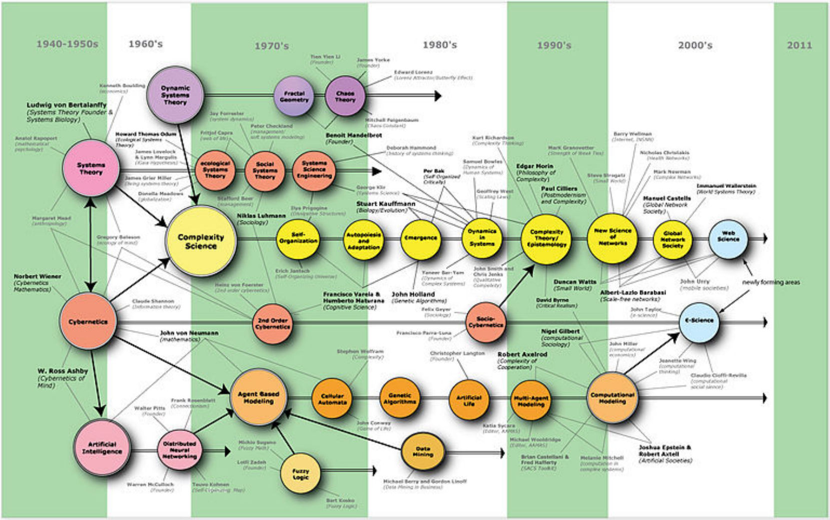
[5] Attributed to M. Chahine, NASA JPL

system theory pre- and post-1986

Ludwig von Bertalanffy [6]	W. Ross Ashby
Anatol Rapoport	Stafford Beer
Kenneth E. Boulding	Herbert Simon
Margaret Mead	Norbert Wiener
Gregory Bateson	John von Neumann
C. West Churchman	Stuart Kauffman
Ralph Gerrard	Heinz von Foerster
James Miller	Jules Poincaré
Ervin Laszlo	Aleksandr Lyapunov
Fritjof Capra	Murray Gell-Mann
George Klir	Jay Forrester

[6] An Outline for General Systems Theory, British Journal for the Philosophy of Science, Vol 1, No. 2, 1950

Bretherton diagram for system science



Wikipedia (see also Facebook page)

- In the most general sense, system means a configuration of parts connected and joined together by a web of relationships. The [ISSS] Primer group defines system as a family of relationships among the members acting as a whole. Von Bertalanffy defined system as "elements in standing relationship."
- **The emphasis with systems theory shifts from parts to the organization of parts**, recognizing interactions of the parts are not "static" and constant but "dynamic" processes.
- In most cases the whole has properties that cannot be known from analysis of the constituent elements in isolation. Elements convey information about one-another.
- The **contradiction of reductionism** in conventional theory (which has as its subject a single part) is simply an example of changing assumptions.

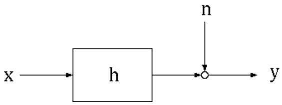
"There exist therefore general system laws which apply to any system of a certain type, irrespective of the particular properties of the system or the elements involved."

"General System Theory is a logico-mathematical discipline, which is in itself purely formal, but is applicable to all sciences concerned with systems. Its position is similar to that, for example, of probability theory, which is in itself a formal mathematical doctrine but which can be applied to very different fields..."

"As opposed to the mechanistic conception, we are led to a different view. **The task of science is to state laws for the different strata of reality.** Even in physics, quantum statistics, molecular statistics, and macrophysical laws represent different strata. Similarly, we may apply statistical values and laws on any level, if this gives results consistent with experience and within a theoretical system. If you cannot run after each molecule and describe the state of a gas in a Laplacean formula, take, with Boltzmann, a statistical law describing the average result of the behaviour of a great many individual molecules..."

- A system is characterized by the mapping between a state vector and its drivers, the rules which take a system from its present to its future state (organization).
- If the state depends on past inputs, the system is dynamic. If superposition does not hold, it is nonlinear. If its orbits change drastically under small perturbations, it is unstable. If all three conditions hold, the system is complex, and emergent phenomena may occur.
- In modeling the mappings mathematically (finding an appropriate system of equations), a balance must be struck between accuracy and simplicity. Judgments must be made regarding which relationships are crucial and which are negligible.
- The task of system identification often defies synthesis and must be accomplished by trial-and-error or statistical means.
- The goal is to find a system which expresses the observed or desired behavior.

system identification



$$\boxed{\underbrace{y}_{\text{state}} = \overbrace{h}^{\text{mapping}} \underbrace{x}_{\text{driver}} + \underbrace{n}_{\text{noise}}}$$

x?: inverse problem
h?: system ident.
hx?: factor analysis

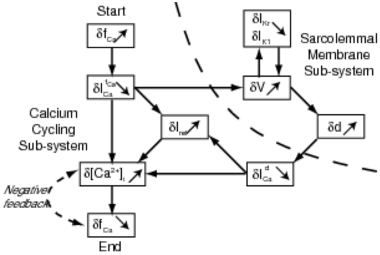
strategy
correlation analysis/ filter
min. projection error (LSE)
optimal basis decomposition (e.g. SVD)
data, model resolution:
$h = y\tilde{x} \rightarrow h = hx\tilde{x}, y = y\tilde{x}x$
hierarchical Bayesian model
$P(h\|y) = P(y\|h)P(h)/P(y)$

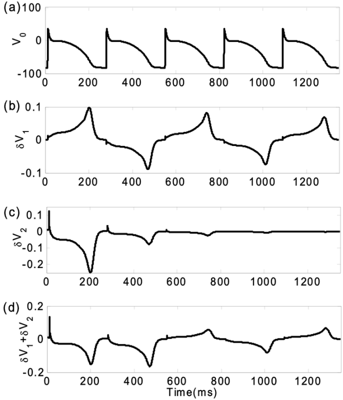
$\Rightarrow$ pseudoinverse $\underbrace{\Rightarrow}_{\text{damping}}$ regularized pseudoinverse

Model order selection: say $y \,\epsilon\, \mathbb{R}^n, x \,\epsilon\, \mathbb{R}^m, h \,\epsilon\, \mathbb{R}^{n \times m}$.

What is the order of h? Different rules for different approaches.

cardiac rhythms





Otani, N. F., et al., What can nonlinear dynamics teach us about the development of ventricular tachycardia/ventricular fibrillation?, doi:10.1016/j.hrthm.2005.07.015, 2005.

POSIWID – Stafford Beer

Ross Ashby, Introduction to Cybernetics, Chapman & Hall LTD, 1957:

Ask not "what is this thing" — ask "what does this thing do"?

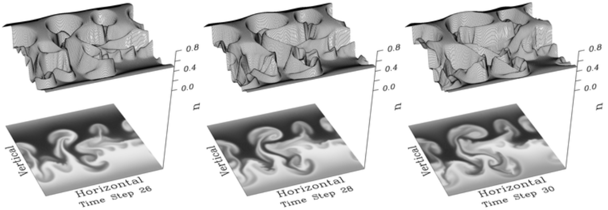
- equilibrium and stability
- the black box
- Markov chains
- variety
- regulation
- amplification

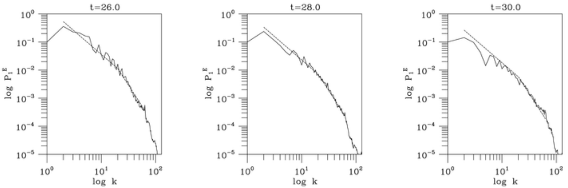
"In the simpler systems, the methods of cybernetics sometimes show no obvious advantage over those that have long been known. It is chiefly when the systems become complex that the new methods reveal their power."

– e.g. cannot "vary one at a time."

- self-similarity, preferential attachment, and power laws (Andrey Kolmogorov, Robert Kraichnan, Herbert Simon)
- conservation principles, variational mechanics (Lagrange, Hamilton, Jacobi)

- stochastic calculus, mean-flow electrodynamics
- multi-scale theory

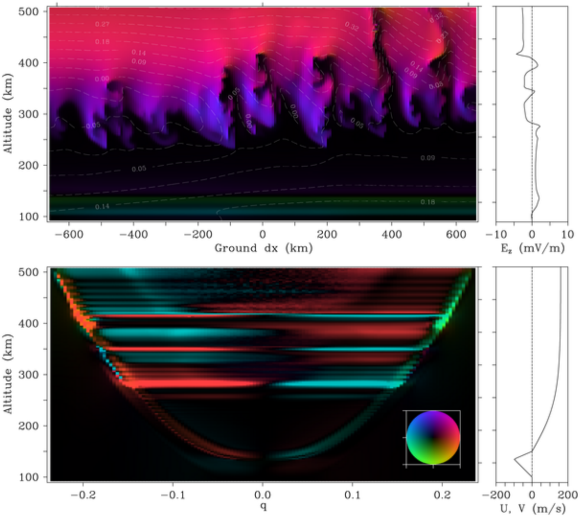




$$\left(\frac{\partial}{\partial t} + \mathbf{v}_i^0 \cdot \nabla\right)\rho + \frac{1}{2}(\hat{y} \times \nabla|\nabla\psi|^2) \cdot \nabla n \quad = \quad -\nu_{in}\rho + g\frac{\partial n}{\partial x} + \eta_* \nabla^2 \rho$$

$$\rho \quad = \quad \nabla \cdot (n\nabla\psi) \quad = \quad \hat{b} \cdot (\nabla \times n\mathbf{v}_i^0)$$

example Ib – ESF



example II – wave propagation in stochastic media

Suppose a system evolves according to

$$\begin{aligned} \dot{u}(t) &= A(t;\varpi)u \\ u(0) &= a \\ A(t;\varpi) &= A_\circ(t) + \alpha A_1(t;\varpi) \end{aligned}$$

where $A_\circ(t)$ is "sure" and $A_1(t;\varpi)$ is stochastic, with ϖ denoting one particular member of an ensemble, with some PDF $F(\varpi)d\varpi$ defined. Note that u is a column vector and A a matrix, in general.

Then an equation for the averages follows:

$$\frac{d}{dt}\langle u(t)\rangle = \left\{ A_\circ + \alpha^2 \int_0^\infty \langle A_1(t) e^{A_\circ \tau} A_1(t-\tau)\rangle e^{-A_\circ \tau} d\tau \right\} \langle u(t)\rangle$$

Van Kampen, N. G., *Physics Reports* (Section C of Physics Letters), *24*(3), 171, 1976.

example III – UH/EB mode coupling near $m\Omega_e$

$$(\omega - \omega_{\mathrm{uh}}(k_x, x))\,(\omega - \omega_{\mathrm{eb}}(k_x, x)) = \frac{m^2 - 1}{2^{m+1} m!}(k_x^2/k^2)\omega_p^2 \chi^{2(m-1)}$$

$$\omega - w_{\mathrm{uh}} = a(k_x - k_\circ) + b(x - x_\circ), \quad \omega - w_{\mathrm{eb}} = f(k_x - k_\circ) + g(x - x_\circ)$$

$$(a(k_x - k_\circ) + b(x - x_\circ))\,(f(k_x - k_\circ) + g(x - x_\circ)) = \eta_\circ$$

$$\boxed{\frac{d\phi_1}{d\xi} - i\left(k_\circ - \frac{b}{a}\right)\phi_1 = i\lambda\phi_2, \quad \frac{d\phi_2}{d\xi} - i\left(k_\circ - \frac{g}{f}\right)\phi_2 = i\lambda\phi_1}$$

where $\lambda = \sqrt{\eta_\circ / af}$.

Cairns, R. A., and C. N. Lashmore-Davies, *Phys. Fluids*, *26*(5), 1268, 1983.

- A system scientist probably would not approach animal behavior by focusing on individual neurons.
- Nor would a system scientist demand to study every neuron (or even one).
- Instead, a system scientist would emphasize the organization of the neurons at an abstract level, seeking universal patterns.
- The system doesn't exist until you define it.
- CEDAR/GEM doing system science already.