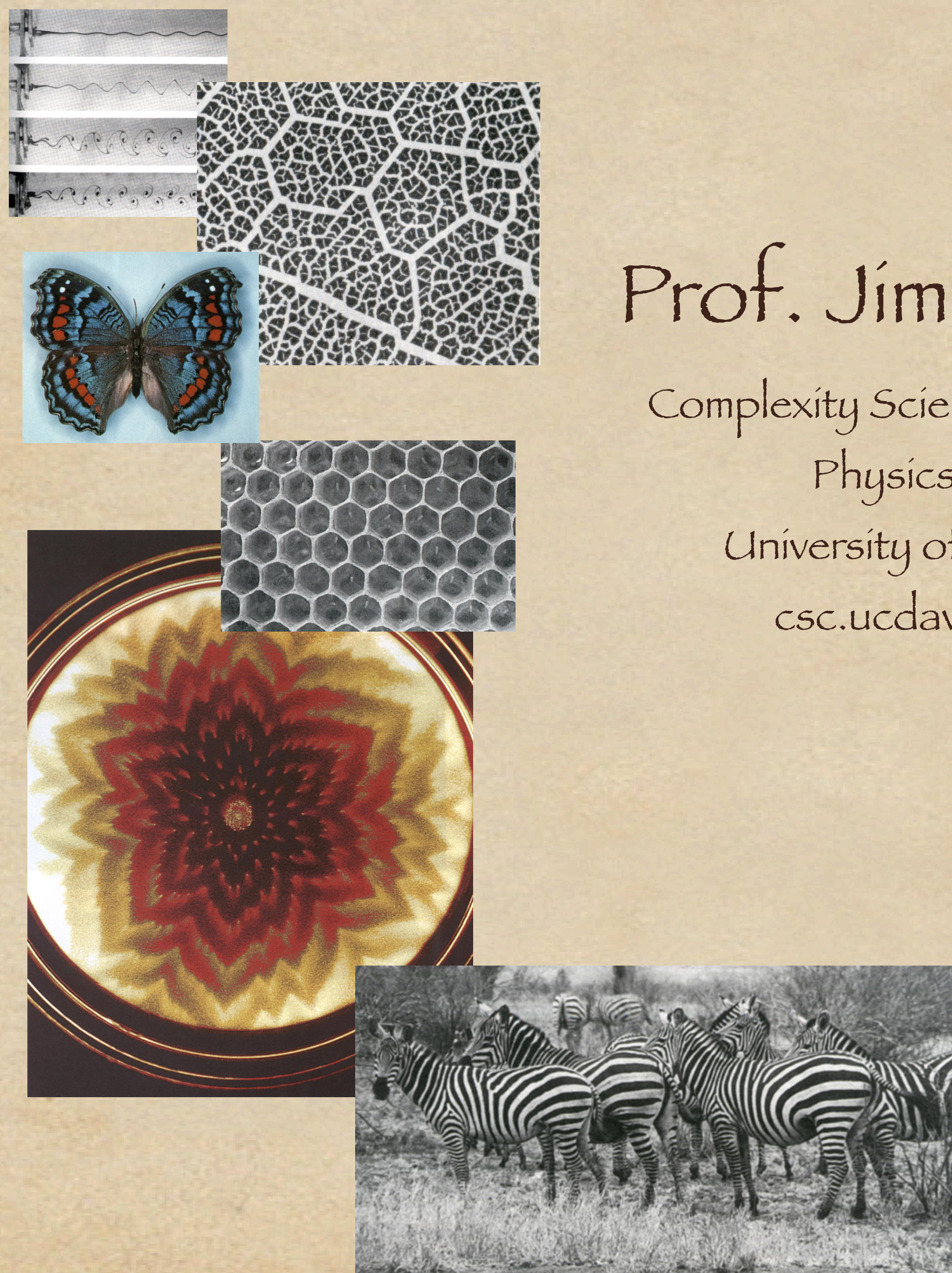
# Physics of Information and Computation

Physics 256AB

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# History

- The Industrial Age and Thermodynamics
- The Information Age and ... What?

# Physics

- To date: Physics is energy book-keeping
  - Energy storage
  - Energy transduction

# Physics ...

- What is the Physics of Information?

# Physics ...

- Energy
- Information
- Two different accountings of same system
- Related?

# Physics ...

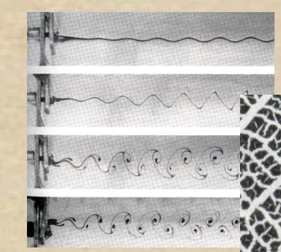
- Information is not Energy

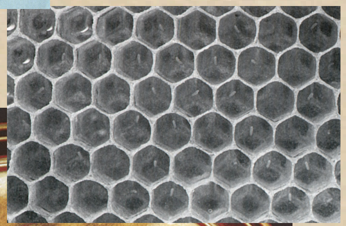
- Role of information & energy in causality

  ... a causal chain ... (Product Placement)

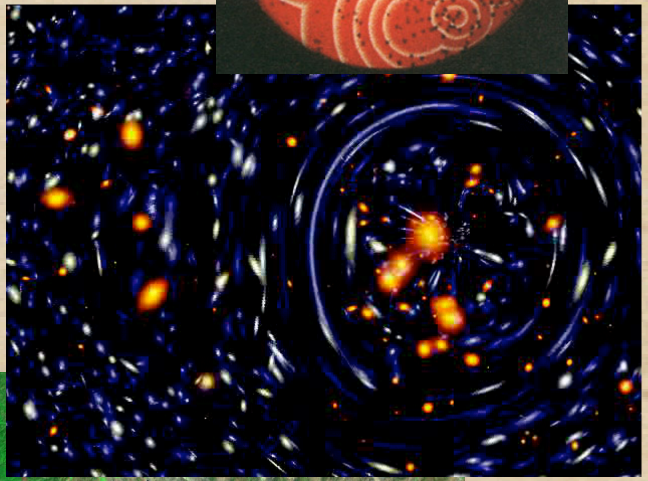
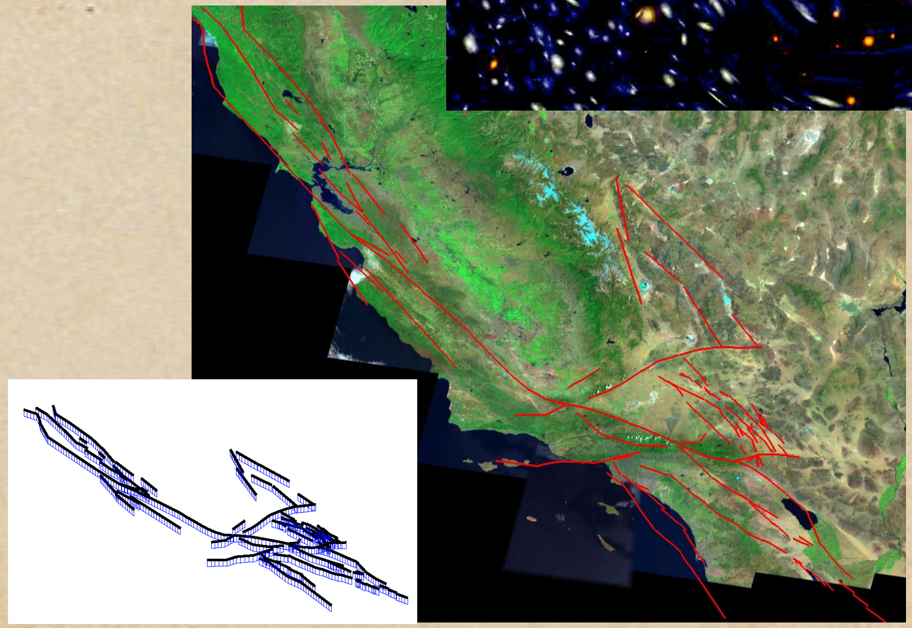
# Mechanism Revived

- Deterministic chaos (stable instability)
  - Nature actively produces information
- What is information? Randomness?
- Where does it come from?




# Spontaneous Self-Organization


# Mechanism Revived ...

- Self-Organization
    - Nature actively produces structure
- What is structure? Order? Regularity?
- Where do they come from?

# Mechanism Revived ...

- How does nature balance

  order and randomness?

# Discovery

- Pattern recognition
- Pattern discovery
- Causal explanation

# Logic of the Course

- Complex systems: order and chaos
- Self-organization:

  Emergence of order

  Emergence of chaos
- Natural Computation:

  How nature stores & processes information

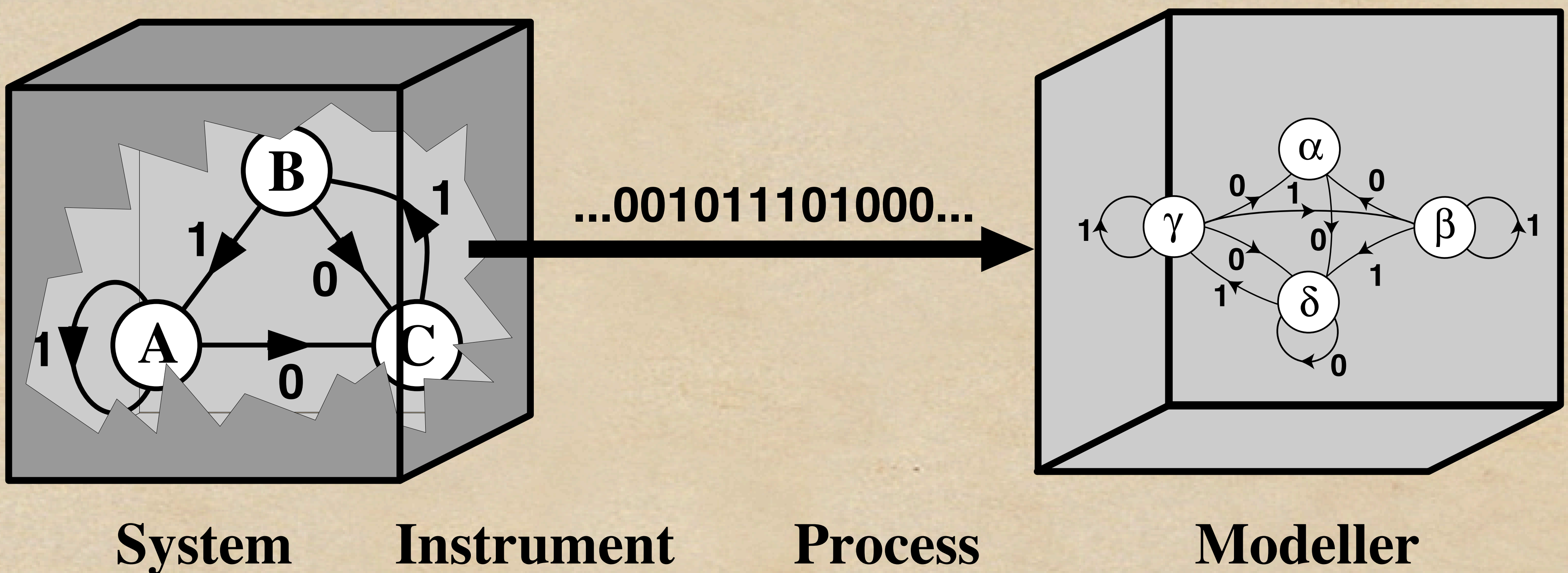
# How to do this?

- Dynamical Systems Theory
- Information Theory
- Computational Mechanics

Winter (256A)

Spring (256B)

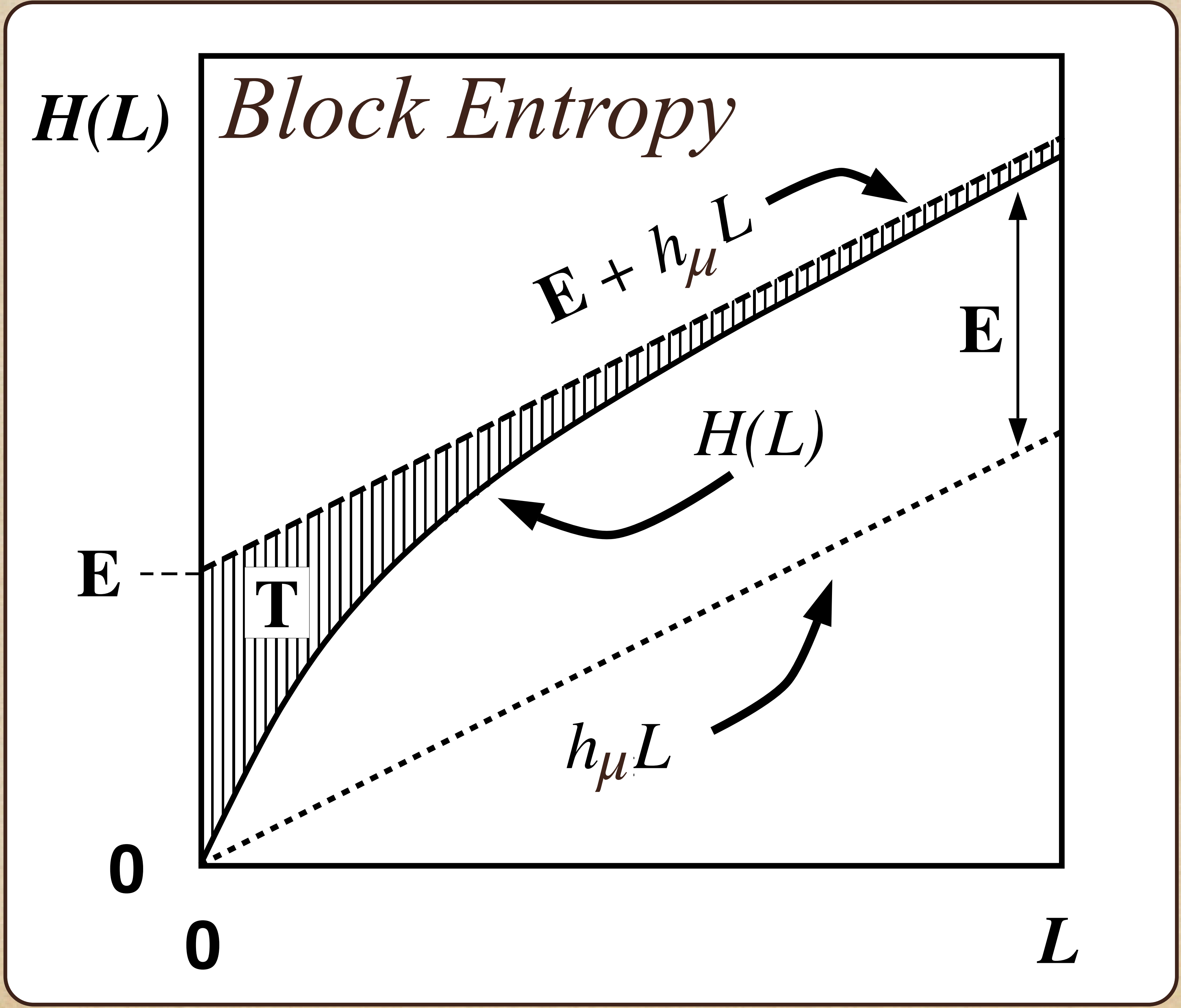
# How to do this?




# The Learning Channel

Physics of Information, Review

Information-Entropy Roadmap for a Stochastic Process:



## Physics of Information, Review

### Regularities Unseen, Randomness Observed:

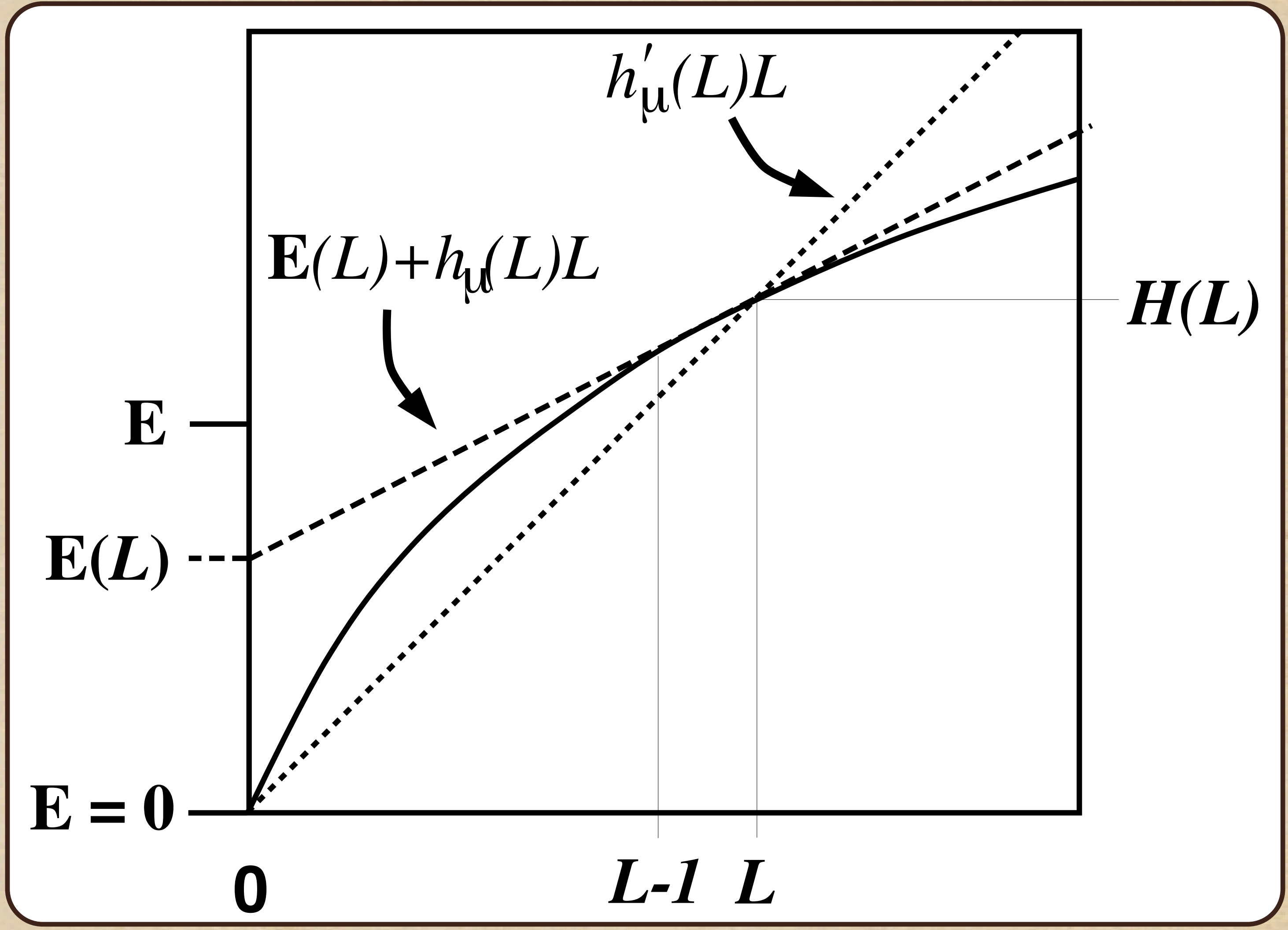
### Ignore process's memory

By assuming

$$\mathbf{E} = 0$$

Over-estimate true randomness:

$$h_\mu{}' > h_\mu$$




Lesson:

Structure $(\mathbf{E}\ \&\ \mathbf{T})$ converted to apparent randomness $(h_\mu)$.

# Physics of Information, Review

## Calculus of the Entropy Hierarchy:

### Via Discrete-Time Derivatives and Integrals

| Level | Gain (Derivative) | Information (Integral) |
|---|---|---|
| 0 | Block Entropy<br>$H(L)$ | Transient Information<br>$\mathbf{T} = \sum_{L=1}^{\infty} [\mathbf{E} + h_\mu L - H(L)]$ |
| 1 | Entropy Rate Loss<br>$h_\mu(L) = \Delta H(L)$ | Excess Entropy<br>$\mathbf{E} = \sum_{L=1}^{\infty} [h_\mu(L) - h_\mu]$ |
| 2 | Predictability Gain<br>$\Delta^2 H(L)$ | Total Predictability<br>(Redundancy)<br>$\mathbf{G} = -\mathcal{R}$ |
| ... | ... | ... |

## Physics of Information, Review

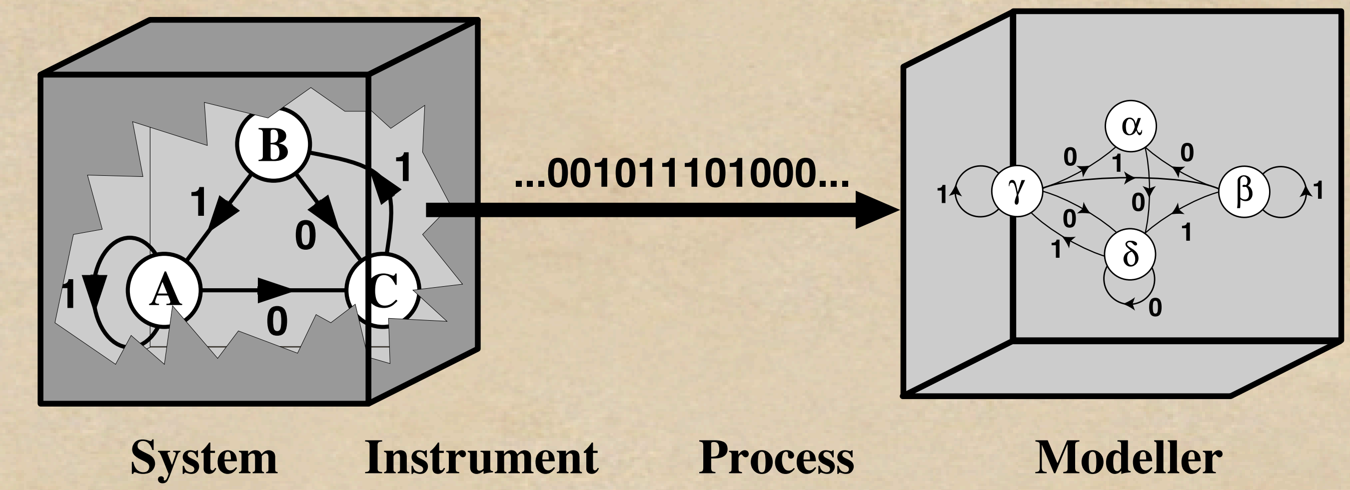
What is information?

Depends on the question!

| | |
|---|---|
| Uncertainty, surprise, randomness, .... | $H(X) \quad h_\mu$ |
| Compressibility. | $\mathcal{R} = \log_2 \lvert\mathcal{A}\rvert - h_\mu$ |
| Transmission rate. | $I[X;Y]$ |
| "Memory", apparent stored information, .... | $\mathbf{E}$ |
| Synchronization. | $\mathbf{T}$ |
| Ephemeral. | $r_\mu$ |
| Bound. | $b_\mu$ |
| ... | |

# Physics of Information, Review

## Analysis Pipeline:




1. An information source:
   a. Dynamical System:
      Deterministic or stochastic?
      Low-dimensional? High? Spatial? Network?
   b. Design instrument (partition)
2. Calculate or estimate $\Pr(s^L)$
3. Information-theoretic analysis: $H(L)$
   a. How much information produced? $h_\mu$
   b. How much stored information? $\mathbf{E}$
   c. How does observer synchronize? $\mathbf{T}$

## Physics of Information (256A), Review

Dynamical systems as sources of complexity:

1. Chaotic attractors (State)
2. Basins of attraction (Initial conditions)
3. Bifurcation sequences (Parameters)

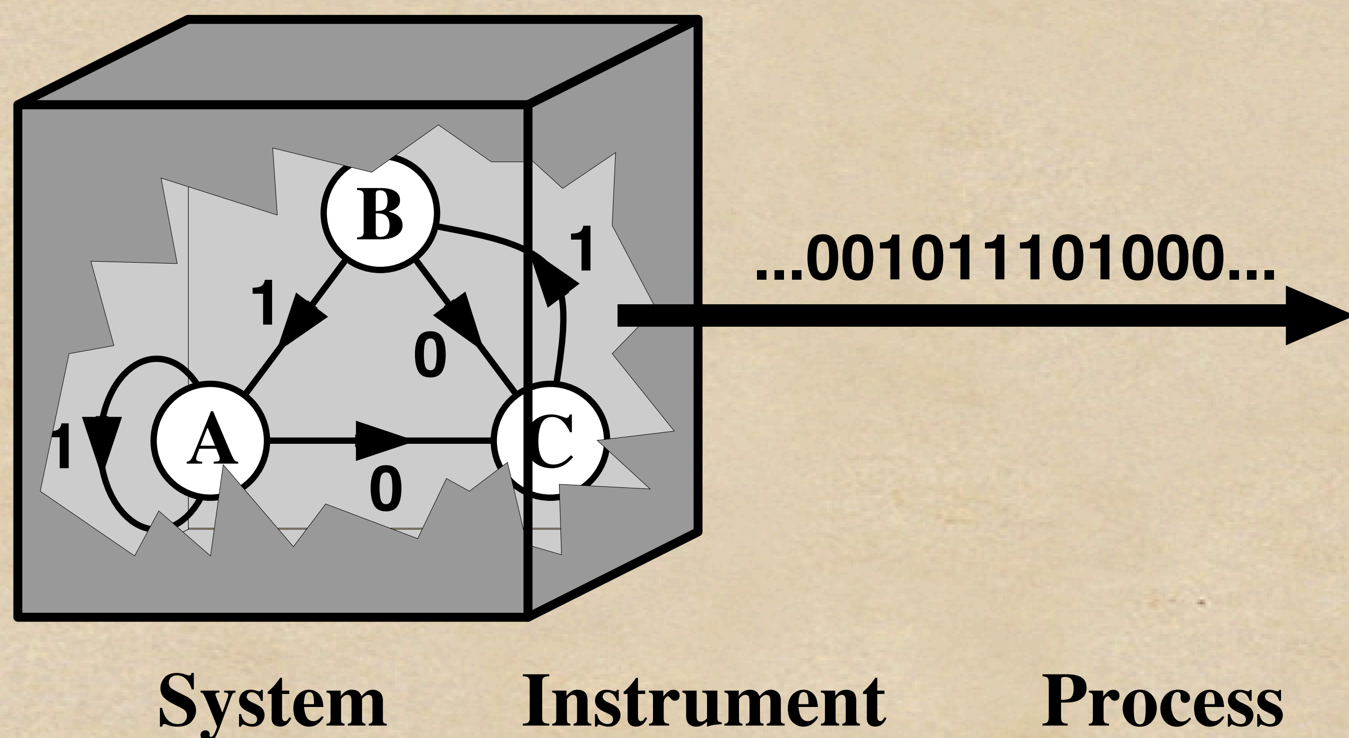
Dynamical systems as information processors:

1. Randomness:
   Entropy hierarchy: block entropy, entropy convergence, entropy rate, ...
2. Information storage:
   1. Total predictability
   2. Excess entropy
   3. Transient information

# Inadequacies of Information Theory

- Never tells you what information content is
- Only measures amounts of information ...
- Granted with operational meaning: compression & error-free transmission.
- No direct measure of structure or organization.

# Information measures, then what?




# The Learning Channel

Structure & Learning

Preview of 256B: Physics of Computation

Answers a number of questions 256A posed:

What does information mean?
What is a model?
What are the hidden states and equations of motion?
Are these always subjective, depending on the observer?
Is there a principled way to model processes?
To discover states & equations of motion?

What are cause and effect? Mechanistic explanation?

To what systems can we apply these ideas?
What can we calculate analytically?
What numerically?
Inferred, estimated from simulation or experimental data?

# Main Idea (of 256B)

Structure = Information + Computation

How Nature is Structured

is How Nature Computes

# Goals

- Identify mechanisms of unpredictability ✓
- Quantify unpredictability ✓
- You can identify & quantify structure
- You see how both relate to computation (aka information processing)

# Applications

- Novel Computation
  - DNA, Analog, Neural, Quantum, ...
  - Nanotechnology
- Biology:
  - Living systems: form versus "function"
- Automated Scientific Inference
- ...

# Staying in touch

- Course Website:

  csc.ucdavis.edu/~chaos/courses/poci/

- Course mail list:

  poci-s25@ucdavis.edu

- Emails:

  chaos@ucdavis.edu

  czpratt@ucdavis.edu@ucdavis.edu

- Office hours

  JPC: Wednesday 3-4 PM, 197 Physics

  TA: See course website, 195 Physics

# Course logistics

- Readings: See course website updates
- Homework: See course CoCalc updates
- 256A (Winter) Exams:
  - Mid-term and Final.
  - Grading: 33% HW + 33% MT + 34% Final
- 256B (Spring): Project oriented
  - Grading: 40% HW + 60% Project

# Course logistics ...

- Projects
  - Choose temporal, spatio-temporal, network dynamical, or statistical mechanical system
  - Analyze informational & computational properties
  - Relate latter to system's organization and behavior
  - Class presentation (10 + 5 minutes)
  - Written report (code!)
  - Website: Schedule, previous years' topics, reports.

# Materials

- Books

[NDAC] Nonlinear Dynamics and Chaos: with applications to physics, biology, chemistry, and engineering, S. H. Strogatz, Addison-Wesley, Reading, Massachusetts (2001).

[EIT] Elements of Information Theory, T. M. Cover and J. A. Thomas, Second Edition, Wiley-Interscience, New York (2006).

- [CMR] Computational Mechanics Reader

(listed on course website; most articles available there as PDFs)

- Lecture Notes: See course website updates

# Simulation/numerical computing ...

- Tools & Development (see website)
- CMPy: Computational Mechanics in Python
- CMPy Labs
- Software and program development
- Account on CMPy server:

  CoCalc.com

# Reading To Do

- CMR articles BOAC and CMPPSS (Intro).
- CMR article "Chance and Order", Stanislaw Lem, New Yorker 59 (1984) 88-98.
- CMR article "Revealing Order in the Chaos", Mark Buchanan, New Scientist, 26 February 2005; available at csc.ucdavis.edu/~chaos/news/.