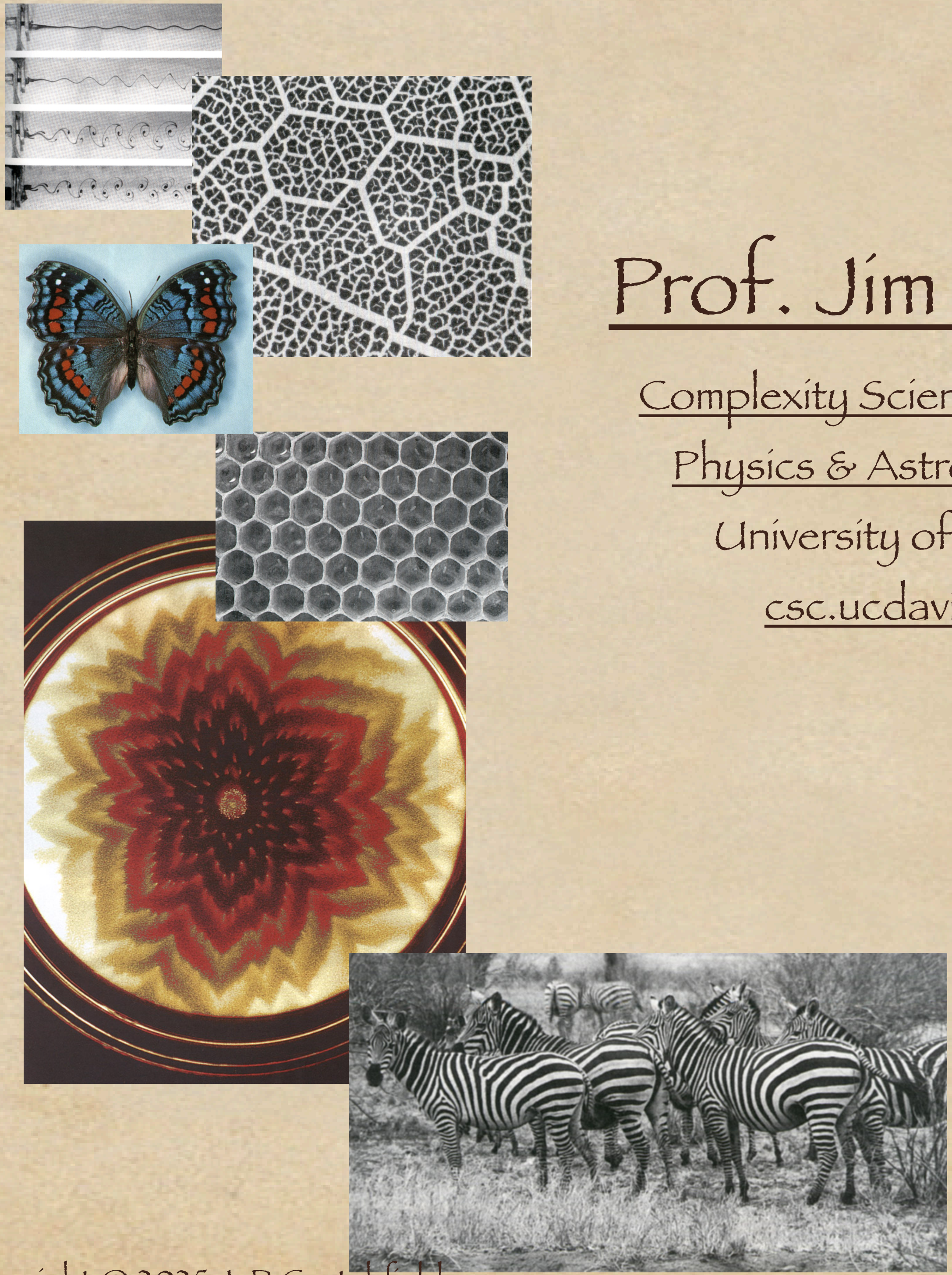
Physics of Information &
Physics of Computation

Physics 256 A + B



Prof. Jim Crutchfield

Complexity Sciences Center, Director
Physics & Astronomy Department
University of California, Davis
csc.ucdavis.edu/~chaos

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 ...

- Information is not Energy
- The role of information in causality

  ... a causal chain ... (Warning! Product Placement) https://www.youtube.com/watch?v=6-F0IqyV-iQ

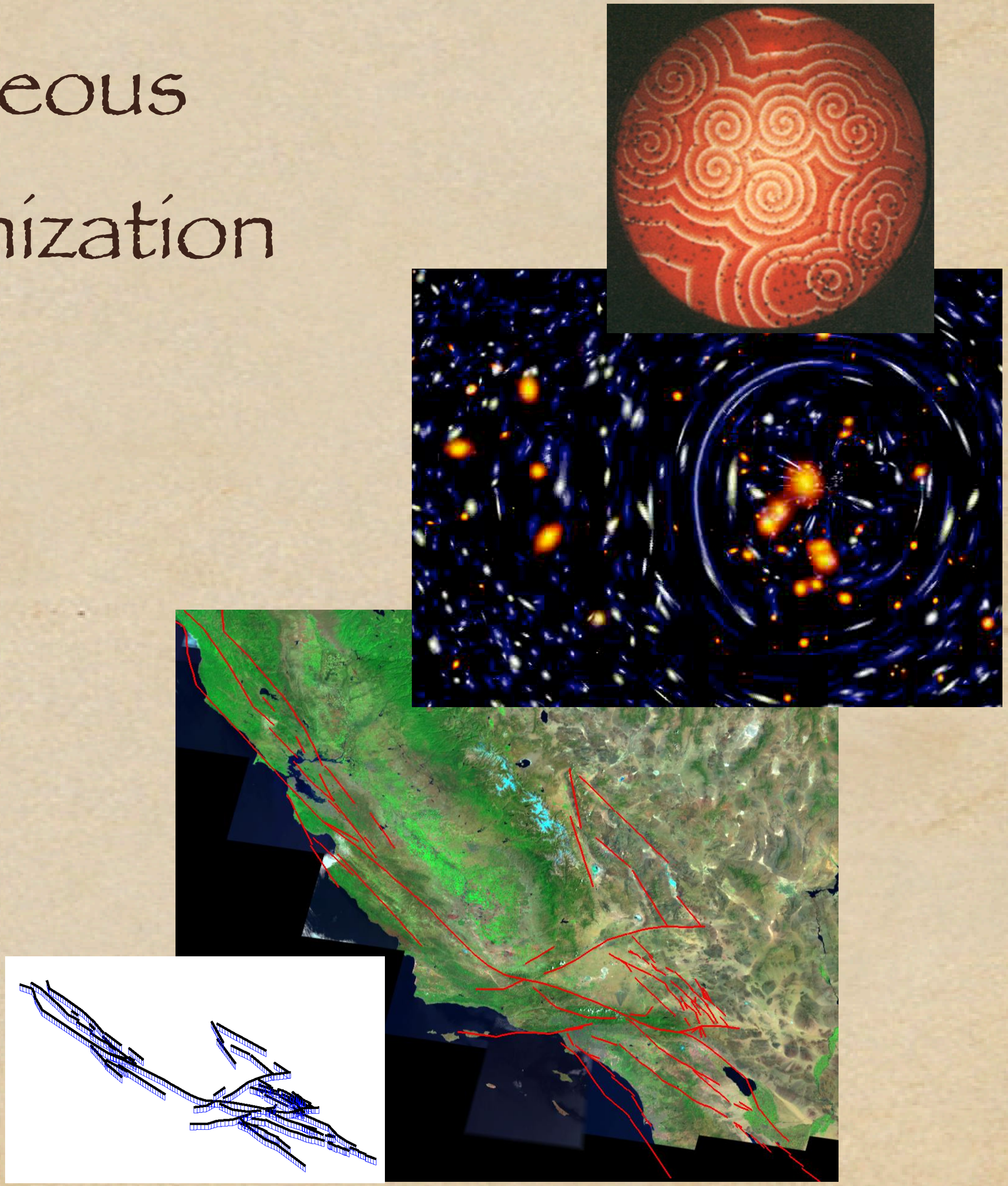
Mechanism Revived

- Deterministic chaos
    - Nature actively produces information
- What is randomness?
- Where does it come from?

Mechanism Revived ...

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

Spontaneous Self-Organization



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 chaos
  - Emergence of order
- Intrinsic Computation:
  - How nature stores & processes information

Main Idea

Structure = Information + Computation

How Nature is Structured
is How Nature Computes

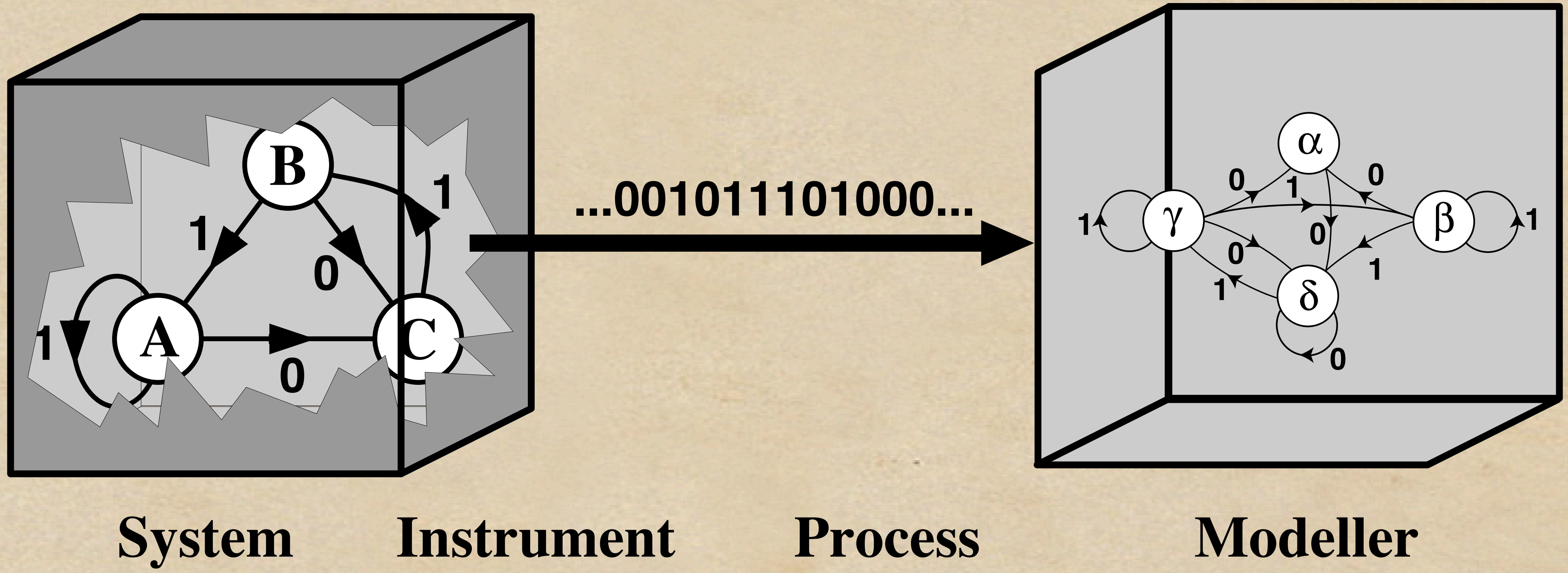
How to do this?

- Dynamical Systems Theory
- Information Theory
- Computational Mechanics

Winter 256A

Spring 256B

How to do this?



The Learning Channel

Goals

- You can quantify unpredictability
- You can quantify structure
- Know both related to computation

  (aka information processing)

Applications

- Intrinsic Computation
  - Analog, Classical, Quantum, ...
  - Neural, Evolution, DNA, ...
  - Nanotechnology
- Biology:
  - Living systems: Form versus function
- Machine Learning
  - Automated Scientific Inference
- ...

Who are we?

- JPC
- Assistants:
  - TA: Chris Pratt(Physics & CSC)
  - Guest lectures & volunteer helpers

Staying in touch

- Course Website:

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

- Mail list:

  poci-w25@ucdavis.edu

- Email:

  chaos@ucdavis.edu (me)

  TA: See WWW

- Office hours:

  JPC: Wednesday 3-4 PM, 197 Physics

  TA: See website for times

Who are you?

- Interests?
- Background?
- Abilities?

Logistics

- Flipped Course!
  - Class Meetings:
    - Labs, problem solving, discussion.
    - Use laptops!
- Online:
  - Lecture videos
  - Readings
  - CoCalc.com server: Homework + Labs

Have account, login!

Logistics

- Weekly updates:
    - Lectures
    - Readings
    - Homework

- 256A (Winter):
    - Exams: Mid-term and Final.
    - Grading: 40% HW + 30% MT + 30% Final
- 256B (Spring): 40% HW + 60% Project

Materials

- Books

  [NDAC] Nonlinear Dynamics and Chaos: with applications to physics, biology, chemistry, and engineering, S. H. Strogatz, Second Edition, Addison-Wesley, Reading, Massachusetts (2015).

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

- [CMR] Computational Mechanics Reader

  On course website; articles available there as PDFs.

- Lecture Notes: Web updates each lecture.

Programming ...

- Learning via Analytical & Numerical
- Abilities?
- Interest?
- Tools & Development (see website)
- CMPy: Computational Mechanics in Python

Programming …

- Labs, homeworks, run in your browser:

  http://cocalc.com/

  Help & get started:

  http://csc.ucdavis.edu/~chaos/courses/poci/cmpycloud.html

  Recommend: Firefox, Chrome, Safari.

- Python: Matlab/R/Mathematica-like, but a real programming language.

Reading To Do

- CMR articles:
  - Stanislaw Lem, "Odds"
  - Crutchfield et al, "Chaos", Scientific American
- NDAC:
  - Chapters 1 & 2

Thursday Meeting

- Field questions about course (Lecture 1 video), basic dynamical systems (Lecture 2 video), & CoCalc use.
- Come with questions!

Presage of Spring

Article

nature physics

INSIGHT | REVIEW ARTICLES

| DOI: 10.1038/NPHYS2190

Between order and chaos

James P. Crutchfield

What is a pattern? How do we come to recognize patterns never seen before? Quantifying the notion of pattern and formalizing the process of pattern discovery go right to the heart of physical science. Over the past few decades physics' view of nature's lack of structure—its unpredictability—underwent a major renovation with the discovery of deterministic chaos, overthrowing two centuries of Laplace's strict determinism in classical physics. Behind the veil of apparent randomness, though, many processes are highly ordered, following simple rules. Tools adapted from the theories of information and computation have brought physical science to the brink of automatically discovering hidden patterns and quantifying their structural complexity.

One designs clocks to be as regular as physically possible. So much so that they are the very instruments of determinism. The coin flip plays a similar role; it expresses our ideal of the utterly unpredictable. Randomness is as necessary to physics as determinism—think of the essential role that 'molecular chaos' plays in establishing the existence of thermodynamic states. The clock and the coin flip, as such, are mathematical ideals to which reality is often unkind. The extreme difficulties of engineering the perfect clock[1] and implementing a source of randomness as pure as the fair coin testify to the fact that determinism and randomness are two inherent aspects of all physical processes.

In 1927, van der Pol, a Dutch engineer, listened to the tones produced by a neon glow lamp coupled to an oscillating electrical circuit. Lacking modern electronic test equipment, he monitored the circuit's behaviour by listening through a telephone ear piece. In what is probably one of the earlier experiments on electronic music, he discovered that, by tuning the circuit as if it were a musical instrument, fractions or subharmonics of a fundamental tone could be produced. This is markedly unlike common musical instruments—such as the flute, which is known for its purity of harmonics, or multiples of a fundamental tone. As van der Pol and a colleague reported in *Nature* that year[2], 'the turning of the condenser in the region of the third to the sixth subharmonic strongly reminds one of the tunes of a bag pipe'.

Presciently, the experimenters noted that when tuning the circuit 'often an irregular noise is heard in the telephone receivers before the frequency jumps to the next lower value'. We now know that van der Pol had listened to deterministic chaos: the noise was produced in an entirely lawful, ordered way by the circuit itself. The *Nature* report stands as one of its first experimental discoveries. Van der Pol and his colleague van der Mark apparently were unaware that the deterministic mechanisms underlying the noises they had heard had been rather keenly analysed three decades earlier by the French mathematician Poincaré in his efforts to establish the orderliness of planetary motion[3–5]. Poincaré failed at this, but went on to establish that determinism and randomness are essential and unavoidable twins[6]. Indeed, this duality is succinctly expressed in the two familiar phrases 'statistical mechanics' and 'deterministic chaos'.

Complicated yes, but is it complex?

As for van der Pol and van der Mark, much of our appreciation of nature depends on whether our minds—or, more typically these days, our computers—are prepared to discern its intricacies. When confronted by a phenomenon for which we are ill-prepared, we often simply fail to see it, although we may be looking directly at it. Perception is made all the more problematic when the phenomena of interest arise in systems that spontaneously organize.

Spontaneous organization, as a common phenomenon, reminds us of a more basic, nagging puzzle. If, as Poincaré found, chaos is endemic to dynamics, why is the world not a mass of randomness? The world is, in fact, quite structured, and we now know several of the mechanisms that shape microscopic fluctuations as they are amplified to macroscopic patterns. Critical phenomena in statistical mechanics[7] and pattern formation in dynamics[8,9] are two arenas that explain in predictive detail how spontaneous organization works. Moreover, everyday experience shows us that nature inherently organizes; it generates pattern. Pattern is as much the fabric of life as life's unpredictability.

In contrast to patterns, the outcome of an observation of a random system is unexpected. We are surprised at the next measurement. That surprise gives us information about the system. We must keep observing the system to see how it is evolving. This insight about the connection between randomness and surprise was made operational, and formed the basis of the modern theory of communication, by Shannon in the 1940s (ref. 10). Given a source of random events and their probabilities, Shannon defined a particular event's degree of surprise as the negative logarithm of its probability: the event's self-information is $I_i = -\log_2 p_i$. (The units when using the base-2 logarithm are bits.) In this way, an event, say i, that is certain ($p_i = 1$) is not surprising: $I_i = 0$ bits. Repeated measurements are not informative. Conversely, a flip of a fair coin ($p_{\mathrm{Heads}} = 1/2$) is maximally informative: for example, $I_{\mathrm{Heads}} = 1$ bit. With each observation we learn in which of two orientations the coin is, as it lays on the table.

The theory describes an information source: a random variable X consisting of a set $\{i = 0, 1, \ldots, k\}$ of events and their probabilities $\{p_i\}$. Shannon showed that the averaged uncertainty $H[X] = \sum_i p_i I_i$—the source entropy rate—is a fundamental property that determines how compressible an information source's outcomes are.

With information defined, Shannon laid out the basic principles of communication[11]. He defined a communication channel that accepts messages from an information source X and transmits them, perhaps corrupting them, to a receiver who observes the channel output Y. To monitor the accuracy of the transmission, he introduced the mutual information $I[X;Y] = H[X] - H[X|Y]$ between the input and output variables. The first term is the information available at the channel's input. The second term, subtracted, is the uncertainty in the incoming message, if the receiver knows the output. If the channel completely corrupts, so

---

Complexity Sciences Center and Physics Department, University of California at Davis, One Shields Avenue, Davis, California 95616, USA.
*e-mail: chaos@ucdavis.edu.

Homework 0

- Find three (3) examples of unpredictability that you encounter directly.
- For each, be prepared to discuss next lecture:
    - Where did you encounter it?
    - What was your interaction?
    - Why do you consider it unpredictable?
    - What effect did its unpredictability have on you?
    - What aspects would you expect to be able to predict?
    - How would you model it?
- For each example, write paragraph summarizing answers.
- Submit via your CoCalc account

(Again see http://csc.ucdavis.edu/~chaos/courses/poci/cmpycloud.html)