UCLA STAT 19
Order in the Stochastic Universe
A *Fiat Lux* Course

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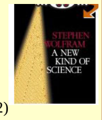
http://www.stat.ucla.edu/~dinov/courses_students.html

Course Organization

Software: SOCR resource,

http://socr.stat.ucla.edu



Texts: *A New Kind of Science* by Stephen Wolfram (2002)

Chance in Biology: Using Probability to Explore Nature by Mark Denny and Steven Gaines (2002)

Course Description, Class homepage, online supplements, VOH's, etc.

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Topics

- The Nature of Chance
- Determinism versus Chance
- Chaos vs. Order
- Experiments, Observations & Distributions
- Types & Causes of Variation, Entropy
- Discrete & Continuous Patterns of Disorder
- The Normal Distribution
- Central Limit Theory
- Randomness in Biology, Genetics, Eng. & Physics
- Random Walks

Topics (cont.)

- Duality Principles: The Uncertainty Principle (momentum vs. position)
- Balancing Quality and Volume of Information
- Statistical vs. Practical Significance
- Statistics of Extremes
- Intra- vs. Extra-polation
- Noise and Perception
- Bayesian Theory

The Nature of Chance

- ***The Nature of Chance*** extends far beyond the random events that shape human existence. Chance is ubiquitous, and its role in Life and the Universe is the subject of this Course.
- ***Examples:*** mountain stream sound, arrival times, MPG mileage, wind patterns (vorticity), (thermal molecular) diffusion/movements/walks, material strength, the drift of genes in a population, longevity of phytoplankton, etc.
- Is **chance** in life **unavoidable**?

The Nature of Chance

- **(Classical) Traditional approach** is to *view chance as a necessary evil* that can be tamed via application of clever techniques (filtering) or inferential statistics.
- **Alternatively**, if chance is a given in life, why not *use it to our advantage*? In other words, if we know that a system will behave in a random (***chaotic***) fashion in the short term and at small scale (as with the random thermal motions of protein chains in spider silk), we can use this information to make accurate predictions as to how the system will behave in the long run and on a larger scale.

The Nature of Chance

- ***Probability theory*** was originally devised to predict the outcome in games of chance, but its utility has been extended far beyond games. ***Life*** itself is a chancy proposition, a fact apparent in our daily lives. Some days you are lucky (every stoplight turns green as you approach) and other days, just by chance, you are stopped by every light.

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Determinism versus Chance

- **Deterministic Processes**: One of Sir Isaac Newton's grand legacies is the idea that much about how the Universe works can be precisely described. *I.e. given sufficient knowledge of the initial state of a system, its future is determined exactly.*
- **Examples**: If we know the exact masses of the Moon and Earth and their current speed relative to each other, **Newtonian mechanics** and the law of gravitation should be able to tell us the exact position of the Moon relative to Earth at any future time (e.g., predict solar and lunar eclipses).
- **Euclidean Geometry**: Given 2 sides of a right-triangle we can determine exactly the length of the 3rd size.

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Determinism versus Chance

- Good examples of real-world deterministic processes are difficult to find. Many of the processes that seem simple when described abstractly are exceedingly complex in reality. Details inevitably intrude, bringing with them an **element of unpredictability**.
- **Approximations**: In some cases, the amount of variability associated with a process is sufficiently small that we are willing to view the system as being *approximately deterministic*, and accept as fact predictions regarding its behavior.
- The physics of a **pendulum clock**, for instance, is so straightforward that we are content to use these machines as an accurate means of measuring time.

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Determinism versus Chance

- In biology, few systems are so reliable, and deterministic behavior can be viewed at best as a wishful-thinking.
- **Fidelity, Imprecision, Repetition and Uncertainty** in virtually all biological processes – read the online article by Miroslav Radman in Nature 413 (Class notes).
- Perfection of organisms and the accuracy of biological processes are still used in religious explanations of the origin of life. However, **in real life it is survival, not fidelity, that is the ultimate virtue.**

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Determinism versus Chance

- Because adaptability involves exploration of genetic possibilities to fit ecological *niches*, **molecular infidelity and repetition are more likely to succeed than a precise, non-repetitive process**.
- Only a tiny fraction of antibodies produced will ever be useful; the rest can be considered as mistakes.
- At least **half of all human embryos fail** during development.
- During chromosome segregation from a mother cell into two daughters, the polymerizing fibers (microtubules) do not know the exact location of the chromosomal target (the centromere) — they **shoot and miss until one hits**.

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Determinism versus Chance

- A precise, **single shot would often miss a target** of uncertain position, whereas **successive, imprecise firing will eventually lead to a hit**.
- Selection at the level of molecules, cells and organisms may give the impression of designed perfection, but **life's structures do not emerge by fully deterministic design**.

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Efficiency vs. Precision

- What about the **fidelity of enzymatic reactions**? In the very precise process of DNA replication, accuracy is achieved by using a ***proofreading*** system to remove erroneously inserted nucleotides, and then by ***quality-checking*** the synthesized DNA using a mismatch-repair system that removes virtually all remaining mistakes.
- ***It would take too long to get it exactly right in the first place***. DNA replication is efficient and therefore relatively imprecise, leaving mistakes to error-correction enzymes which are themselves efficient because their substrates are specific mistakes made by other enzymes.

Determinism versus Chance

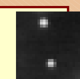
- If a system or process is not deterministic, it is by definition **stochastic**. Even if we know exactly the state of a stochastic system at one time, we can never predict exactly what its state will be in the future.
- **Stochasticity** can manifest itself to a variable degree (**wind speed could easily double** in 1 second in a turbulent environment, whereas **random washer-thickness variations** in a precise engineering design could often be within 10^{-10} %).

Determinism versus Chance

- Many stochastic processes are approximately predictable with just a minor overlay of random behavior.
- **Example**: The light intensity reflected from a mountain stream is chaotic. Yes, there are minor random short-term light fluctuations. However, if we were to take 5-minute averages of the light level (long-time picture exposure) this intensity could be predicted fairly accurately. Note the word **average** above, this is a key concept we'll discuss later in stochastic process modeling.
- In other cases, the predictability of a system is negligible, and chance alone governs its behavior (the movement of molecules in a room-temperature gas).

Determinism versus Chance

- Minor random fluctuations.



Demo of 2 micrometer diameter particles in pure water. As can be seen, each particle is constantly moving, and its motion is uncorrelated with the other particles.

- Chance alone governs its behavior

A bead-labeled RecBCD molecule translocating along a single DNA molecule. Initially, the free diffusion of beads in solution is seen. After a few seconds, one of the bead-labeled enzyme molecules attaches to the end of a DNA molecule at the center of the field (arrows); attachment is detected as the cessation of free diffusion and the commencement of characteristic tethered-particle Brownian motion in the vicinity of a single point on the microscope slide. Subsequent translocation of the enzyme along the DNA molecule is visualized as a gradual decrease in the spatial range of the Brownian motion; this decrease continues until the beads ceases visible movement altogether. The video is real time; the frame size is 6.5 μm wide by 6.6 μm tall.

Determinism versus Chance

- Practically, the dividing line between deterministic & stochastic is open to interpretation.
- **Example**, usually (both in games and texts on probability theory) we accept the P(Coin = Head) as a chance proposition, a stochastic process. But if you know enough about the height above the ground at which the coin is flipped, the angular velocity initially imparted to the coin, and the effects of air resistance, it may be possible to decide in advance whether the coin will land heads up.
- Indeed, much of what we accept as stochastic may well be deterministic given sufficient understanding of the experiment design.

Determinism versus Chance

- So, the line between **deterministic** & **stochastic** is often drawn as a matter of convenience.
- If the precise predictions that are possible in theory are too difficult to carry out in practice, we shift the line a bit and think of the process as being stochastic.
- This is not to imply that all processes are deterministic, however. As far as physicists have been able to divine, there are aspects of nature, encountered at very small scales of time and space, that are unpredictable even in theory (will talk about the **Uncertainty Principle**, Heisenberg's inequality, later).

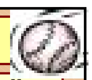
Determinism versus Chance

- There are limits to the precision with which you can know both the velocity and the location of an object.
- <u>If you could know exactly where an electron is at some point in time, you couldn't know what its velocity is</u>.
- Conversely, <u>if you know exactly what its velocity is, you can't know exactly its position</u>.
- This is the strange realm of quantum/statistical mechanics, where chance reigns and human intuition is of little use.

Chaos

- The deterministic/stochastic dividing line may become even fuzzier.
- Lately, a wide variety of physical systems that should behave deterministically were found in fact to behave unpredictably. These systems are said to exhibit **deterministic chaos**, or just chaos for short. But if they are deterministic, how can they be unpredictable?
- This apparent conflict is solved by the fact that chaotic systems are very sensitive to the state in which they are started (**initial conditions**).

Chaos



- Example, the **flight path of a baseball** through still air. In this case, if we know the initial speed of the ball (20 m/s), its initial location, and its direction of motion (45^o to the horizontal), we may **<u>predict where the ball will land</u>**.
- A **small error in the measurement** of any of these initial conditions (say, the ball is moving at 20.001 rather than 20.000 m/s), the error in predicting the ball's landing is concomitantly small.
- If the motion of a baseball were chaotic, however, its flight would be quite different. Every time a deterministic ball were launched at exactly 20 m/s and an angle of exactly 45^o from the center of home plate, it would land in the same spot near second base;

Chaos

- If, however, a chaotic ball were launched with even a slight error in any of these initial conditions, its eventual landing spot would be drastically different. A shift from 20.000 to 20.001 m/s might cause it to land outside the stadium.
- Granted, every time the ball is launched at exactly 20.001 m/s, it ends up in the same place, so the system is still deterministic, but it is extremely sensitive to the initial conditions.
- This is related to the three **types of randomness** which we'll discuss later on.

Chaos

- The primary **<u>disadvantage</u>** of treating a chaotic system as if it were **just stochastic** is a loss of insight. Once a process is stamped with the title **random** – it is easy to stop looking for a <u>mechanistic cause for its behavior</u>.
- It is interesting to note that the <u>motion of the planets</u>, which has long been cited as the **classical example of deterministic mechanics, is in fact chaotic**. Because each planet is subject to a gravitational pull from all other planets and other external forces (e.g., comets!), there is the possibility that at some time in the future the alignment of the solar system may be such that one of the planets could be thrown substantially off its present orbit, and this potential makes it virtually impossible to predict accurately where the planets will be at a given date in the future.

Order vs. Chaos

- A classical rotor subject to deterministic and random forces shows a broad spectrum of motion including <u>deterministic</u>, <u>deterministic chaos</u>, <u>random</u> and, <u>erratic</u> behavior.
- One of the main achievements of twentieth-century physics has established that **deterministic and random phenomena complement rather than contradict each other**.

Ordered vs. Chaotic motion

- *Deterministic motion.* If θ is the particle position and t is the time, there are PDE's that describe the motion in terms of the time. If the initial condition $\theta_0 = \theta(t = 0)$ uniquely determines the values of θ for all t, i.e. the motion is fully deterministic.
- *Random motion.* If one adds a random force to the equation, a rotor is capable of overcoming barriers at $\theta = m\pi$, and the motion becomes random (noise-induced instability).
- *Deterministic chaos.* Initial conditions play a major role.

Matter vs. Patterns

- *What is the Universe?*
  - *A pool of particles (stuff)?*
  - *Or a collection of patterns (of particles)?*
- If I ask the question, **Who am I?** I could conclude that, perhaps I am this stuff here, i.e., the ordered and chaotic collection of atoms & molecules (particles) that comprise my body.
- However, the specific set of particles that comprise my body are completely different from the atoms and molecules than comprised me only a few weeks ago.

Matter vs. Patterns

- So, I am a completely different set of stuff than I was a month ago. All that persists is the pattern of organization of that stuff. The pattern changes also, but slowly and in a continuum from my past self.
- From this perspective I am rather like the pattern that water makes in a stream as it rushes past the rocks in its path. The actual molecules (of water) change every millisecond, but the pattern persists for hours or even years. Even atomic structures are rearranged with time.
- It is patterns (e.g., people, ideas, objects, not elementary particles) that persist, and constitute the foundation of what fundamentally exists. The view of the Universe ultimately is a pattern of information.

Matter vs. Patterns

- The information is not just embedded as properties of some other substrate (as in the case of conventional computer memory) but rather **information is the ultimate reality**.
- What we perceive as matter and energy are simply abstractions, i.e., properties of patterns. As a further motivation for this perspective, it is useful to consider that the vast majority of processes underlying human intelligence are based on the recognition of patterns.
- **AI** !?!

Three Types of Randomness (S. Wolfram)

- **Randomness from environment** (continuous random feedback from the ambient environment) – this is like considering the random movement of a boat in the ocean. The randomness of boat movement is apparent from the randomness of sea surface movement at each time point.
- **Randomness from initial condition** – which is like rolling a dice in a controlled environment, where only the random momentum and direction of the force (initial conditions) determine the outcome.
- **Intrinsic Randomness** – which is acclaimed as the only pure random phenomenon. Example – Geiger counter in vacuum.

Types of Randomness

- Wolfram considered that intrinsic randomness could emerge from very simple rules and very simple initial conditions. Still there should be something at the start. Something should come from something else & every outcome should have input beforehand.

Information & Entropy

- A sequence of N coin tosses (of a fair coin) has $2N$ possible outcomes: there is an uncertainty in the outcome that we measure by the **entropy**, which is the logarithm of the number of possible equally likely outcomes:
  - $S = \log_2 2^N = N \log_2 2 = N$
- We could use the sequences e.g. {H, H, T, …, H} to send a message, and we could send 2^N different messages. The **information capacity** of this scheme is again measured by the logarithm of the number of possible messages
  - $I = \log_2 2^N = N \log_2 2 = N$

Information & Entropy

- In this context we would often use base 2 for the log and say there are N bits of information.
- An alternative point of view is that the measurement of a particular result i.e. sequence of heads and tails has told us something about the system and we have learned $N \log_2 2$ bits of information.
- Uncertainty of the outcomes (**entropy**) and what has been learned from a measurement (**information**) are complementary.
- Generalizing these ideas to a system of N possible results with different independent probabilities p_i gives the expression for the entropy of the system S or the information learned by finding a particular result.

Kolmogorov Complexity – Entropy

- In Shannon's information theory, the degree of randomness of a finite sequence of discrete values can be quantified by calculating the **entropy** (amount of information) as

$$-\sum_{p_k \neq 0} p_k \log_2(p_k)$$

- where p_k is the probability of occurrences of value i. Using this criterion, the **higher the entropy, the more the randomness**. For instance, the sequence 00100010 (entropy= – 0.25*log(0.25) – 0.75*log(0.75) = 0.81) is less random than 01010101 (entropy = – 0.5*log(0.5) – 0.5*log(0.5) = 1).

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- as