• Questions about Walker?
  – To get started on the rest of Project 1, try to recreate Figures 3 & 4

• Another example of assessing coupled dynamics with information theory

• Evolution & Genetics
  – Review readings
  – The Central Dogma
  – Does Evolutionary Theory need a rethink?
  – Time permitting, Wagner’s neutral networks and entropy
Mutual information as a tool for identifying phase transitions in dynamical complex systems with limited data

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(Received 20 December 2006; published 30 May 2007)

We use a well-known model [T. Vicsek et al., Phys. Rev. Lett. 15, 1226 (1995)] for flocking, to test mutual information as a tool for detecting order-disorder transitions, in particular when observations of the system are limited. We show that mutual information is a sensitive indicator of the phase transition location in terms of the natural dimensionless parameters of the system which we have identified. When only a few particles are tracked and when only a subset of the positional and velocity components is available, mutual information provides a better measure of the phase transition location than the susceptibility of the data.

FIG. 1. Multiple particles interact if within a radius $R$ of each other. Each of the $N_R$ particles within $R$ (here $N_R=4$) contributes its angle of propagation to the average $\langle \theta_n^\text{prop} \rangle$, which is assigned to the particle at the center of $R$. 

![Diagram showing multiple particles interacting within a radius R. Each particle contributes its angle of propagation to the average angle, which is assigned to the particle at the center of the radius.](image)
It is interesting to contemplate a tangled bank, clothed with many plants of many kinds, with birds singing on the bushes, with various insects flitting about, and with worms crawling through the damp earth, and to reflect that these elaborately constructed forms, so different from each other, and dependent upon each other in so complex a manner, have all been produced by laws acting around us.

Charles Darwin
Natural Selection

“Nothing in Biology makes sense, except in the light of evolution.” T. Dobzhansky

Charles Darwin, 1859, The Origin of Species

3 key ingredients for evolution by natural selection

– Exponential growth of populations
– Struggle for existence: Limited Capacity for any population
– Variable, heritable survival and reproduction
Evolution by Natural Selection

Variation
Inheritance
Selection
Evolution by Natural Selection

Variation

Diversity
Evolution by Natural Selection

Variation
Diversity
Inheritance
Mutation & Recombination
Evolution by Natural Selection

Variation
Diversity

Inheritance

Mutation & Recombination

Selection
Environment
Natural Selection

- The unity of life: all species have descended from other species
- Domestic breeding shows hereditary modification is possible

- Fitness is a characteristic of individuals
- Natural Selection operates on populations
- Fitness is defined only for a particular environment
  - Environments always change
  - Species form the selective environments of other species

- Is ‘survival of the fittest’ a circular statement?
- Is natural selection an optimization process?
Natural Selection

- Natural selection
  - is often slow, but arms races result in complex, wonderful, bizarre (and stupid) things
  - can lead to cooperation
  - (largely) based on the fitness of reproductive individuals

- Natural selection is not
  - learned behavior passed on *
  - group selection * (Dawkins: selection acts on genes & on individuals, not groups)
    - Exceptions?

- There’s a lot we don’t know about evolution
  - The role of symbiosis & cooperation
  - The ‘right’ definition of species

* Except when it is
Darwin did not have a mechanism for heritable, variable fitness

The Central Dogma
Genes: strings of DNA that get transcribed to RNA, translated to proteins and expressed as phenotype
Genetics

• Mendel: showed that genes exist by breeding pea plants, genes exist as recessives and dominants, one copy from each parent
  – Given dominant AA mom and recessive aa dad, offspring are all Aa, and look like mom
  – Variation comes from combining genes from mom (BBCCddZz) and dad (bbccDdZZ)
  – Overly simplified. Still didn’t know what a gene was.

• In 1953 Watson & Crick & Rosalind Franklin discover the molecular structure of DNA
DNA

- The molecule that carries heritable information

- Every cell in your body has ~30,000 bp of DNA that is transcribed into RNA and translated into proteins
  - Proteins do all the work: Make your eyes blue, your hair curly, your muscles strong, your heart pump

- DNA is arranged into genes on chromosomes
  - Humans have 23 chromosomes, 2 copies each (46)
  - Fits by supercoiling: 2-3m DNA / cell. All of your DNA together would stretch 67 billion miles.
What mechanisms allow for heritable, variable fitness?

**Heritable**

Genes:
- encoded in DNA,
- transcribed to RNA
- translated to proteins whose expression determines phenotype & fitness

**Variable**

Mutations--copies are not perfect

Sex—genes are combined from 2 parents

Crossing over—allows for many different possible combinations
The Central Dogma

DNA → Replication → RNA → Translation → Protein
The Central Dogma

DNA (info storage) → RNA (info transfer) → protein (work)

- Segment of DNA is unwound
- An mRNA strand is transcribed from the template strand of DNA
- mRNA → travels out of nucleus (degrades quickly)
- RNA travels to ribosomes in cytoplasm, where it is translated

Why go through all this trouble?

The nature of biological information, the possibilities for variation, and the process of selection depend on these mechanisms.
RNA codon TRANSLATION table

4 bases, 3 per codon = $4^3$ codons = 64 codons

20 amino acids (redundancy is possible)

This table shows the 64 codons and the amino acid each codon codes for.
The direction is 5' to 3'.

<table>
<thead>
<tr>
<th>Amino Acid (Single Letter)</th>
<th>Codons</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ala/A</td>
<td>GCU, GCC, GCA, GCG</td>
</tr>
<tr>
<td>Arg/R</td>
<td>CGU, CGC, CGA, CGG, AGA, AGG</td>
</tr>
<tr>
<td>Asn/N</td>
<td>AAU, AAC</td>
</tr>
<tr>
<td>Asp/D</td>
<td>GAU, GAC</td>
</tr>
<tr>
<td>Cys/C</td>
<td>UGU, UGC</td>
</tr>
<tr>
<td>Gln/Q</td>
<td>CAA, CAG</td>
</tr>
<tr>
<td>Glu/E</td>
<td>GAA, GAG</td>
</tr>
<tr>
<td>Gly/G</td>
<td>GGU, GGC, GGA, GGG</td>
</tr>
<tr>
<td>His/H</td>
<td>CAU, CAC</td>
</tr>
<tr>
<td>Ile/I</td>
<td>AUU, AUC, AUA</td>
</tr>
<tr>
<td>Met/M</td>
<td>AUG</td>
</tr>
<tr>
<td>Leu/L</td>
<td>UUA, UUG, CUU, CUC, CUA, CUG</td>
</tr>
<tr>
<td>Lys/K</td>
<td>AAA, AAG</td>
</tr>
<tr>
<td>Phe/F</td>
<td>UUU, UUC</td>
</tr>
<tr>
<td>Pro/P</td>
<td>CCU, CCC, CCA, CCG</td>
</tr>
<tr>
<td>Ser/S</td>
<td>UCU, UCC, UCA, UCG, AGU, AGC</td>
</tr>
<tr>
<td>Thr/T</td>
<td>ACU, ACC, ACA, ACG</td>
</tr>
<tr>
<td>Trp/W</td>
<td>UGG</td>
</tr>
<tr>
<td>Tyr/Y</td>
<td>UAU, UAC</td>
</tr>
<tr>
<td>Val/V</td>
<td>GUU, GUC, GUA, GUG</td>
</tr>
<tr>
<td>START</td>
<td>AUG</td>
</tr>
<tr>
<td>STOP</td>
<td>UAG, UGA, UAA</td>
</tr>
</tbody>
</table>
Proteins

Proteins are strings of amino acids

- Primary, secondary and tertiary structure
- Proteins do all the work but
- 99% of human DNA is not translated into protein
  - Why carry around all that ‘junk’?
    - Some is not expressed in some cells or conditions
    - Some is evolution’s play ground
    - Some regulates other genes

![Diagram of protein structure](image)

- The sequence of amino acids
- Local folding maintained by short distance interactions
- Additional folding maintained by more distant interactions
Variation in DNA

- How can the genetic content of a strand of DNA change?
  - Mutagens – many types of direct mutations – UV, particle radiation, oxygen radicals, other chemicals
  - Sex (Mendelian genetics)
  - Chromosomal crossing over
  - Gene exchange via gene transfer in bacteria
  - Viral DNA insertion and exchange (viruses do not have cellular machinery to reproduce their genomes, so use ours – mistakes happen)
  - Many ways we don’t understand
Sex & Crossing Over

- Each diploid human cell has 2 copies of each (of 23) chromosome.
- Sex cells (sperm & eggs) are haploid with 1 copy of each chromosome.
- Crossing over shuffles genes shuffled from both parents onto 1 chromosome.
- Your children can have grandma’s near-sightedness and grandpop’s left-handedness.
Crossing over
(Important in Genetic Algorithms)

Mom: AAA_CAT_CCG_GTA…
tall, blue eyes, left-handed, no toe hair

Dad: AAG_CCT_TCC_GGA…
short, brown eyes, Right-handed, hairy toes

Baby -------> AAACATTCCGGA
tall, brown eyes, right handed, hairy toes
Summary: Genetics & Natural Selection

3 key ingredients for adaptation by natural selection
– Exponential growth of populations
– Struggle for existence: Limited Capacity for any population
– Variable, heritable survival and reproduction

Genetics: A discrete 4 letter alphabet (AGCT)
packaged into genes
Transcribed into RNA
3 letter codons are translated into amino acids which form proteins

Variation and Heredity
Letters can change: mutations, insertions, deletions
Chromosomes crossover to create sperm & eggs
Sperm and eggs combine to make new offspring
Traditional Science
Reductionism: zoom in
Learn more & more about less & less

Complexity Science
Look across scales: zoom in & zoom out
Use multiple perspectives
Understand how structure emerges from interactions within & across levels
Does evolutionary theory need a rethink?


08 October 2014

Researchers are divided over what processes should be considered fundamental.

Pair up
Make a list of the key points from each side

1. **Needs a rethink**: Without an extended evolutionary framework, the theory neglects key processes

2. **Existing Theory is adequate**: Theory accommodates evidence through relentless synthesis
Connected genotype networks facilitate accessibility of diverse phenotypes.

Cryptic variation can facilitate evolutionary adaptation.

• Information theory, evolutionary innovations and evolvability (Wagner 2017)
  – Phenotypes may contain information about their environment
  – Natural selection can increase information encoded in the distribution of a population’s allele frequencies

• The Fitness Value of Information (Donaldson-Matasci, Bergstrom, Lachmann 2010)
  – The fitness value of a developmental cue is exactly equal to the reduction in uncertainty about the environment, as described by the mutual information
  – Organisms can bet-hedge more effectively if they can extract information from cues in the environment