IV. Evolutionary Computing

B. Thermodynamics, Life & Evolution

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Thermodynamics and Self-organization

- *Macrostates* vs. *microstates*, and macroscopically indistinguishable microstates
- *Order*: macroscopic properties can be used to predict microscopic properties
- There are many more ways to be disordered than to be ordered
- The macrostate follows the most probable trajectory
- In the thermodynamic limit, the *likely* becomes *inevitable*, and the *unlikely*, *impossible*
- *Second Law*: an isolated system approaches the most likely (maximum entropy) macrostate
- *Maximum entropy principle*: an open system follows the most likely (maximum entropy producing) trajectory

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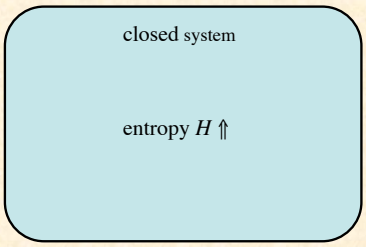
The Second Law of Thermodynamics



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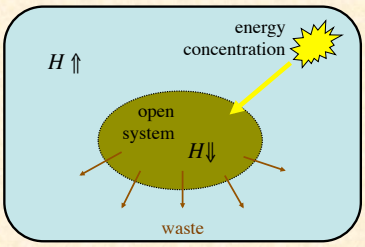
The Second Law and Open Systems



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Nonequilibrium Thermodynamics

- Classical thermodynamics limited to systems in equilibrium
- Extended by thermodynamics of *transport processes*
  - i.e. accounting for entropy changes when matter/energy transported into or out of an *open system*
- Flow of matter/energy can maintain a *dissipative system* far from equilibrium for long periods
- Hence, *nonequilibrium thermodynamics*

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An Energy Flow Can Create Structure

(photo from Camazine & al. *Self-Org. Bio. Sys.*)

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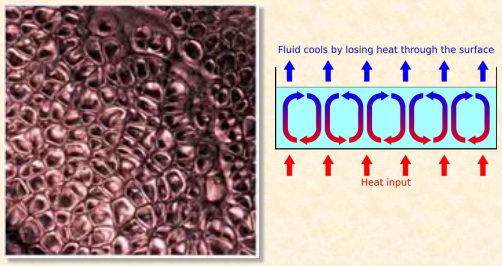
Bénard Convection Cells



2014/3/6 (photo from Camazine & al. *Self-Org. Bio. Sys.*, fig. from wikipedia) 7

Persistent Nonequilibrium Systems

- *If* flow creates system so structured to maintain flow
- *then* positive feedback causes nonequilibrium (NE) system to persist indefinitely
  - but not forever (2nd law)
- Systems we tend to see are those most successful at maintaining NE state
- Applies to species as well as organisms

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"Nature abhors a gradient"

— Eric D. Schneider

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Selection Among Dissipative Systems

- If in a population some systems are more capable of converting free energy to entropy than others,
- then they will consume a higher fraction of the available free energy.
- Some systems get more free energy because they can use more free energy.

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Decreased Internal Entropy

- Increasing the energy gradient forces the NE system to new states and modes, some of which may have a greater capacity to reduce the gradient.
  - bifurcations, symmetry breaking
    - far-from equilibrium system
- NE systems can increase capacity to accept free energy by using it to decrease internal entropy

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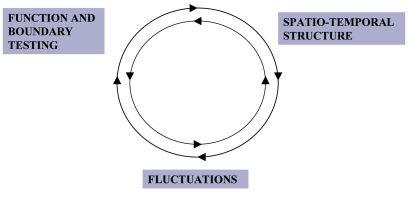
Order Through Fluctuations



- Fluctuations (esp. when system forced out of ordinary operating range) test boundaries & nonlinear effects
- May lead to stabilization of new structures

2014/3/6 fig. < Hart & Gregor, *Inf. Sys. Found.* 12

Stratified Stability: Higher Levels of Organization

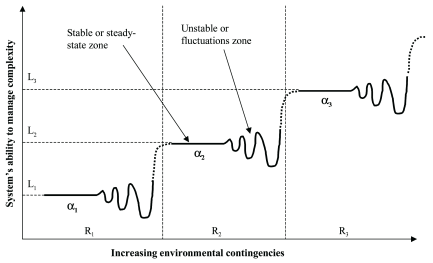


fig. < Hart & Gregor, *Inf. Sys. Found.*

Autocatalytic Processes

- Autocatalytic (self-reinforcing) processes may arise
  - stable cyclic behavior
    - attractor basins, bifurcations, chaos
  - growth and proliferation
    - access to new material & energy from environment

Selection

- Nonlinearities can lead to abrupt selection between more and less successful gradient reducers
- Small advantages can trigger rapid evolution
  - exponential selection

Storage

- NE systems may use generated internal structure (negentropy) to store material and energy
- thus maintaining a constant rate of entropy production in spite of fluctuations in external energy
  - immediate dissipation deferred to create internal gradients

Life

- Life and other complex systems exist because of the 2nd Law.
- They reduce pre-existing gradients more effectively than would be the case without them.
- Living systems optimally degrade energy for: growth, metabolism, reproduction.

Biological Organization

- "Entropic dissipation propels evolutionary structuring; nature's forces give it form." (Wicken)
- The simple-looking gradient represents potential complexity.
- "Order for free": the complexity of organisms is always paid for by the richness of pre-existing gradients.

"Order for Free"

- Relatively simple sets of rules or equations can generate rich structures & behaviors
- Small changes can lead to qualitatively different structures & behaviors
- A diverse resource for selection
- A basis for later fine tuning (microevolution)
- See Kaufmann (*At Home in the Universe*, etc.) and Wolfram (*A New Kind of Science*)

Thermodynamic Selection

- "Even before natural selection, the second law 'selects' from the kinetic, thermo-dynamic, and chemical options available those systems best able to reduce gradients under given constraints." (Schneider)
- "Natural selection favors systems adept at managing thermodynamic flows." (ibid)

Evolution of Species

- Evolution proceeds in such a direction as to make the total energy flux through the system a maximum compatible with the constraints.
- But organisms and species must also channel energy toward the preservation and expansion of themselves as material systems.

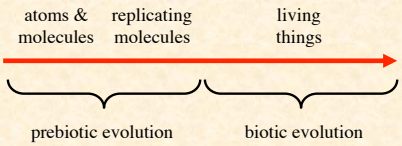
Ecosystem Evolution

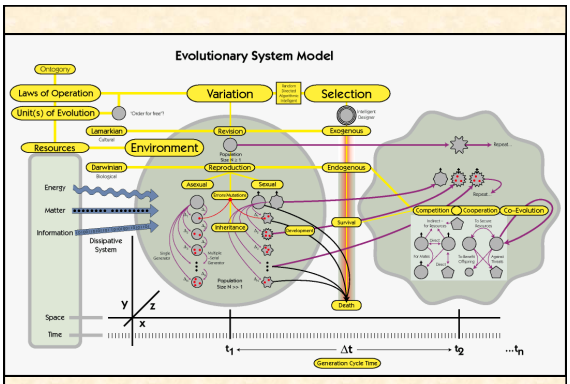
- Ecosystems evolve in the way they handle energy:
- Earlier:
  - fast growth
  - more similar units
- Later:
  - slower growth
  - more diversity

Evolution in Broad Sense

- Evolution in the broadest terms:
  - blind variation
  - selective retention
- Has been applied to nonbiological evolution
  - evolutionary epistemology
  - creativity
  - memes

Evolution





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Genotype vs. Phenotype

- Genotype = the genetic makeup of an individual organism
- Phenotype = the observed characteristic of the organism
- Through interaction with environment, a genotype is *expressed* in a phenotype

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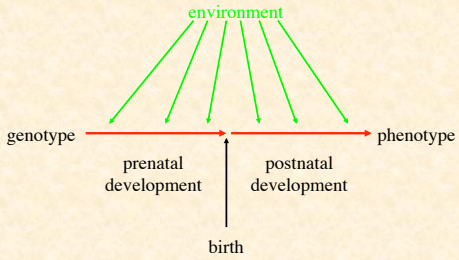
Ontogeny



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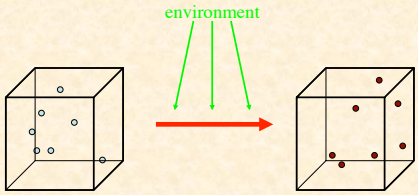
Genotype Space vs. Phenotype Space



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Selection

- Selection operates on the phenotype, not the genotype
- Selection of genotypes is indirect

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"Central Dogma" of Genetics

- "The transfer of information from nucleic acid to nucleic acid, or from nucleic acid to protein may be possible, but transfer from protein to protein, or from protein to nucleic acid is impossible."
  – Francis Crick
- A hypothesis (not a dogma)
- "New" Lamarckism: "jumping genes" and reverse transcription

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Essentialism vs. "Population Thinking"

- Essentialism: each species has a fixed, ideal "type"
  - actual individuals are imperfect expressions of this ideal
  - species have sharp boundaries
  - the type is real, variation is "illusory" (secondary)
- Population thinking: a species is a reproductive population
  - only individual organisms exist
  - species have blurred boundaries
  - species are time-varying "averages"
  - variation is real, the type is an abstraction

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Fitness

- 1st approximation: the relative ability of an individual organism to optimize the energy flow to maintain its nonequilibrium state long enough to reproduce (survival fitness)
- 2nd approximation: reproductive fitness = the relative efficiency at producing viable offspring
  - of oneself (exclusive fitness)
  - of oneself or close relatives (inclusive fitness)

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"Selfish Gene"

- An organism is a gene's way of making more copies of itself
- A gene (or collection of genes) will tend to persist in a population if they tend to produce physical characteristics & behavior that are relatively successful at producing more copies of itself
- Nevertheless, it is physical organisms (phenotypes) that confront the environment

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Complicating Factors

- Individual genes influence multiple characteristics & behaviors
- Genes are not independent
- "Fitness" is in the context of a (possibly changing) environment including:
  - conspecifics
  - coevolving predators and prey
- Conclusion: beware of oversimplifications
  - keep entire process in mind

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The Red Queen Hypothesis

"Now, *here*, you see, it takes all the running *you* can do, to keep in the same place."
— *Through the Looking-Glass and What Alice Found There*

- *Observation*: a species probability of extinction is independent of time it has existed
- *Hypothesis*: species continually adapt to each other
- Extinction occurs with insufficient variability for further adaptation

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Can Learning Guide Evolution?

- "Baldwin Effect":
  - proposed independently in 1890s by Baldwin, Poulton, C. Lloyd Morgan
  - spread of genetic predispositions to acquire certain knowledge/skills
- Gene-culture coevolution
- Special case of *niche construction*: organisms shape the environments in which they evolve
- Also involves *extragenetic inheritance*
- Indirect causal paths from individual adaptation to genome

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Example Effects of Single Genes

Butterfly Eyespots

- Major changes within 6 generations
- May lead to patterns not seen in previous generations

 (photos from *Science* 1 Nov 2002)

Two Populations of *Astyanax mexicanus*

- Two populations of one species
- Regulation of one gene (controlling head development)
  - eyes, smaller jaws, fewer teeth
  - blind, larger jaws, more teeth

 (photos from *Science* 1 Nov 2002)

Human Fear Response

 (photos from *Science* 19 July 2002)

Single Gene Affecting Human Fear Response

- Two alleles for gene:
  - short allele ⇒ greater anxiety response to angry or frightened faces
  - long allele ⇒ lesser response
- Gene encodes transporter protein, which carries serotonin back into neuron after release
- Short allele produces 1/2 amount of protein
- Accumulating serotonin affects neighboring cells

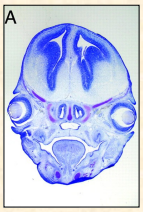
Human vs. Rat Cortex

- Human cortex relatively larger
- Also more structured

Experiment

- Problem: How do organs know when to stop growing?
- Genetically engineer rats to express a mutant form of protein (β-catenin)
- More resistant to breakdown, ∴ accumulates
- Spurs neural precursor cells to proliferate

Results



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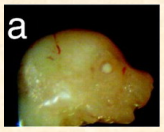
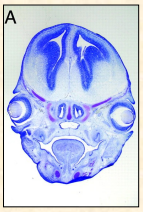


(photos from Chenn & Walsh 2002)

Results



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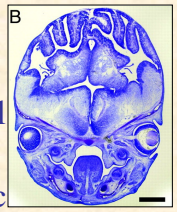
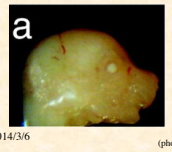
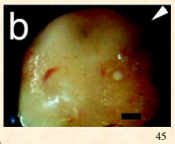


transgenic

⇒





(photos from Chenn & Walsh 2002)

Why are Our Brains Bigger than Chimp Brains?

- Genes controlling NK white blood cells differ slightly between humans & chimps
- Chimp NK cells give them immunity to HIV, malaria, etc.
- But NK cells also control blood-flow to the fetus
- In humans, it is critical that the fetus have an adequate blood supply for its large brain
- Studies suggest NK cells can be optimized for one or the other, not both
- Peter Parham (Stanford): Abi-Rached, Moesta, Rajalingam, Guethlein, Parham (2010), *PLoS Genetics* 6 (11): e1001192. doi:10.1371/journal.pgen.1001192

Additional Bibliography

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3. Schneider, E.D., & Sagan, D. *Into the Cool: Energy Flow, Thermodynamics, and Life*. Chicago, 2005.