V. Evolutionary Computing

B. Thermodynamics, Life & Evolution

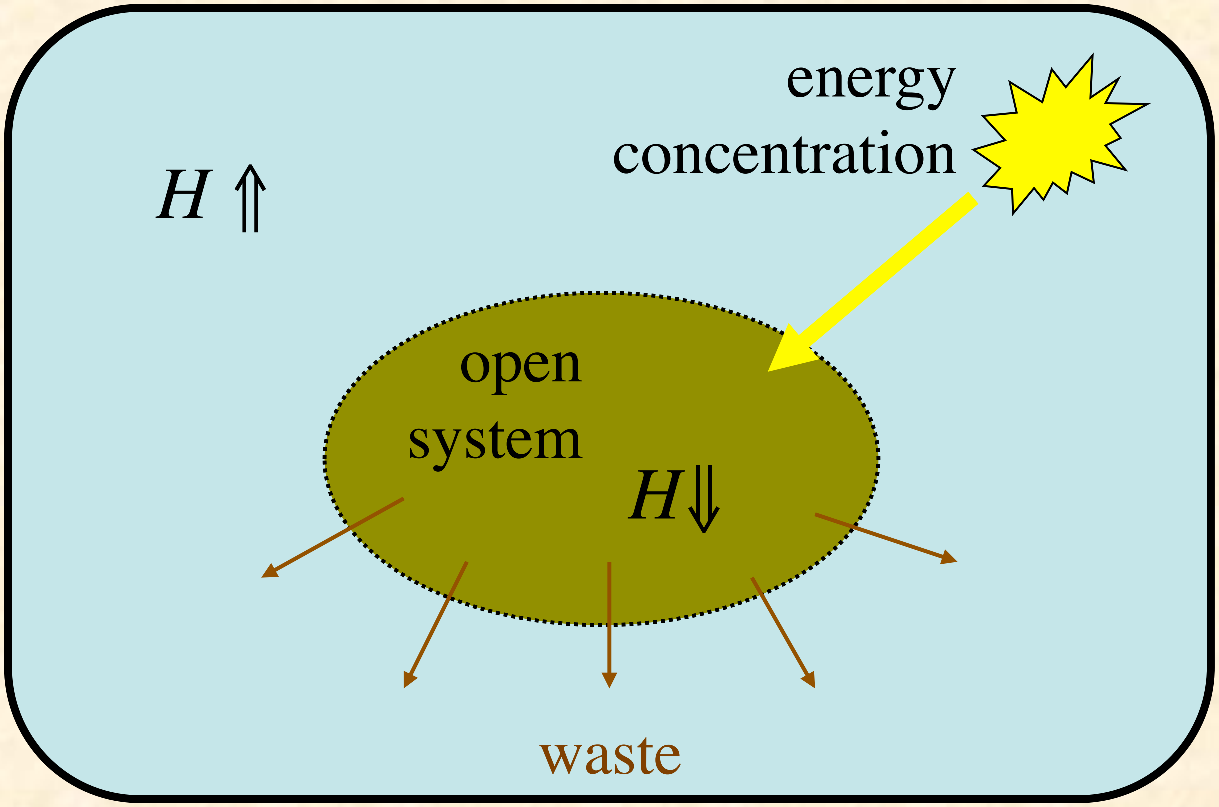
DARPA Physical
Intelligence Program

The Second Law of Thermodynamics

closed system

entropy $H \Uparrow$

The Second Law and Open Systems



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*

An Energy Flow Can Create Structure

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

Bénard Convection Cells

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

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 (2^{nd} law)
- Systems we tend to see are those most successful at maintaining nonequil. state
- Applies to species as well as organisms

“Nature abhors a gradient”

— Eric D. Schneider

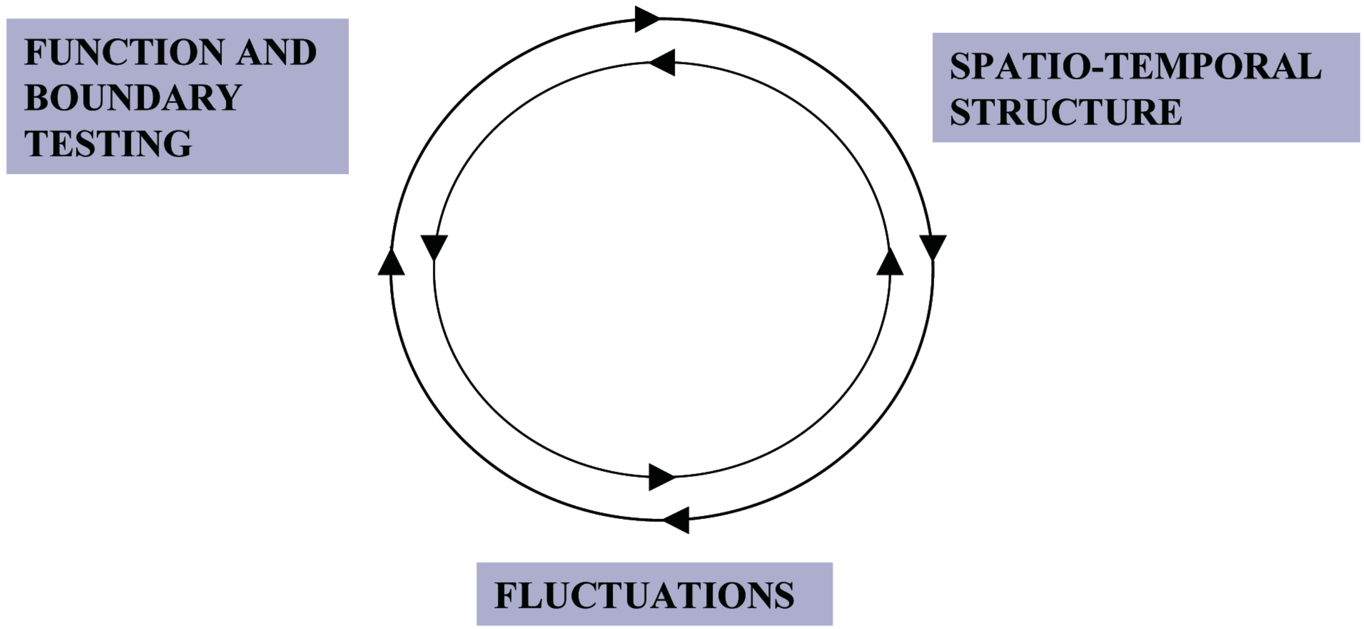
Selection Among Dissipative Systems

- 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.

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

Order Through Fluctuations



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

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

Stratified Stability: Higher Levels of Organization

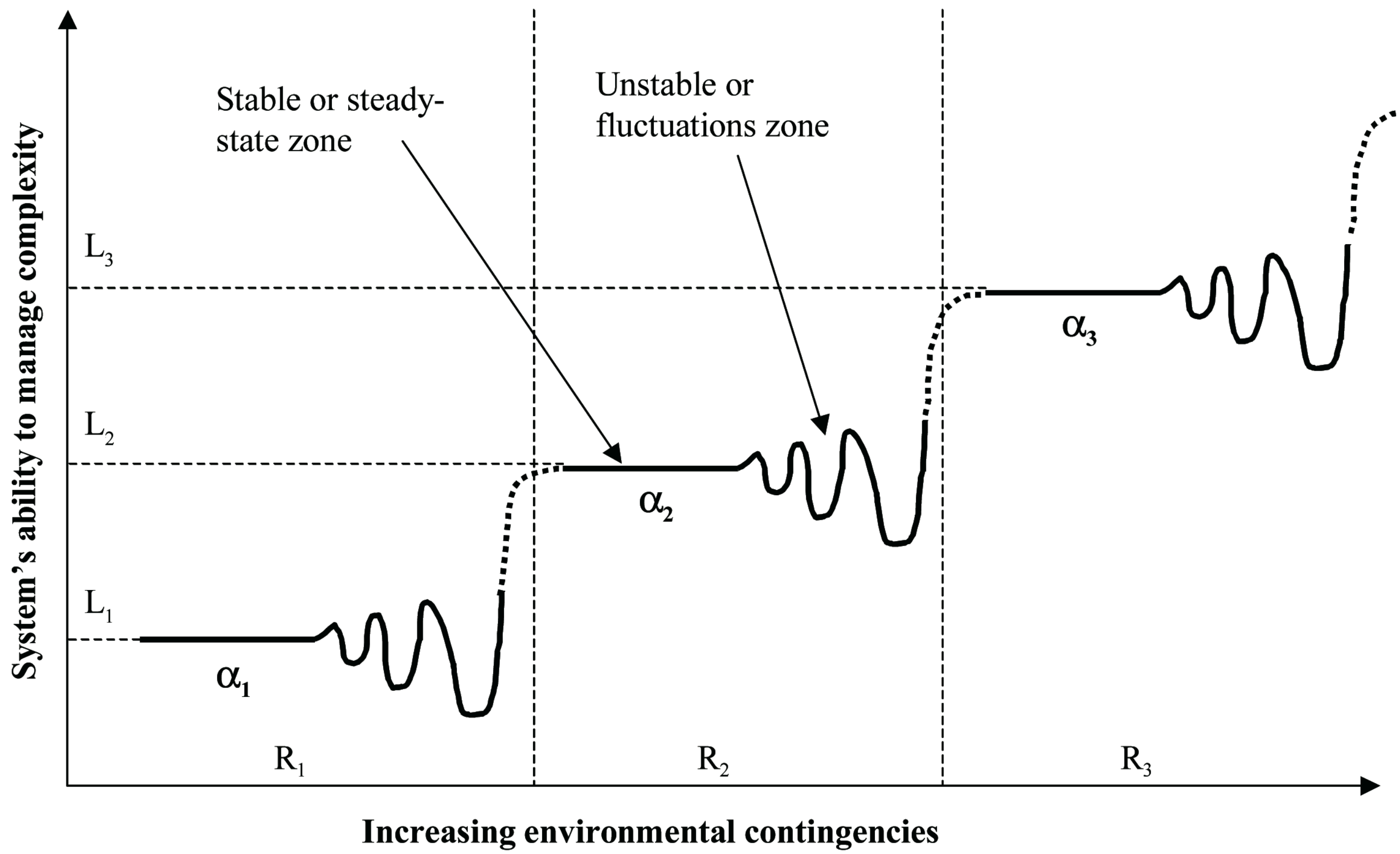


fig. < Hart & Gregor, *Inf. Sys. Found.*

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

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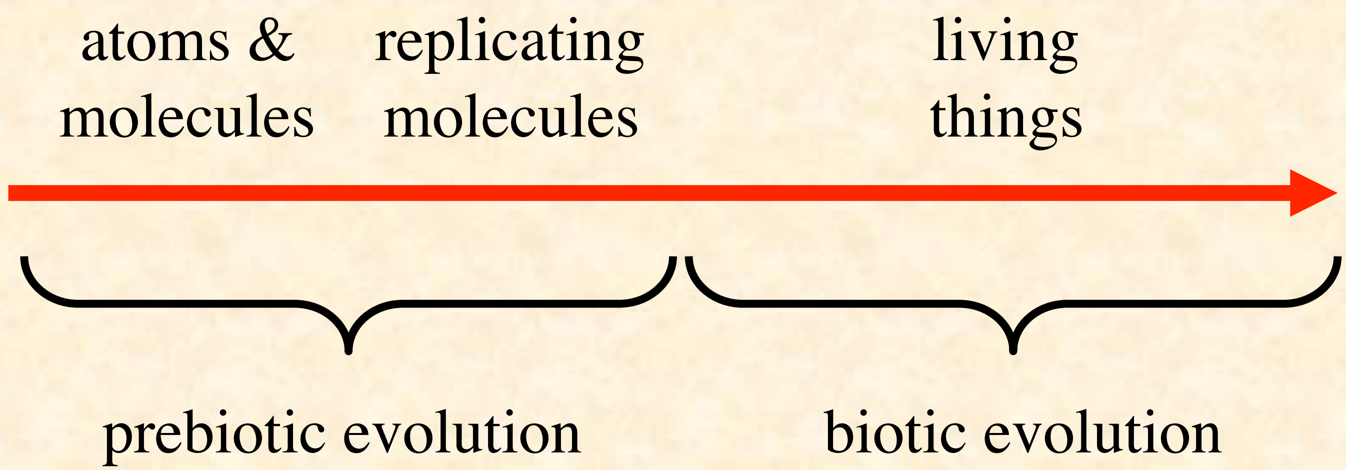
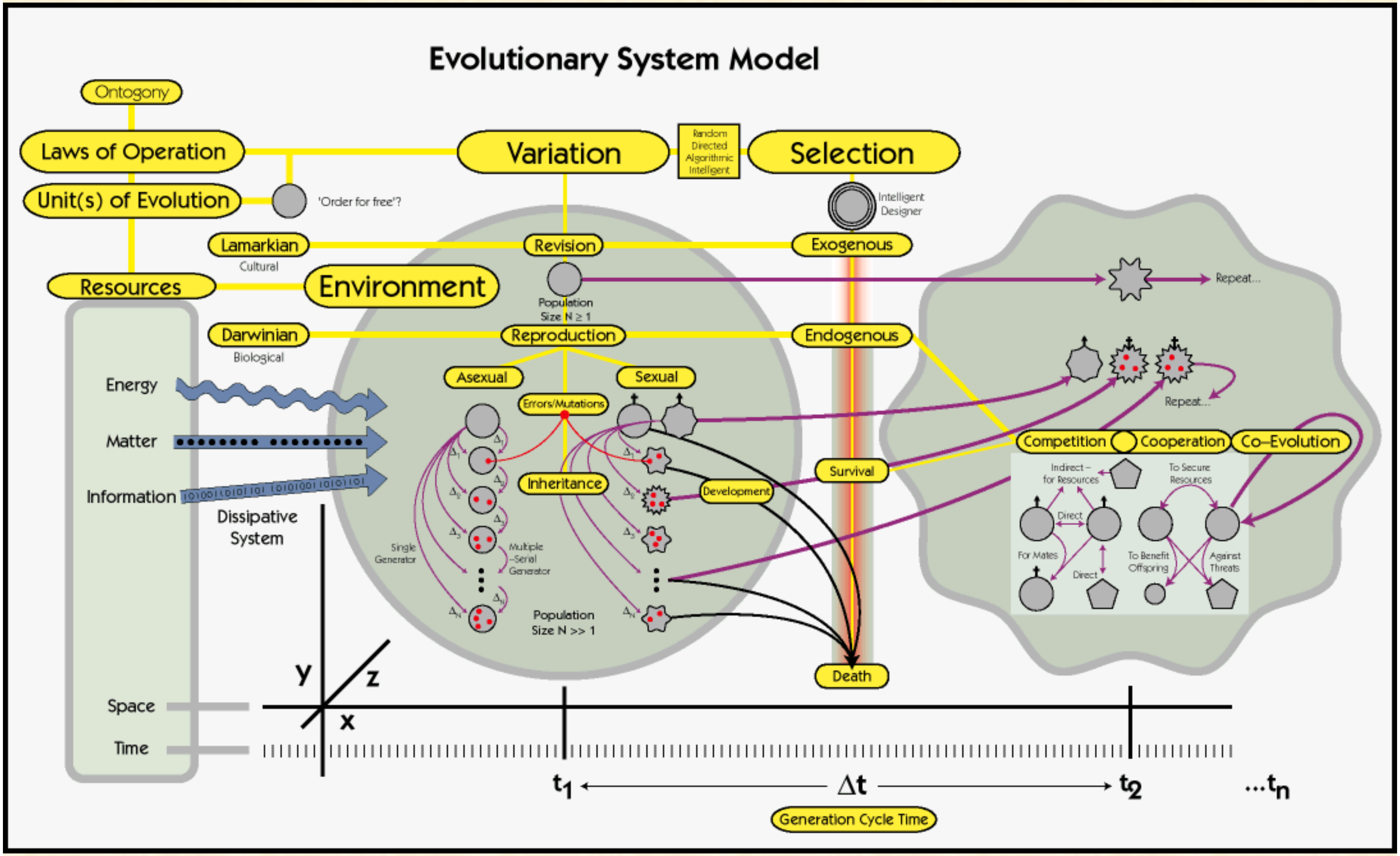
Evolution



atoms & molecules
replicating molecules
living things
prebiotic evolution
biotic evolution

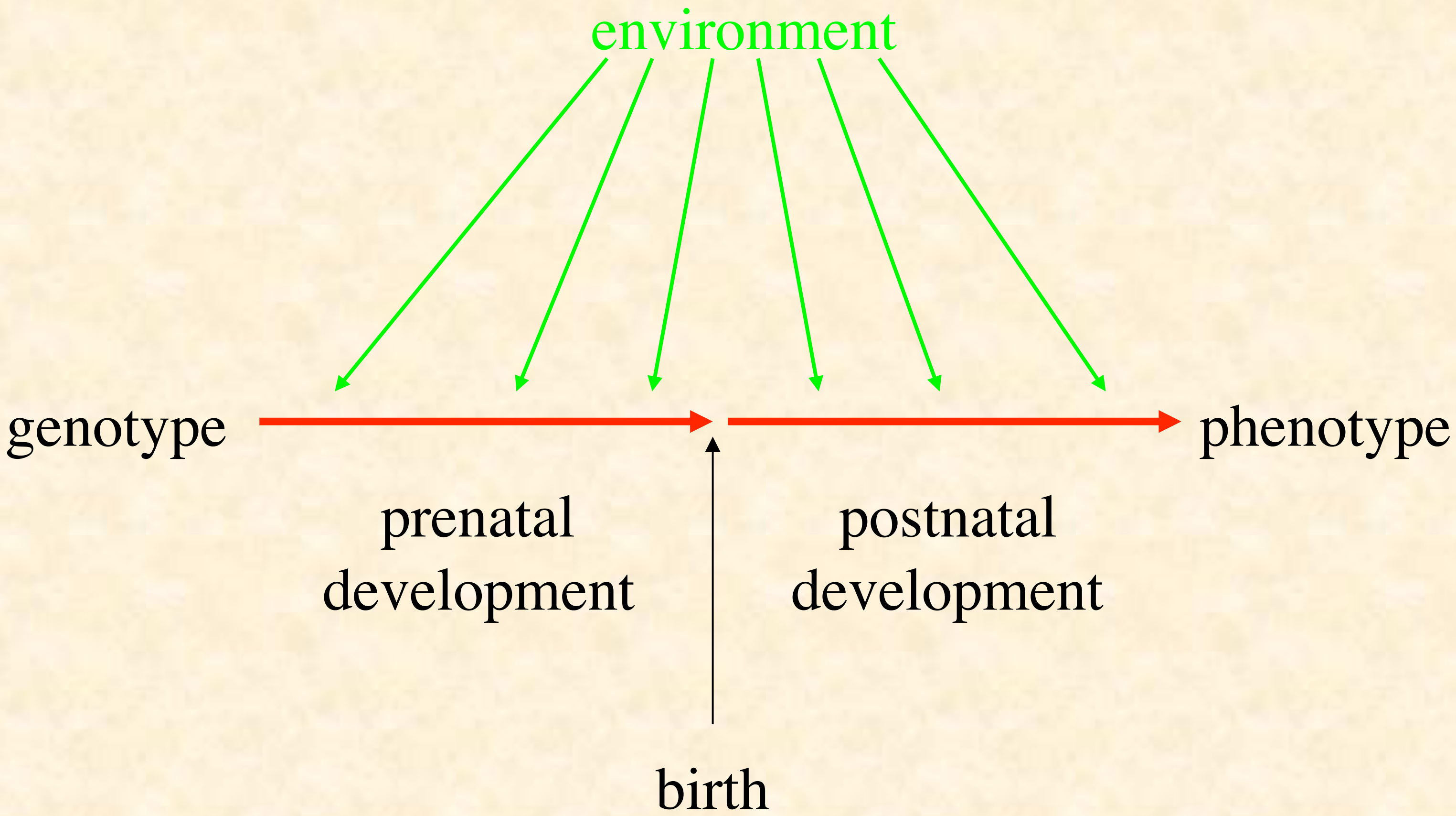

Evolutionary System Model
Ontogony
Laws of Operation
Unit(s) of Evolution
'Order for free'?
Variation
Random
Directed
Algorithmic
Intelligent
Selection
Intelligent
Designer
Lamarkian
Cultural
Revision
Exogenous
Resources
Environment
Population
Size N ≥ 1
Repeat...
Darwinian
Biological
Reproduction
Endogenous
Asexual
Sexual
Errors/Mutations
Energy
Matter
Information
Dissipative
System
Inheritance
Development
Survival
Single
Generator
Multiple
-Serial
Generator
Population
Size N >> 1
Competition
Cooperation
Co-Evolution
Indirect –
for Resources
To Secure
Resources
Direct
For Mates
To Benefit
Offspring
Against
Threats
Death
Space
Time
y
z
x
t1
Δt
t2
...tn
Generation Cycle Time

(from NECSI)

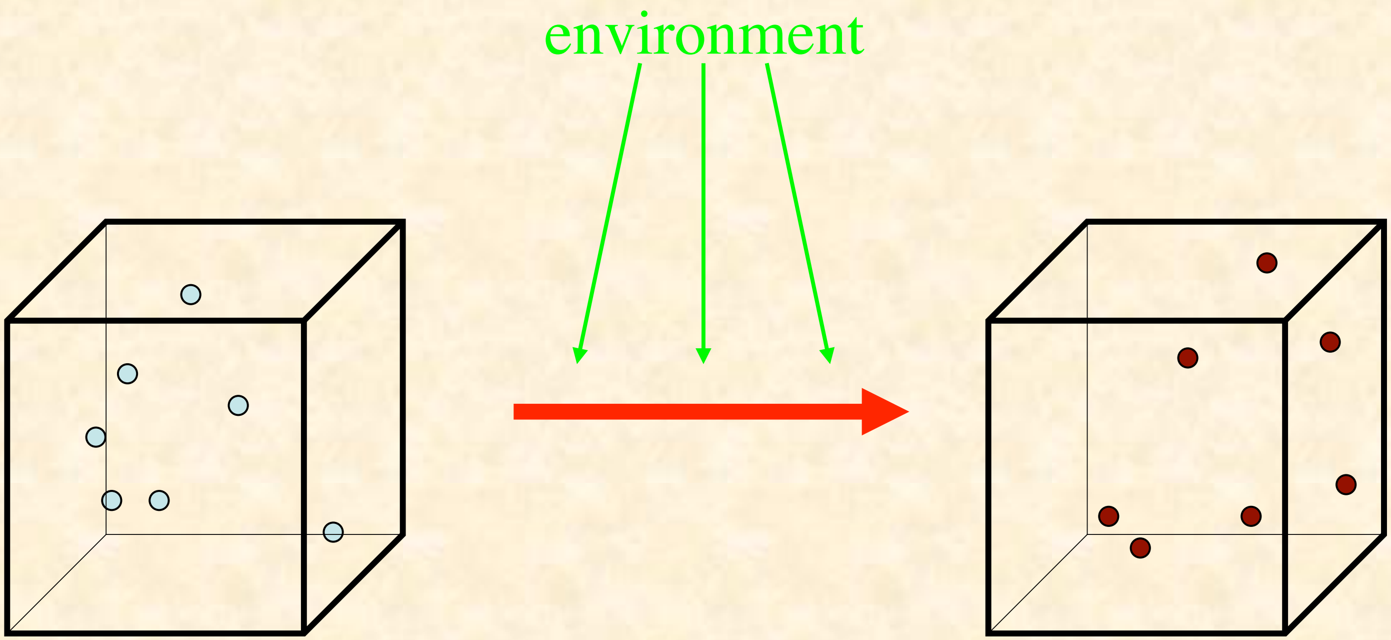
Genotype vs. Phenotype

- 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

Ontogeny


environment
genotype
phenotype
prenatal development
postnatal development
birth

Genotype Space vs. Phenotype Space



population of genotypes

population of phenotypes

Selection

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

Read ch. 16

“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

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

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)

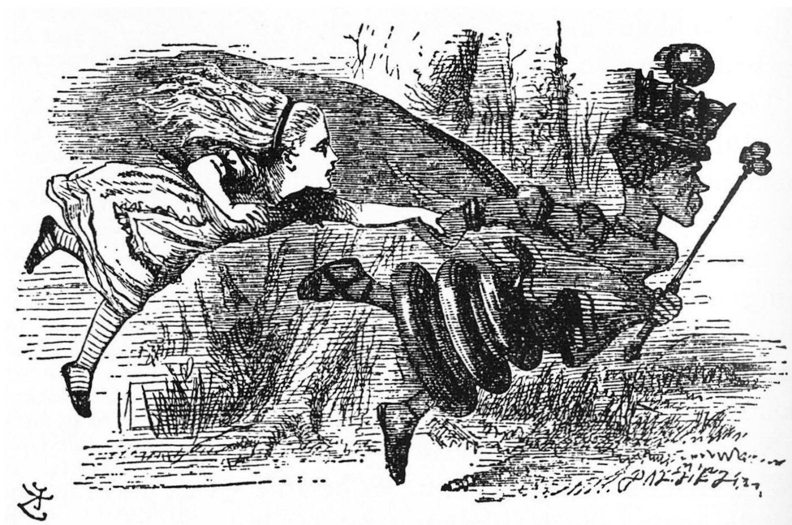
“Selfish Gene”

- 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

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

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

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

Example Effects of Single Genes

Butterfly Eyespots

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

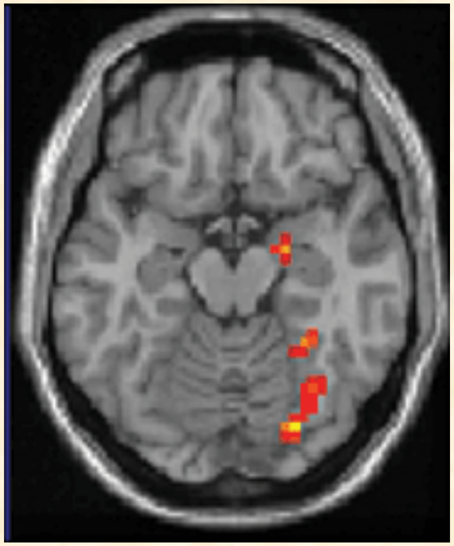
(photos from *Science* 1 Nov 2002)

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

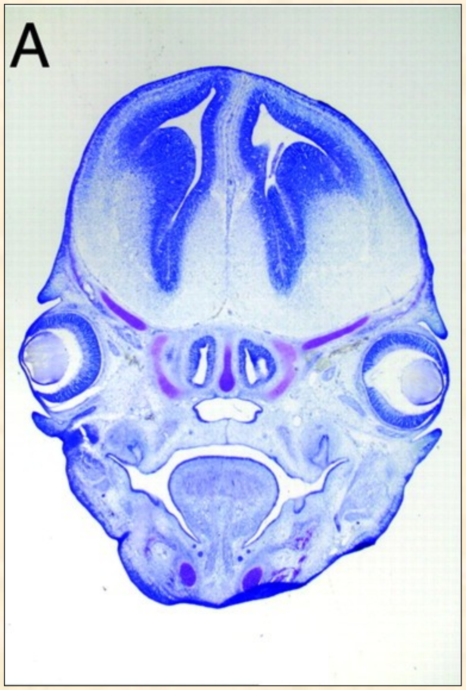
- Two alleles for gene:
  - short allele ⇒ greater anxiety response to angry or frightened faces
  - long allele ⇒ lesser response
- Gene encodes transporter protein, which carries serotonin back into neuron after release
- Short allele produces 1/2 amount of protein
- Accumulating serotonin affects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

Human vs. Rat Cortex

- Human cortex relatively larger
- Also more structured

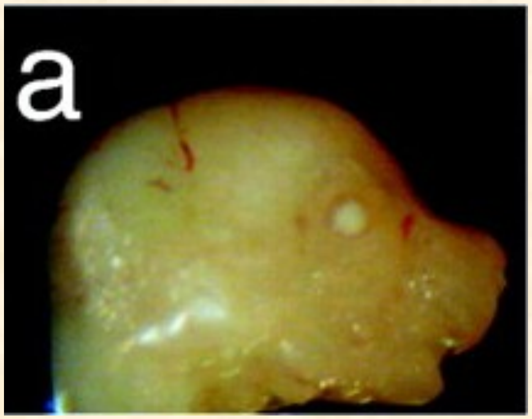
Experiment

- 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



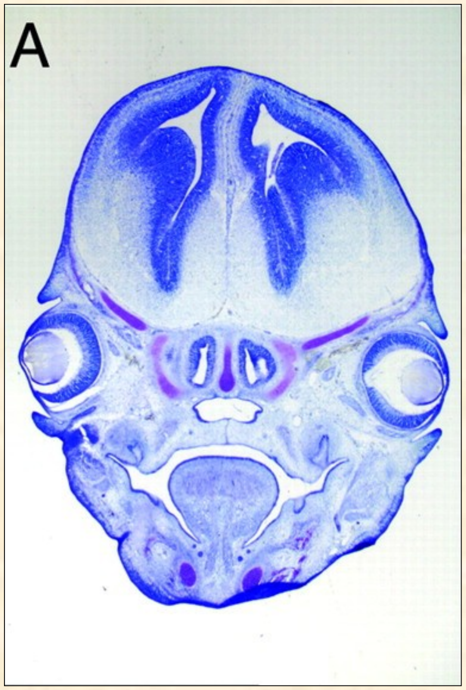
Results

⇐ normal



(photos from Chenn & Walsh 2002)

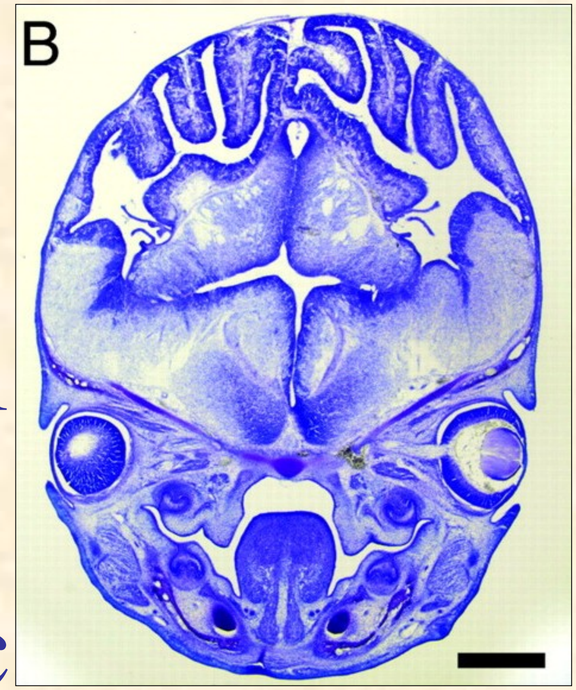
Results

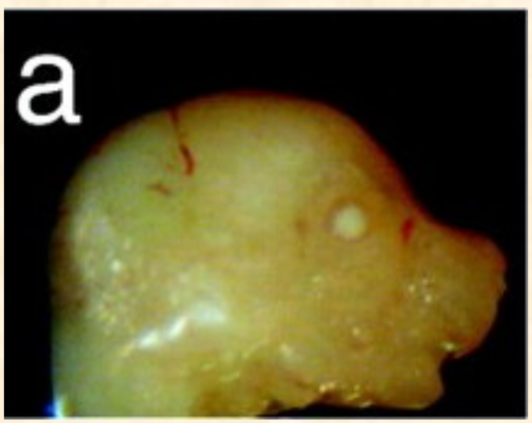


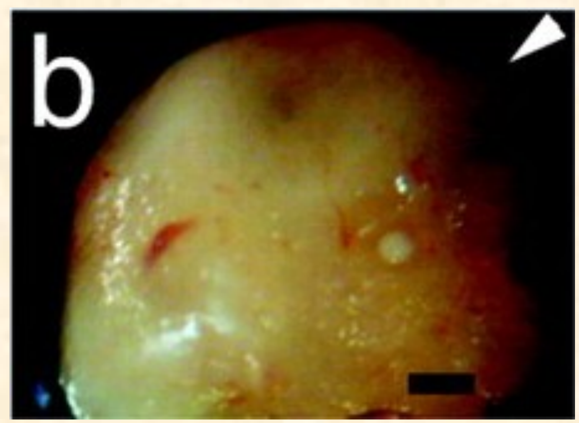
⇐ normal

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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2. Milner, R. *The Encyclopedia of Evolution*. Facts on File, 1990.
3. Schneider, E.D., & Sagan, D. *Into the Cool: Energy Flow, Thermodynamics, and Life*. Chicago, 2005.

Next: Autonomous Agents and Self-Organization

(Re)read ch. 16