Exploring Complexity

In Science and Technology

Dec. 1, 2010

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Logistics

- Due Today Lab 7
- Paper due Friday
- Check that Blackboard grades are accurate
- Final Paper Questions?
- Other Questions?

Scaling in Biology

- General Question:
  - How do properties of living systems change as their size is varied?
- Example:
  - How does basal metabolic rate (heat radiation) vary as a function of an animal's body mass?
  - Cells converting nutrients to energy give off heat, so heat radiation is a measure of metabolic rate

- **Hamster**
  - Radius = 2 × Mouse radius
  - Mass ∝ 8 × Mouse radius
  - Surface area ∝ 4 × Mouse radius
- **Hippo**
  - Radius = 50 × Mouse radius
  - Mass ∝ 125K × Mouse radius
  - Surface area ∝ 2,500 × Mouse radius

- Volume of a Sphere = $4/3 \pi r^3$
- Surface area of a Sphere = $4 \pi r^2$

- Hypothesis 1: metabolic rate ∝ body mass
- Problem: mass is proportional to volume of animal but heat can radiate only from surface of animal

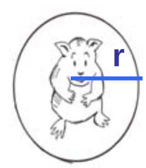
- Volume of a Sphere = $4/3\ \pi\ r^3$
  - "Volume of a sphere scales as the radius cubed"
- Surface area of a Sphere = $4\ \pi\ r^2$
  - "Surface area of a sphere scales as the radius squared"
- Surface area scales with volume to the 2/3 power
- Hypothesis 2 (): metabolic rate $\propto$ mass$^{2/3}$
  - Max Rubner 1883 the "surface hypothesis"

Mouse

Hamster
(8 x mouse mass)

Hippo
(125,000 x mouse mass)

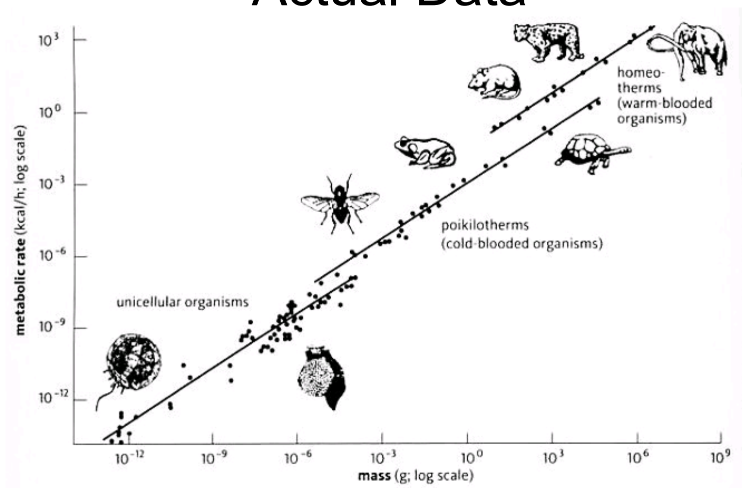
Metabolic Scaling



- Surface hypothesis:
  - Body is made of cells, in which metabolic reactions take place.
  - Can "approximate" body mass by a sphere of cells with radius r.
  - Can approximate metabolic rate by surface area
- Body mass $\propto r^3$
- Metabolic rate $\propto r^2$

- Thus, metabolic rate $\propto (r^3)^{2/3} \propto$ body mass$^{2/3}$

Actual Data



1 kcal/h = 1.162 watts

- Kleiber's law (1930's): metabolic rate $\propto$ body mass$^{3/4}$
- http://universe-review.ca/I10-83-metabolic.jpg

Cause of Kleiber's law?

- "What common aspect of nearly all organisms could give rise to this simple, elegant law?" (p. 261)
- For sixty years, no explanation

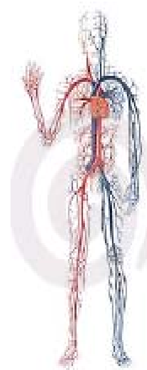
Other Observed Biological Scaling Laws

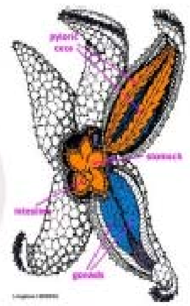
- Heart rate $\propto$ body mass$^{-1/4}$
- Blood circulation time $\propto$ body mass$^{1/4}$
- Life span $\propto$ body mass$^{1/4}$
- Growth rate $\propto$ body mass $^{-1/4}$
- Heights of trees $\propto$ tree mass$^{1/4}$
- Sap circulation time in trees $\propto$ tree mass$^{1/4}$
- **Why quarter-power scaling laws?**

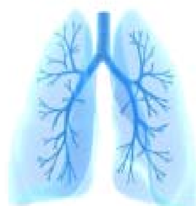
West, Brown, and Enquist's Theory (1990s)

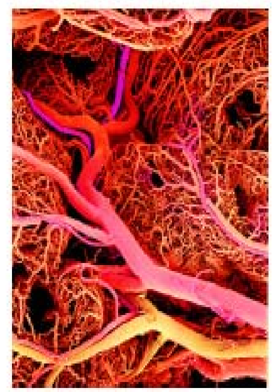
- General idea: "metabolic scaling rates (and other biological rates) are limited not by surface area but by rates at which energy and materials can be distributed between surfaces where they are exchanged and the tissues where they are used."
- How are energy and materials distributed?
  - Depends on delivery system (e.g. circulatory system)

Distribution Systems









Prediction of Theory

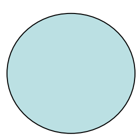
- Distribution network will have fractal branching structure, and will be similar in all / most organisms (i.e., evolution did not optimize distribution networks of each species independently)
- Therefore, Euclidean geometry is the wrong way to view scaling; one should use fractal geometry instead!
- With detailed mathematical model using three assumptions, they derived:

  metabolic rate $\propto$ body mass$^{3/4}$

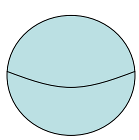
Their interpretation of their model

- Metabolic rate scales with body mass like surface area scales with volume...

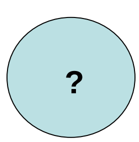
  but in four dimensions!



- Circle
  - circumference = 2π
  - area = πr^2
  - circumference scales as area to the ???? power?



- Sphere
  - surface area = $4\pi r^2$
  - volume = $4/3\ \pi r^3$
  - surface area scales as volume to the ???? power?



- Hypersphere
  - surface volume (hyperarea) = $2\pi^2 r^3$
  - hypervolume = $½\ \pi^2 r^4$
  - surface volume scales as hypervolume to the ???? power?

- “Although living things occupy a three-dimensional space, their internal physiology and anatomy operate as if they were four-dimensional. . . Fractal geometry has literally given life an added dimension.”
  – West, Brown, and Enquist

Genetics Revolution (Complexification)

- What is a gene?
  - Genes can overlap other genes (share DNA)
  - Jumping genes
  - Single genes code for more than one protein type
    - Humans have 100K proteins, but one 25K genes
    - RNA alternative splicing; RNA editing
  - Non-linear information processing regulatory networks
  - Epigenetics, e.g. methylation
  - Non-coding mRNA

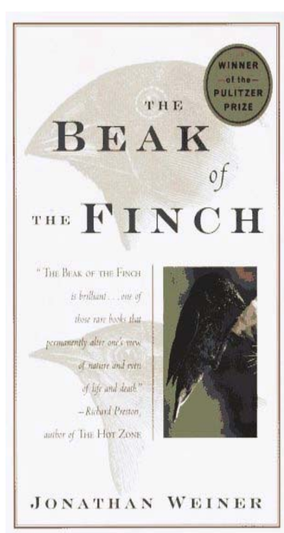
Evo-Devo (Evolutionary Developmental Biology)

- Main question: How do complexity and diversity in living systems come about through evolution?
- Examples:
  - Humans have only ~25K genes; how can we be so complex?
  - Human DNA very similar to many other species, what makes us different from them?
    - > 90% same as mice; > 95% same as chimps
  - Assuming punctuated equilibrium, how does body morphology change in a relatively short time?

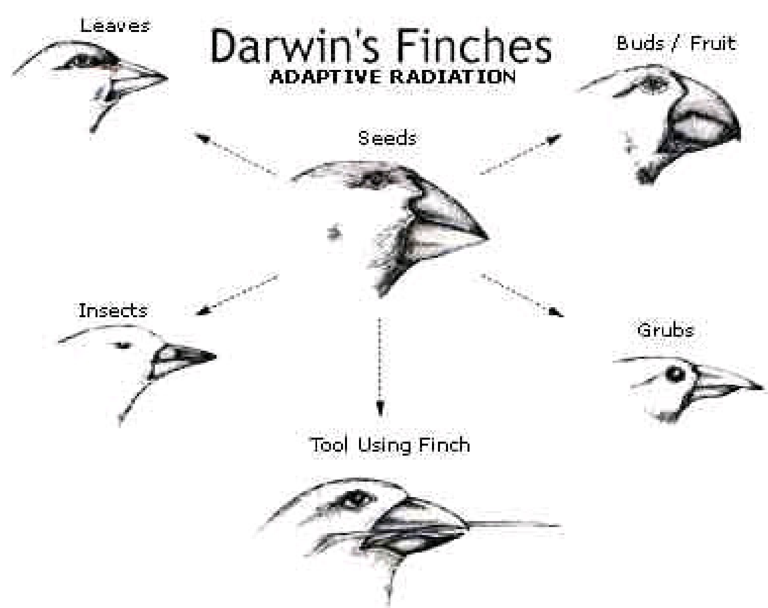
Evo-Devo's answers:

- Same answers as traditional Darwinians, except these are not the whole story!
- Organisms become complex not because of increased number or complexity in genes but because of increased complexity of genetic regulatory networks controlling development
- Notion of active (versus passive) genome
- Evolution not only modifies genes, but modifies "genetic switches", allowing for huge variety of possibilities of gene-expression patterns.
- This could explain "punctuated equilibria"

Example: Finches' Beaks




small ground finch
Geospiza fuliginosa
medium ground finch
Geospiza fortis
large ground finch
Geospiza magnirostris
cactus finch
Geospiza scandens
large cactus finch
(Genovesa)
Geospiza conirostris
large cactus finch
(Española)
Geospiza conirostris
sharp-beaked ground finch
Geospiza difficilis
small tree finch
Camarhynchus parvulus
large tree finch
Camarhynchus psittacula
woodpecker finch
Cactospiza pallidus
vegetarian finch
Platyspiza crassirostris
warbler finch
Certhidea olivacea


Darwin's Finches
ADAPTIVE RADIATION
Leaves
Buds / Fruit
Seeds
Insects
Grubs
Tool Using Finch

What caused diversity of finches' beaks?

- Traditional Darwinian answer:
  – Gradual process of adaptation via mutations, recombination of genes
- Result: Different finches have significantly different genomes

What caused diversity of finches' beaks?

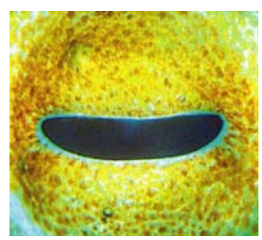
- Possible Evo-Devo answer:
  – Changes in regulation of BMP4 gene, itself a regulatory gene that controls beak size and shape by regulating other genes that produce bones
  – The more strongly BMP4 is expressed during development, the larger and stronger the beak.
  – Also, changes in regulation of calmodulin (associated with long, thin beaks).
- Result: No major changes in "structural" genes; Minor changes to regulatory genes

- “To verify that the BMP4 gene itself could indeed trigger the growth of grander, bigger, nut-crushing beaks, researchers artificially cranked up the production of BMP4 in the developing beaks of chicken embryos. The chicks began growing wider, taller, more robust beaks similar to those of a nut-cracking finch. . . . As with BMP4, the more that calmodulin was expressed, the longer the beak became. When scientists artificially increased calmodulin in chicken embryos, the chicks began growing extended beaks, just like a cactus driller. . . .So, with just these two genes, not tens or hundreds, the scientists found the potential to re-create beaks, massive or stubby or elonnoded.”
  - (Carol Kaesuk Yoon, New York Times)
- Conclusion: Large changes in the morphology of beaks (and other traits) can take place rapidly without the necessity of waiting for many chance mutations over a long period of time.

Another example: Evolution of eyes in different organisms

Human eye

Fly eye



Octopus eye

Traditional Darwinian answer: "convergent evolution"

- "Although the eyes of the octopus, and of other cepaholopds, and the eyes of vertebrates have evolved entirely independently, each has a retina, a cornea, an iris, a lens, and a fluid-filled interior. These similarities of structure, despite different origins, provide a classic example of biological convergence."
  - http://www.daviddarling.info/encyclopedia/O/octopus_eye.html

Possible evo-devo answer:

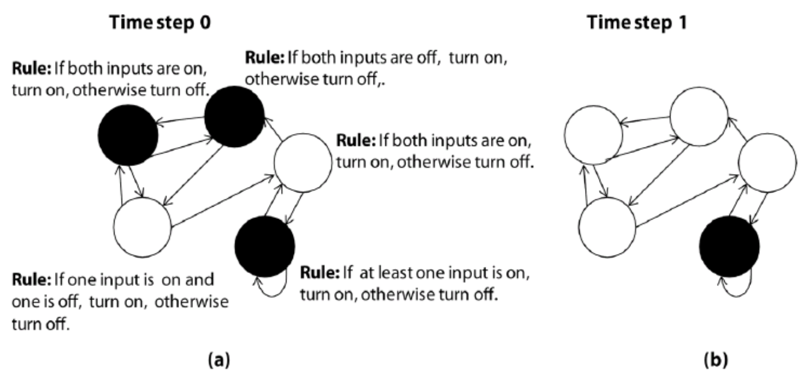
- PAX6 gene, which regulates development of the eye, is common to different species.
- Gehring's experiment:
  - Take PAX6 genes from mice and insert them in genomes of fruit flies in three different places:
    - parts of genome that direct development of legs
    - same for wings
    - same for antennae.
  - **Results:**
    - eye-like structures developed on these body parts
    - **fly** eye-like rather than **mouse** eye-like
  - **Controversial conclusion:** eye evolved not many times independently but only once in a common ancestor with the PAX6 gene.

How does development bias the production of variation or constrain evolutionary trajectories?

- Traditional Darwinian view:
  – Every trait can vary indefinitely
- Evo-Devo view:
  – Our reliance on common regulatory genes in development constrains how evolution can vary body plans.
  – http://en.wikipedia.org/wiki/Body_plan

Random Boolean Networks (RBNs)
as models of genetic regulatory networks (Stuart Kauffman)

- CA features + network features
- Network of N nodes [cells], each with K directed links (arrows) arriving from other nodes



RBNs as abstract models of genetic regulatory networks

- Kauffman used these RBNs as an abstract models of genetic regulatory networks.
- Nodes = genes
- Links = (directional) regulation by one gene of another gene
- Why “Boolean”?
- What does “random” mean here?

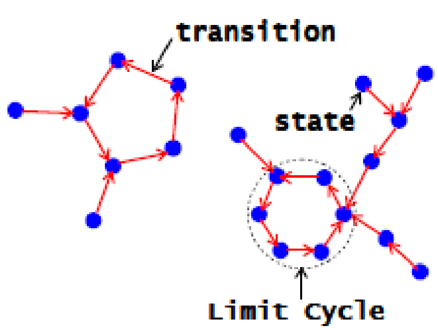
Kauffman's Experiments with RBN

- K = Number of inputs to each node
- N = Number of nodes
- For each node:
  1. Choose its function from the 2^{2^K} Boolean functions of arguments uniformly at random
  2. Choose its K inputs uniformly at random from all nodes
  3. Choose its starting state uniformly at random
- Run the network deterministically

This formula says if K = 2, then there are 16 different Boolean functions. What would Boolean function 0 mean? What would Boolean function 10 mean?

Dynamics of RBNs

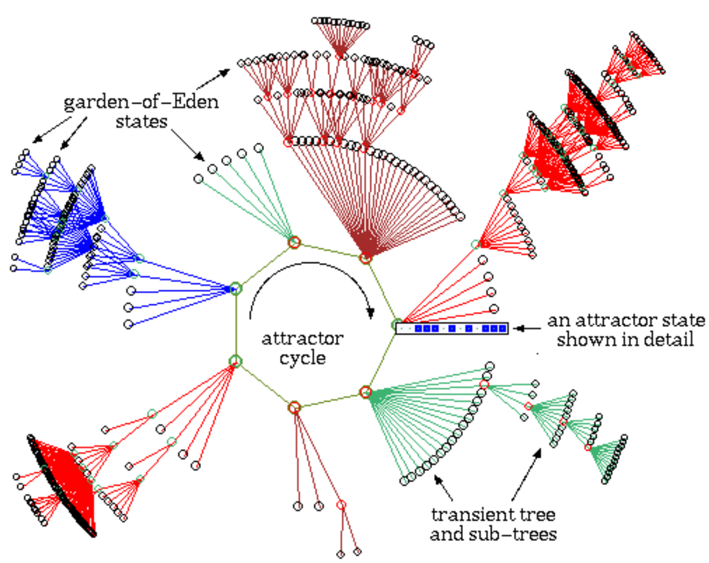
- http://www-users.cs.york.ac.uk/susan/cyc/n/nk.htm
- "States" of RBNs
- What happens if an RBN returns to a previous state?



Limit Cycles of States

- Long-term behavior of the genomic network: limit cycle.
- Interpret limit cycle as a cell type (after differentiation) in a multicellular organism.

Limit Cycle Attractors of RBNs



Classification of Behavior

- Ordered:
  - Most nodes stabilize (stop changing state) quickly.
  - Most nodes can be perturbed without affecting the limit cycle entered.
  - Limit cycle is short.
- Chaotic:
  - Many unstable nodes.
  - 2. Sensitivity to initial conditions.
  - 3. Limit cycle is long.
- Ordered behavior is characteristic of genomic and metabolic networks: they quickly settle down into periodic patterns of activity that resist disturbance.

Kauffman's results

- As K is varied from 1 to 3, there is a transition from “order” to “chaos”, similar to what Langton saw in cellular automata.
- When K=2 the number of possible attractors of RBNs is small: about square root of N.
- On average, from any starting position, the system takes about square root of N steps to get there.

Can these results be taken as evidence that:

- Biological systems exist at the edge of chaos?
- Self-organization occurs spontaneously in living systems?
  - (and non-living systems)
- Other researchers have made similar claims:
  - Bak (self-organized criticality)
  - Langton
  - Packard
  - Wolfram

Kauffman's Conclusions

- "Order for free": Don't necessarily need natural selection to produce complexity; dynamics of networks do it automatically.
- Kauffman argues against the 'extreme neo-Darwinists' such as Richard Dawkins who seem to suggest that natural selection can explain just about all biological phenomena.
- Kauffman's claim is that here, and elsewhere, there are CONSTRAINTS on what is possible that come from intrinsic properties of network dynamics, and evolution 'merely' selects within these constraints.

Critiques of Kauffman

- See text

Summary of Hot Topics

- Complexity and Emergence
- Chaotic Dynamics
- Measuring Complexity
- Information Theory
- Self-reproduction in computers
- Genetic Algorithms (GAs)
- Cellular Automata (CAs)
- Edge of Chaos
- Analogy Making (what is thinking?)
- Modeling and computers
- Network Theory
- Biological Scaling
- Genetics (simple and complex)
- Random Boolean Networks