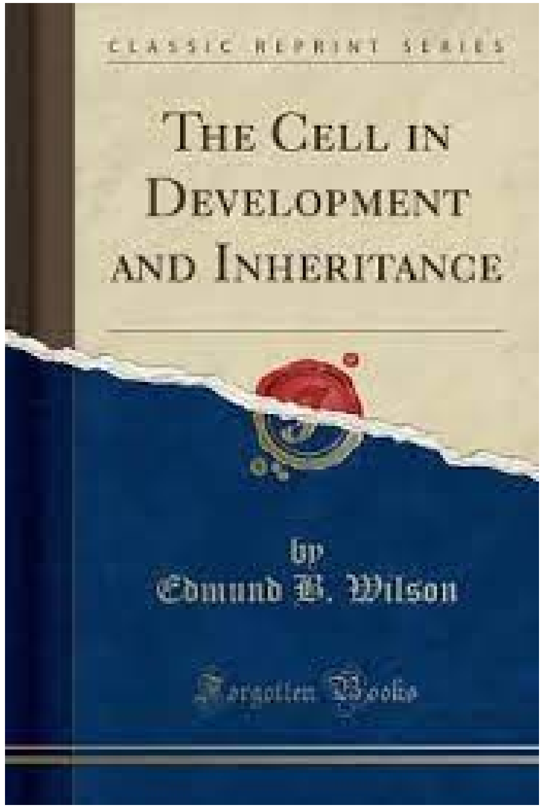
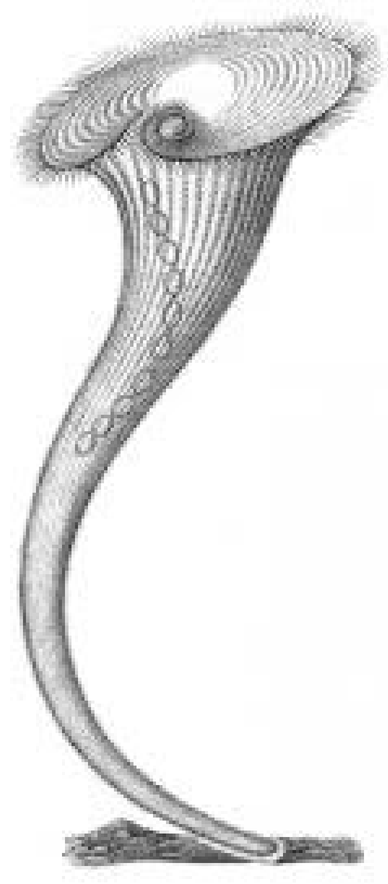
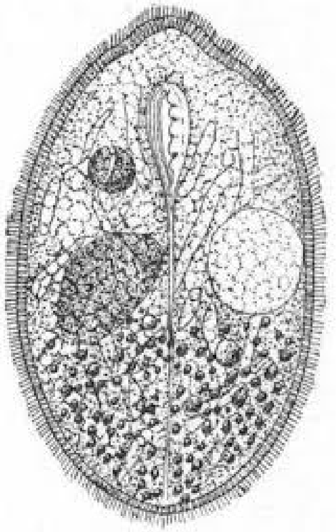
The Origins of Cell Biological Features

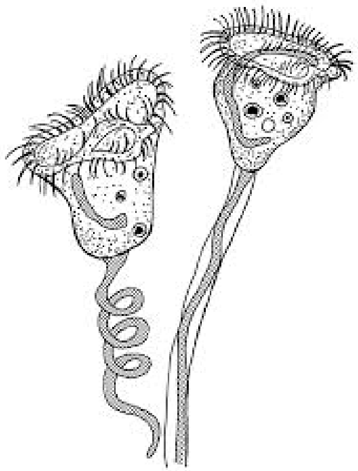


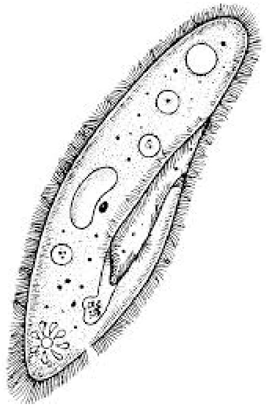
"The key to every biological problem must finally be sought in the cell, for every living organism is, or at some time has been, a cell."

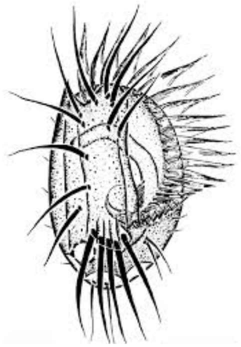
E. B. Wilson, 1925

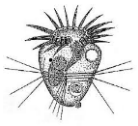




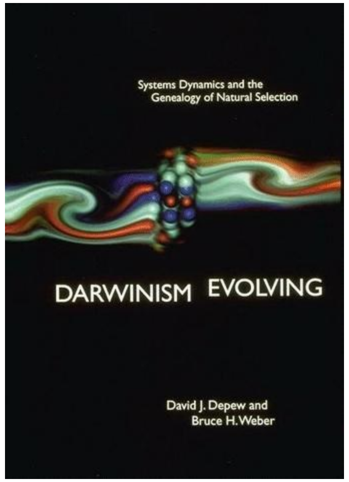


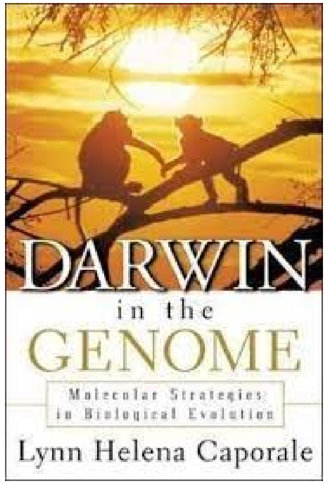


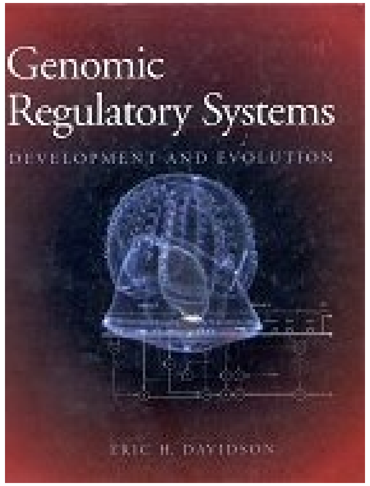


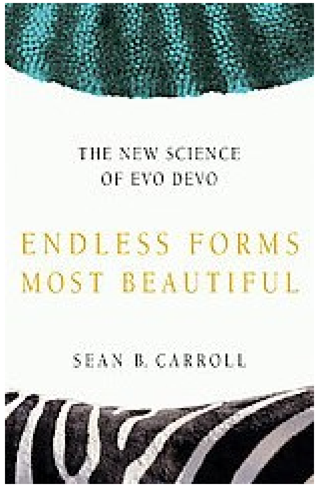


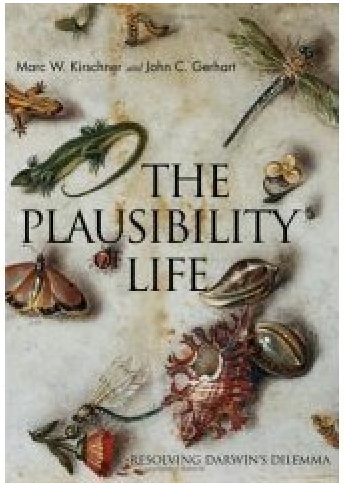
Evolutionary Mythology versus Evolutionary Science

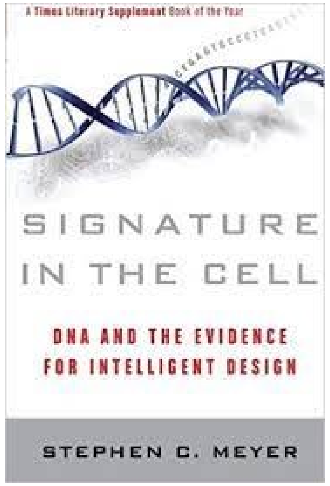


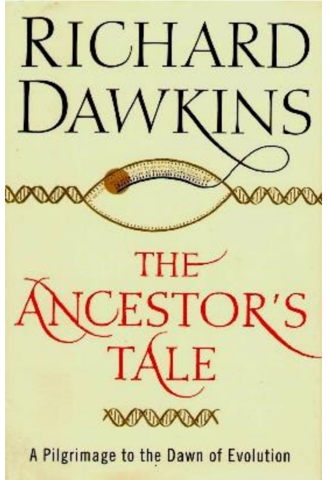


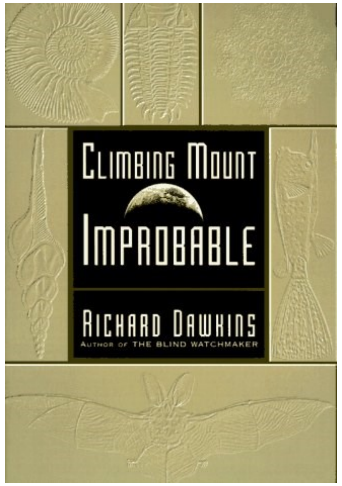


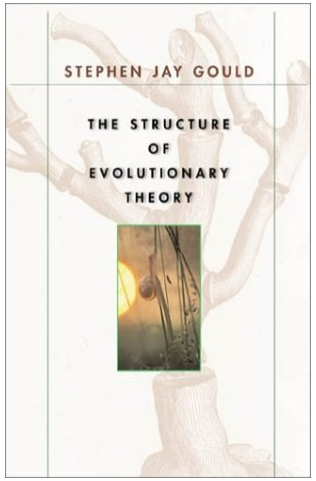


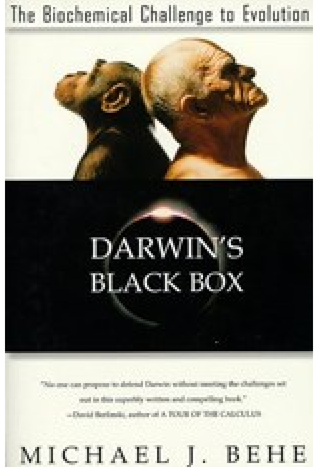












“Since the Modern Synthesis, most expositions of the evolutionary process have focused on microevolutionary mechanisms. Millions of biology students have been taught the view (from population genetics) that ‘evolution is change in gene frequencies.’ Isn’t that an inspiring theme?

This view forces the explanation towards mathematics and abstract descriptions of genes, and away from butterflies and zebras… The evolution of form is the main drama of life’s story, both as found in the fossil record and in the diversity of living species.

So, let’s teach that story. Instead of ‘change in gene frequencies,’ let’s try ‘evolution of form is change in development’.”

Little Wing by Jimi Hendrix

Well she's walking through the clouds
With a circus mind that's running round
Butterflies and zebras
And moonbeams and fairy tales
That's all she ever thinks about
Riding with the wind.

When I'm sad, she comes to me
With a thousand smiles, she gives to me free
It's alright she says it's alright
Take anything you want from me,
Anything.

Fly on little wing,
Yeah yeah, yeah, little wing

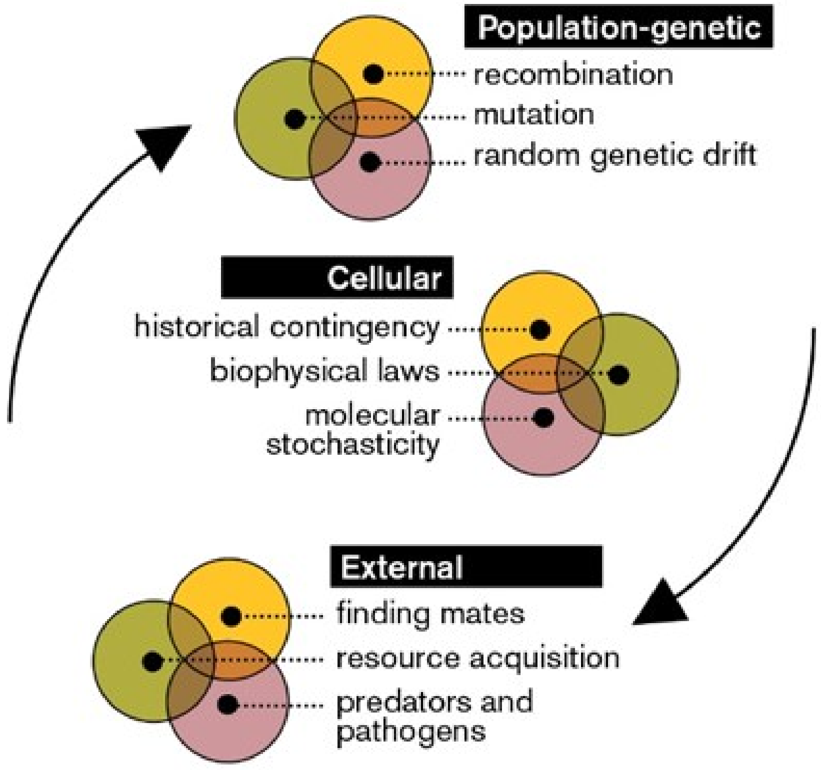
https://vimeo.com/166581864

What is Evolutionary Cell Biology?

- All evolutionary change begins at the cellular level. This motivates the need for eliminating the intellectual disconnect between cell biology (including microbiology) and evolutionary theory.

- ECB provides a natural platform for integrating the three big engines of quantitative biology (population genetics, biophysics, and biochemistry) with comparative and experimental analyses across the Tree of Life.

- ECB strives to find the connections between genotype, phenotype, and fitness essential to the development of a mechanistic theory of evolution.



Three Aspects of the Environment Relevant to Evolutionary Processes

What Can a Cell-biological Perspective Do For Evolutionary Biology?

- Is cell biology important from an evolutionary perspective?
- Do the internal workings of cells constrain the outward evolution of phenotypes in significant ways?
- How much of cellular evolution is a consequence of natural selection?
- Prokaryotes are more about metabolism; eukaryotes more about morphological/structural changes.

- The need for a field of ECB is further justified by the composition of the biosphere.

The Dominance of Unicellular Life

- The estimated number of prokaryotic cells on Earth is ~10^{30}.
- Total amount of global prokaryotic biomass exceeds that of all animals by a factor of 40.
- Estimates of the number of prokaryotic species fall in the range of 10^6 to 10^{12}.
- Taking the logarithmic midpoint, 10^9, implies an average of 10^{21} individuals per prokaryotic species.

Unicellular eukaryotes:

- Of the 10^7 described eukaryotic species, ~90% are animals, 6% fungi, 3% plants, and the small remainder protists. The latter could be vastly underestimated given the lack of attention to the taxonomy of such organisms.
- The total number of unicellular eukaryotic cells is ~0.25% of that for bacteria in marine and soil environments. This suggests that the total number of unicellular eukaryotic cells on Earth exceeds 10^{27} or so.
- Assuming the average volume of a eukaryotic cell is ~1000x that of a prokaryote, the global biomass of unicellular eukaryotes ≈ that of prokaryotes.
- Assuming 10^6 unicellular eukaryotic species implies an average ~10^{21} individuals per species, similar to prokaryotes.

Multicellular eukaryotes:

- There are ~10^{13} trees on Earth, and ~60,000 tree species, implying an average of ~10^{8} individuals per species.

- Three of the most abundant groups of invertebrates are: 1) ants, comprising ~10^{13} individuals distributed over ~10^{4} species; 2) Antarctic krill with ~10^{13} individuals in a single species; and 3) nematodes, comprising ~10^{20} individuals distributed over ~10^{6} species.

- As most animals have global population sizes $<< 10^{15}$, assuming ~10^{7} animal species suggests that the total number of animals on Earth is $<10^{20}$, many orders of magnitude below the numbers for unicellular species.

Vertebrates:

- An upper-bound estimate to the total number of vertebrate individuals on earth is 10^{16}, distributed over 10^{5} species (mostly fish), implying an average of 10^{11} individuals/species. For birds, the average number is 10^{7} individuals/species.

- The average human harbors a microbiome of 10^{13} bacterial cells, which exceeds the total number of humans that have ever lived.

The Vast Majority of Biological Research Focuses on Only a Tiny Fraction of Phylogenetic Diversity Across the Tree of Life

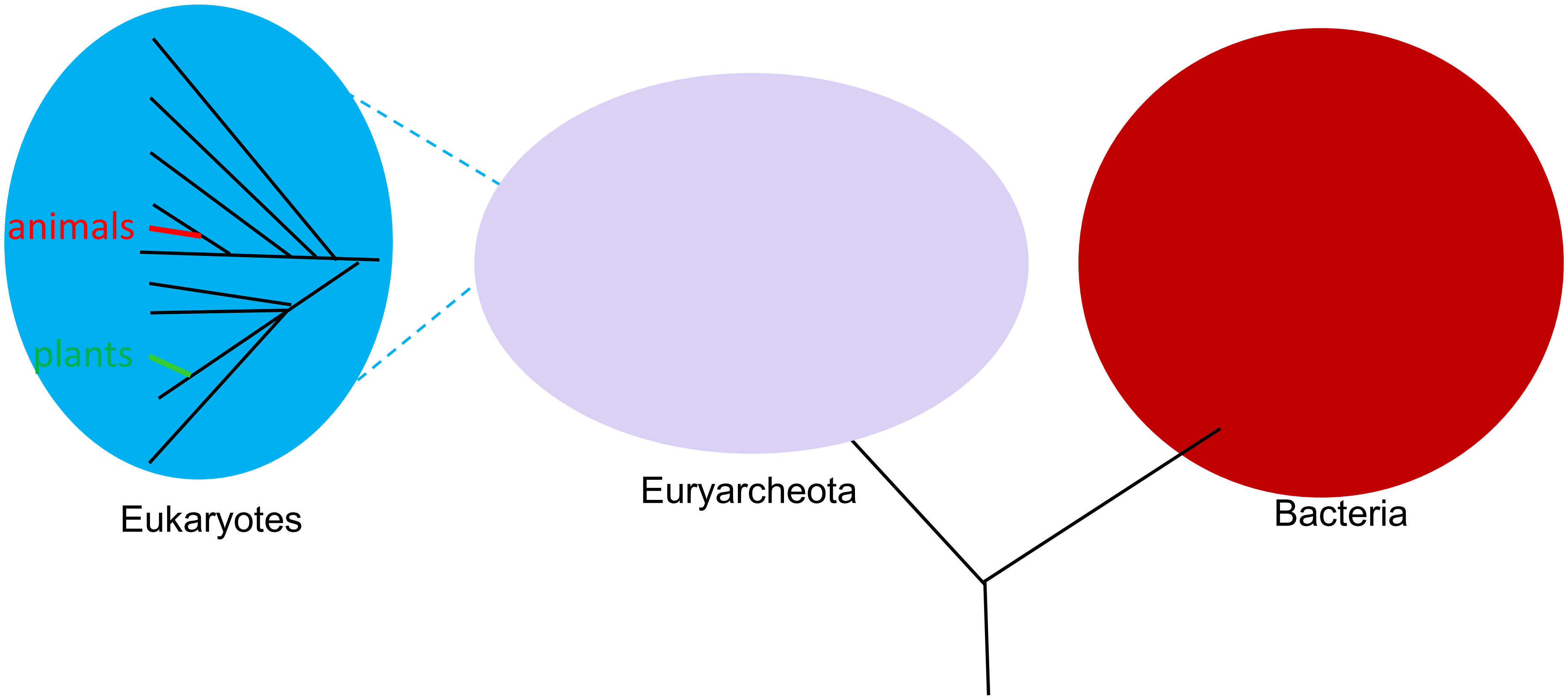
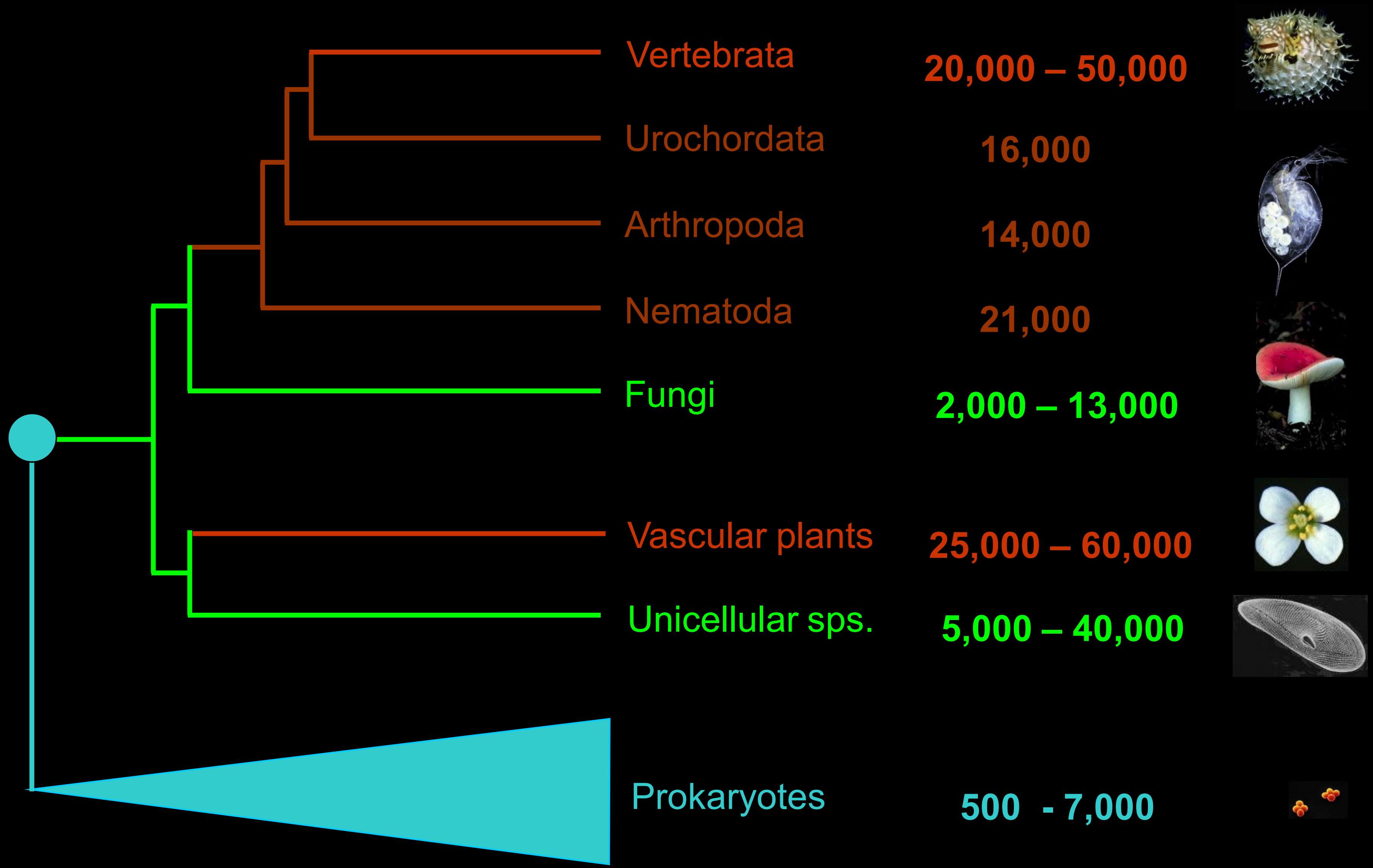


Figure 1.1. A broad overview of the Tree of Life. The overall structure is presented in an idealized fashion, some details of which are covered in Chapter 3. The main points here are that: 1) the overall tree is primarily prokaryotic, with eukaryotes being derived from one small lineage (highlighted by the small blue ball) within the major domain called the Euryarcheota; and 2) the land-plant (green) and animal (red) lineages comprise only a small fraction of the diversity within eukaryotes, as shown by the expansion of the total eukaryotic lineage to the left (dashed lines).

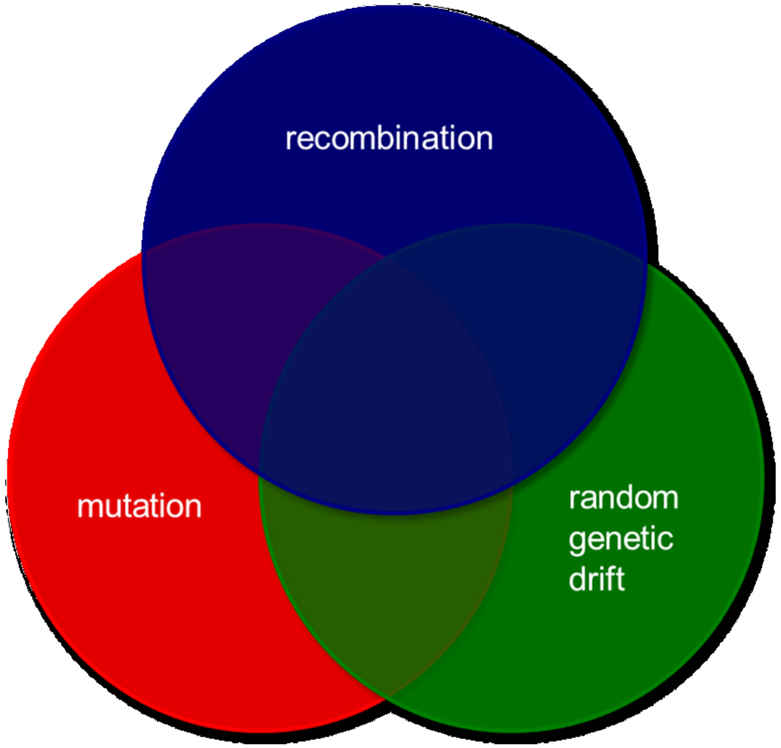
Expansion in Genome Complexity with the Evolution of Multicellularity: Cause or Effect?



The Completeness of Evolutionary Theory

- Evolution is a population-genetic process.
- Evolutionary theory, grounded in principles of Mendelian genetics and stochastic transmission of gene frequencies, is as well-established as any area of quantitative biology.
- Provides an essential platform for developing a mechanistic understanding of the origin and diversification of cellular features by the progressive fixation of new mutations.
- Although natural selection is the most powerful force in the biological world, it is not all powerful.
- Rather, the efficiency of selection is dictated by the population-genetic environment, the dimensions of which vary by orders of magnitude among phylogenetic lineages

Major Dimensions of the Population-genetic Environment



Nonadaptive Hypotheses and Our Understanding of Cellular Evolution

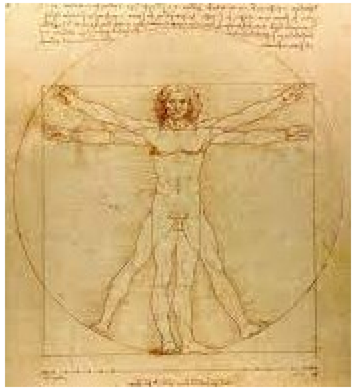
- Many aspects of molecular / genome evolution reflect the inability of natural selection to act:
  - Silent-site and conservative amino-acid substitutions in protein-coding genes.
  - Genomic bloating by mobile-genetic elements, pseudogenes, and intronic DNA in multicellular species.
- Effectively neutral evolution also occurs at the cell biological level:
  - Rewiring and nonorthologous gene replacement in regulatory and metabolic pathways.
  - Mutimerization of proteins, e.g., monomeric vs. dimeric vs. tetrameric forms.
  - Drift in the regulatory vocabulary used at transcription-factor binding sites.
  - Modifications in mutation rates across the Tree of Life.

Some of the Grand Challenges for Evolutionary Biology

- **The Origin of Life:**

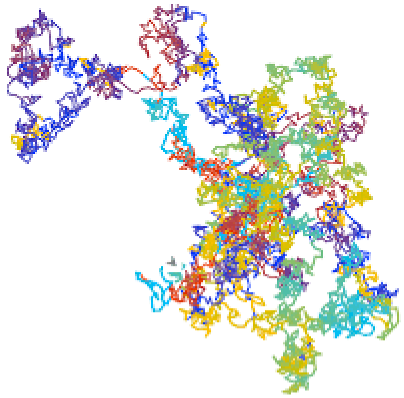
  - How were the universal aspects of cellular biochemistry set down in a few hundred million years?
  - Are the features of today's biochemistry essentially historical artifacts of the mechanisms of origin, e.g., reliance on particular trace metals; the use of RNA for central processes involving transcription and translation; and the arcane mechanism of energy production by ATP synthase?
  - Did life even originate on Earth?

- **The Roots of Organismal Complexity:**



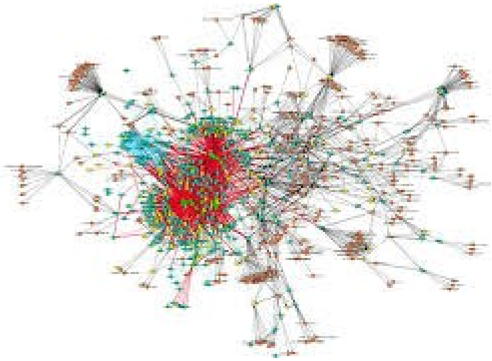
  - Is cellular / organismal complexity promoted by natural selection?
  - If so, how do we explain morphological (but not biochemical) stasis in bacteria, and why has complex multicellularity evolved only twice?
  - Are large molecular complexes such as the ribosome and the spliceosome intricate adaptive solutions to complex problems or are they examples of overdesign resulting from nonadaptive processes?

- **Molecular Stochasticity:**



  - Finite numbers of molecules per cell induce variation among individuals with the same genotype. How does such background noise compromise the efficiency of natural selection by weakening the genotype-to-phenotype link?
  - Does mutation generate differences in levels of genetic variation among individuals in meaningful ways across phylogenetic lineages?
  - How does the tempo and mode of evolution differ among phylogenetic lineages?

- **Cellular Networks:**

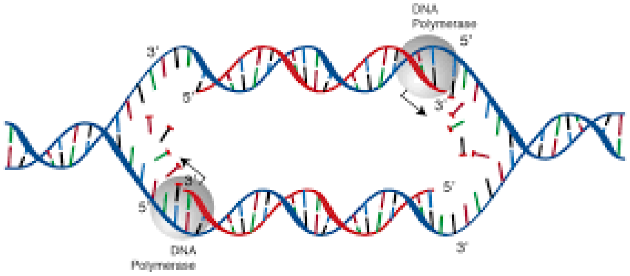


  - Are the sometimes baroque structures of regulatory and metabolic pathways, especially in multicellular species, promoted by natural selection for their profitable kinetic and/or dynamical processes, or are they simple consequences of systems drift?
  - Are there sufficient degrees of freedom to allow cellular communication systems to drift over time in an effectively neutral fashion, much like human languages have diversified across the planet?

- **Cellular Surveillance Systems:**

  - Do multi-layered systems, such as DNA polymerase with proof-reading domains, evolve so as to make organisms more robust or are they in the end no more efficient than simpler systems?

  - What constrains the error rates of enzymes, and why do they vary by up to 1000-fold among organisms?



- **Biological Scaling Laws:**

  - The mean phenotypes of many traits scale with cell size in ways that transcend phylogenetic boundaries, e.g., cell metabolic and growth rates, mutation rates, and swimming speeds.

  - Are such relationships consequences of biophysical constraints, population-genetic constraints, or both?

  - Do the scaling relationships differ between prokaryotes and eukaryotes, and why?

  - Do patterns of evolutionary scaling reflect patterns of physiological responses?

Body Size and Intrinsic Rate of Increase 319

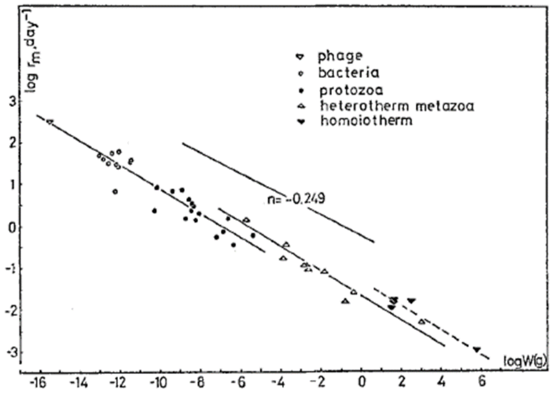


Fig. 1. The relationship between r_m and body weight for 42 species. Included is also the slope $y = K \cdot x^{-0.249}$ characteristic for the relation between body weight and metabolic rate per unit weight