Lecture I. Introduction and General Principles.

"Biology is the study of living things."

- **Characteristics of Organisms.**

  a. Consist of one or more cells.

  b. Contain information to function & reproduce.

  c. Related by common descent; have evolved.

  d. Convert chemicals from the environment into bio-molecules.

  e. Extract / utilize energy from environment

- **Questions.**

1. Why is it necessary for organisms to obtain energy?

2. How do green plants obtain energy?

3. How do animals obtain energy?

4. What is the ultimate source of energy for all animals and plants?

- **Hierarchical Nature of Biological Organization.**

  a. Biological systems are organized hierarchically.

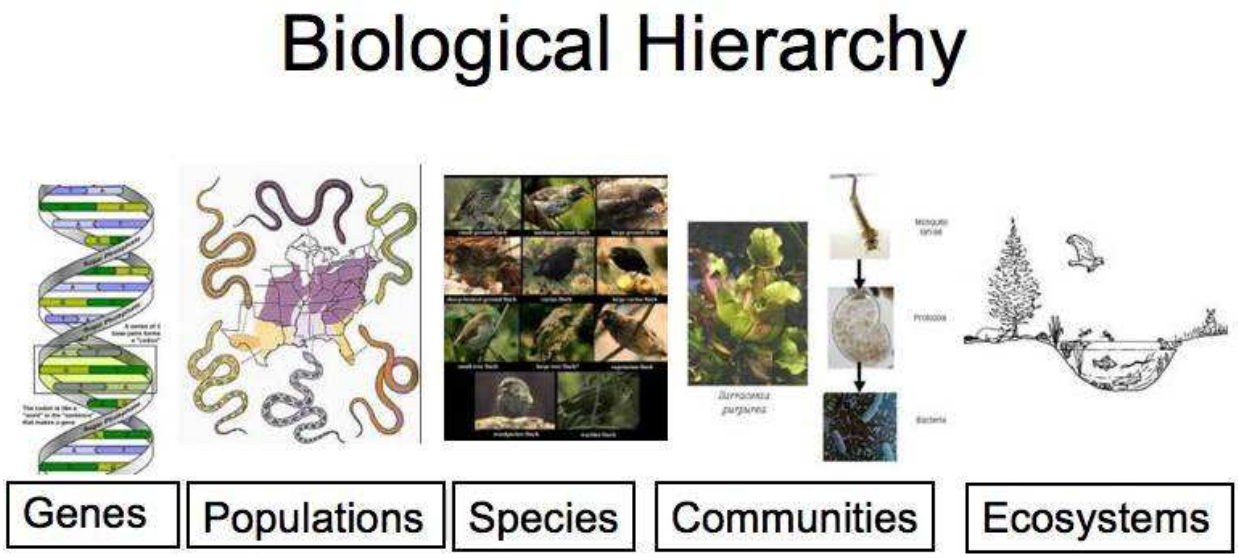
  b. Molecules → Cells → … → Ecosystems.

  c. In each case, the larger structure is assembled from multiple sub-structures.

  d. Disciplinary structure of biology (biochemistry, physiology, ecology, *etc*.) a consequence.

- **Question.**

5. The figure below shows some of the levels in the biological hierarchy discussed in introductory texts. List four additional levels that fit between genes and populations.



- **Biological Order and the Second Law of Thermodynamics.**

  a. Conservation of Energy: Absent nuclear fission / fusion, energy can be transformed from one form to another, **but it can neither be created nor destroyed**.

  b. **Closed systems**: Neither energy nor materials can enter or leave.

  c. **Entropy**: A measure of a system's disorder.

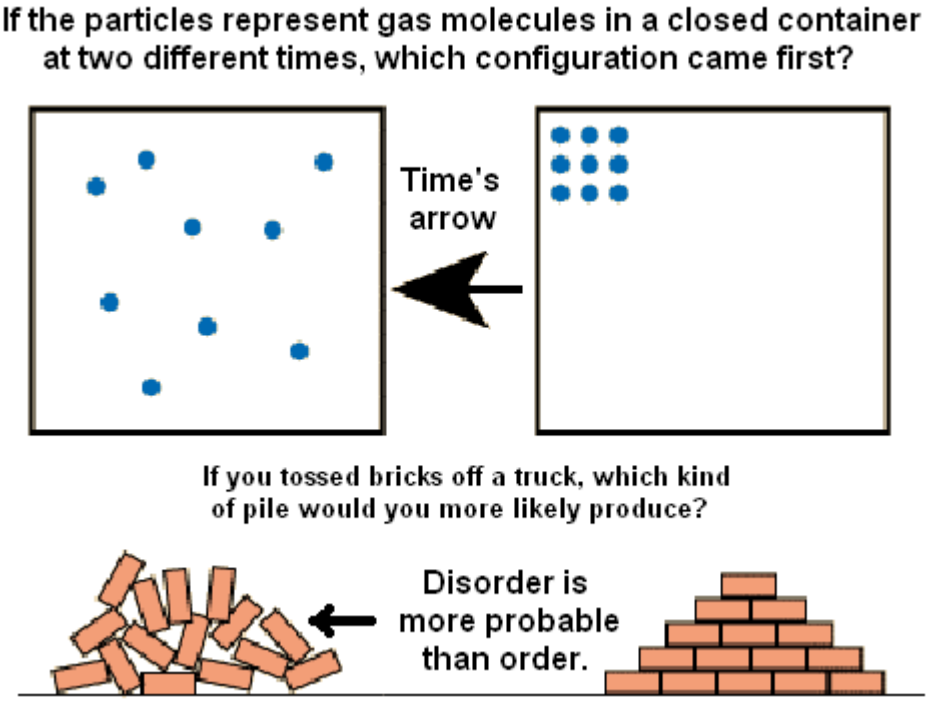
  d. **Second Law of Thermodynamics**: Entropy of a closed system must always increase consequent to *any* process occurring within that system.

  e. **Consequence**: If the universe is closed, entropy of the whole will always increase and order will decrease until absolutely nothing is happening – "Heat Death."

- **Question.**

6. Disorder in the Department of Entropy. List three things you could do to reduce entropy in the office. What would each reduction require?

- **Time's Arrow and Probability.**



Two illustrations of the Second Law. **Top.** Molecules initially confined to a small region, *e.g.*, of a box, will distribute themselves as shown with the passage of time. **Bottom.** Disordered states (high entropy) are more probable than ordered states (low entropy).

a. Differences in quantities such as concentration, in adjacent compartments of a subdivided system => existence of "**potential function**."

b. As concentrations equalize, potential energy is converted to a form that can do useful **work**.

- **"Hoyle's Fallacy."**

A core belief of evolutionary biology is that life arose from inorganic matter spontaneously, if not on earth (preferred hypothesis), then elsewhere in the universe whence it was transported by comets or meteorites. Fred Hoyle (right) rejected this idea. He wrote,

Sir Fred Hoyle (1915-2001), a famous astronomer, rejected the idea that life arose spontaneously. Evolutionary biologists refer to his argument as "Hoyle's fallacy."

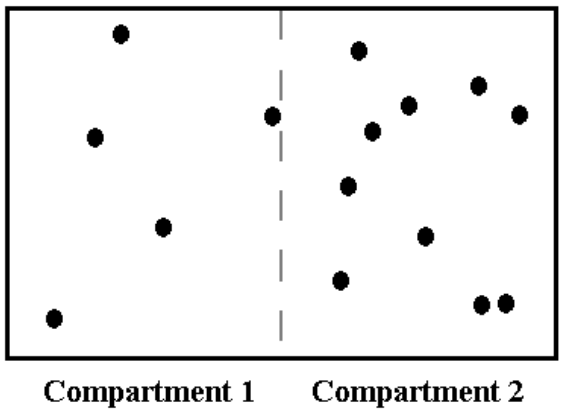
> "If one proceeds directly and straightforwardly in this matter … one arrives at the conclusion that biomaterials with their amazing measure or order must be the outcome of intelligent design. …
>
> "The notion that not only the biopolymer but the operating program of a living cell could be arrived at by chance in a primordial organic soup here on the Earth is evidently nonsense of a high order."

- **Questions.**

7. Hoyle argued that the spontaneous origin of life on earth is incompatible with the Second Law. How might an evolutionist respond?

8.-11.

Consider gas molecules in a box divided into two equal sized compartments by a permeable membrane. Let p_1 be the fraction of molecules in compartment 1, and p_2, the fraction in compartment 2. Then the entropy, E, of the system is given by the expression



$$E = -(p_1 \log p_1 + p_2 \log p_2), \qquad (1)$$

where log p_1 is the base 2 logarithm of p_1, and log p_2 is the base 2 logarithm of p_2. Note that $p_1 + p_2 = 1$. Also, recall that

$$\log_2 x = (\log_{10} x)/\log_{10} 2 \approx 3.322 \log_{10} x \qquad (2)$$

8. What are the values of p_1 and p_2 in the figure?

9. Compute E for p_1 = .01, .10, .25, .5, .75, .9, and .99.

10. For what value(s) of p_1 on [0, 1] is E minimal?

11. For what value(s) of p_1 on [0, 1] is E maximal?

- **Biological Systems are "Open."**

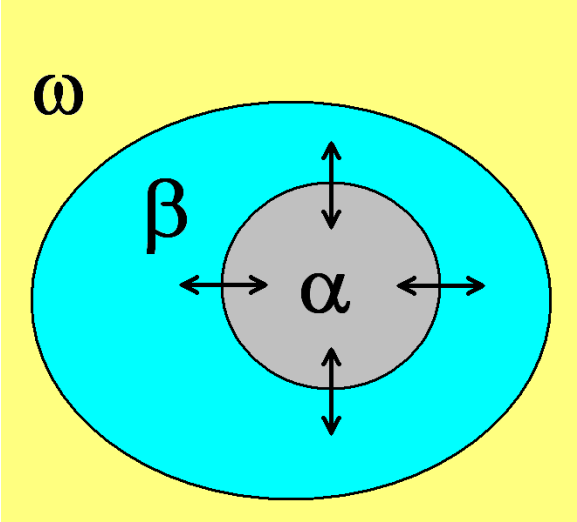
a. Exchange energy and materials with their environment.

b. Permits **local** reversal of the 2nd Law and the existence **biological order**

c. By biological order, we mean **complex biological structures** and **behavior**.

d. Biological order achieved at the **cost** of increased **global disorder**.

e. **Entropic "pollution"** an inevitable consequence of maintaining islands of order in a disordered universe – no free lunch.



Three regions of the universe: α is an open system that exchanges energy and materials with its environment, β, which is isolated from the rest of the universe, ω. The Second Law necessitates that reductions of entropy in α are only achievable at the expense of greater increases in the entropy of β, *i.e.*, (α+β) form a closed system, the entropy of which must increase consequent to any process occurring therein.

- **Question.**

12. Crudely, one can think of cells as "bags" of biological molecules that permit controlled molecular exchange with their environment. From the perspective of the Second Law, why should biological molecules be so packaged?

- **Erwin Schrödinger** famously observed that there are two sources of biological order:

  a. *Order from order*:
     1. Information stored in an "aperiodic crystal."
     2. Consumption of already organized materials.

  b. *Order from disorder*: Use of energy to create complex structures and complex behaviors – *i.e.*, local reversal of the Second Law.

E. Schrödinger spent WWII in Ireland. His 1943 lectures at the University of Dublin were later published as *What is Life*?

- **Questions.**

13. Why did Schrödinger imagine his information-bearing crystal to be aperiodic, *i.e.*, why wouldn't a "periodic" crystal (right) suffice?

14. Schrödinger's crystal was later discovered to be _____.

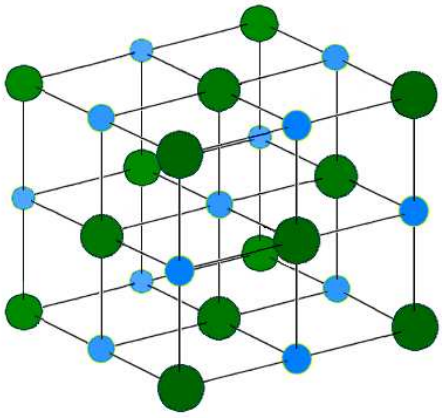
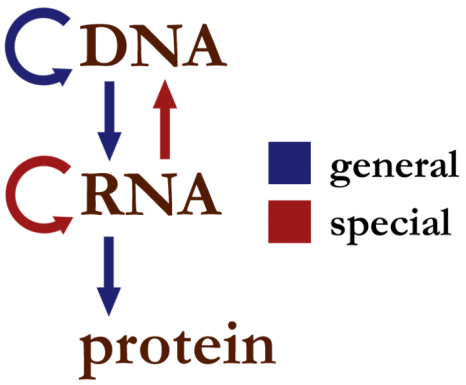


Table salt (NaCl) is a "periodic" crystal,

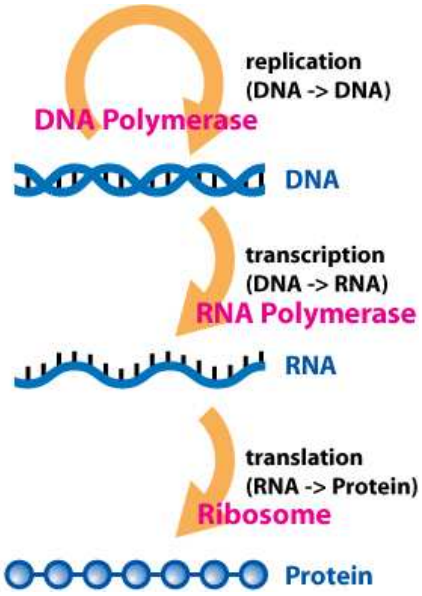
- **Central Dogma of Molecular Biology.**

a. DNA is Schrödinger's "aperiodic crystal."



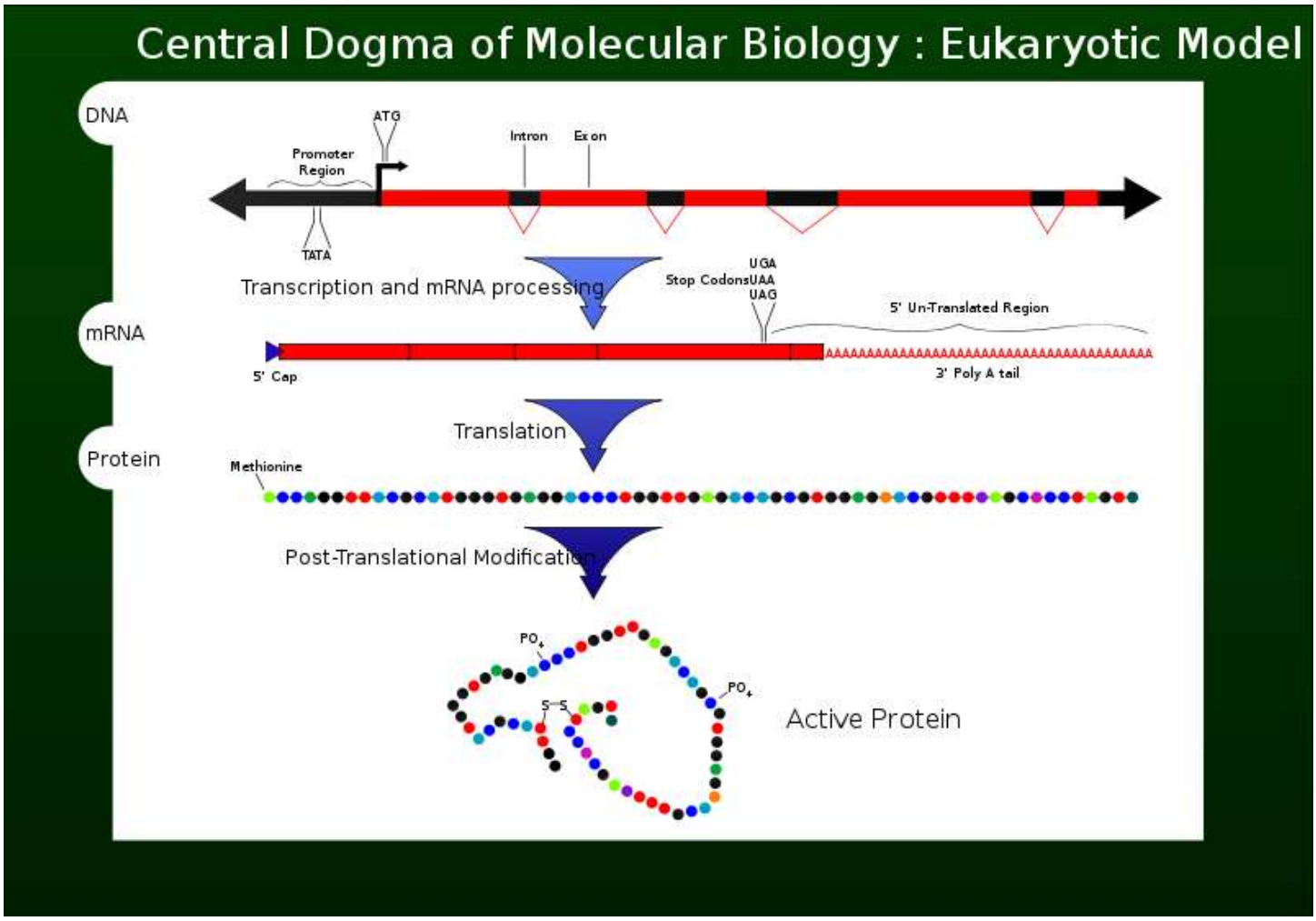
b. "Central dogma" refers to information flow from nucleic acids to proteins but not back.

1. Triplet code.
   a. Each three base pairs (codon) => an amino acid or other function.
   b. Code is degenerate.
   c. Gene consists of many codons.



2. Passed from one generation to the next when DNA replicates.

3. Passed to proteins in a two-step process.
   a. DNA → RNA (transcription)
   b. RNA → protein (translation)



c. Exceptions.

1. RNA → RNA. RNA viruses.

2. RNA → DNA. Retroviruses.

3. Protein → Protein, Prions induce conformational changes in proteins of same type.

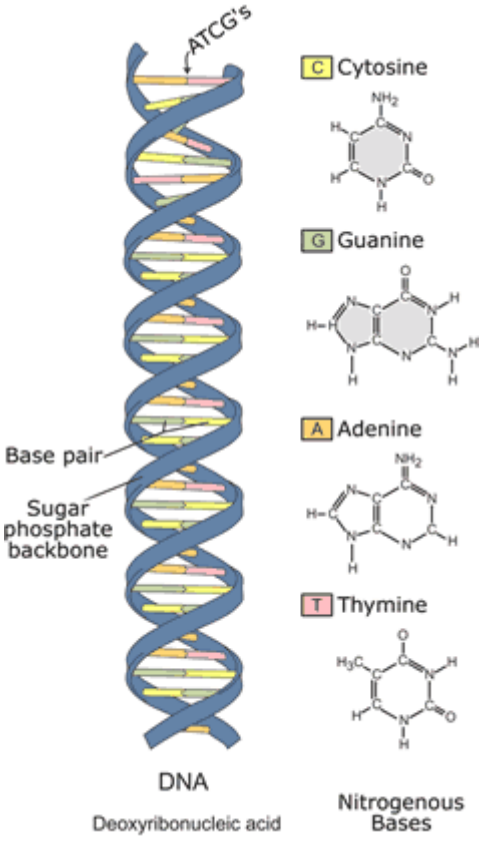
- **Central Dogma – Review.**

a. **DNA Structure**

1. Two chains consisting of a sugar-phosphate backbone linked to nitrogenous bases.

2. Chains are held together by H-bonds between the bases.

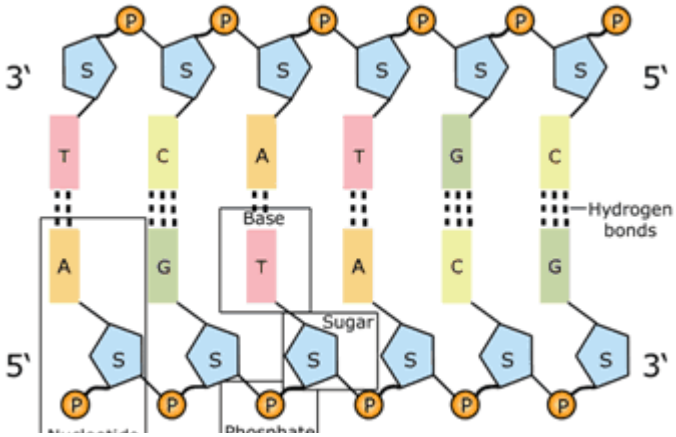
3. Bases are adenine (A), cytosine (C), guanine (G), thymine (T).



b. **Triplet code**

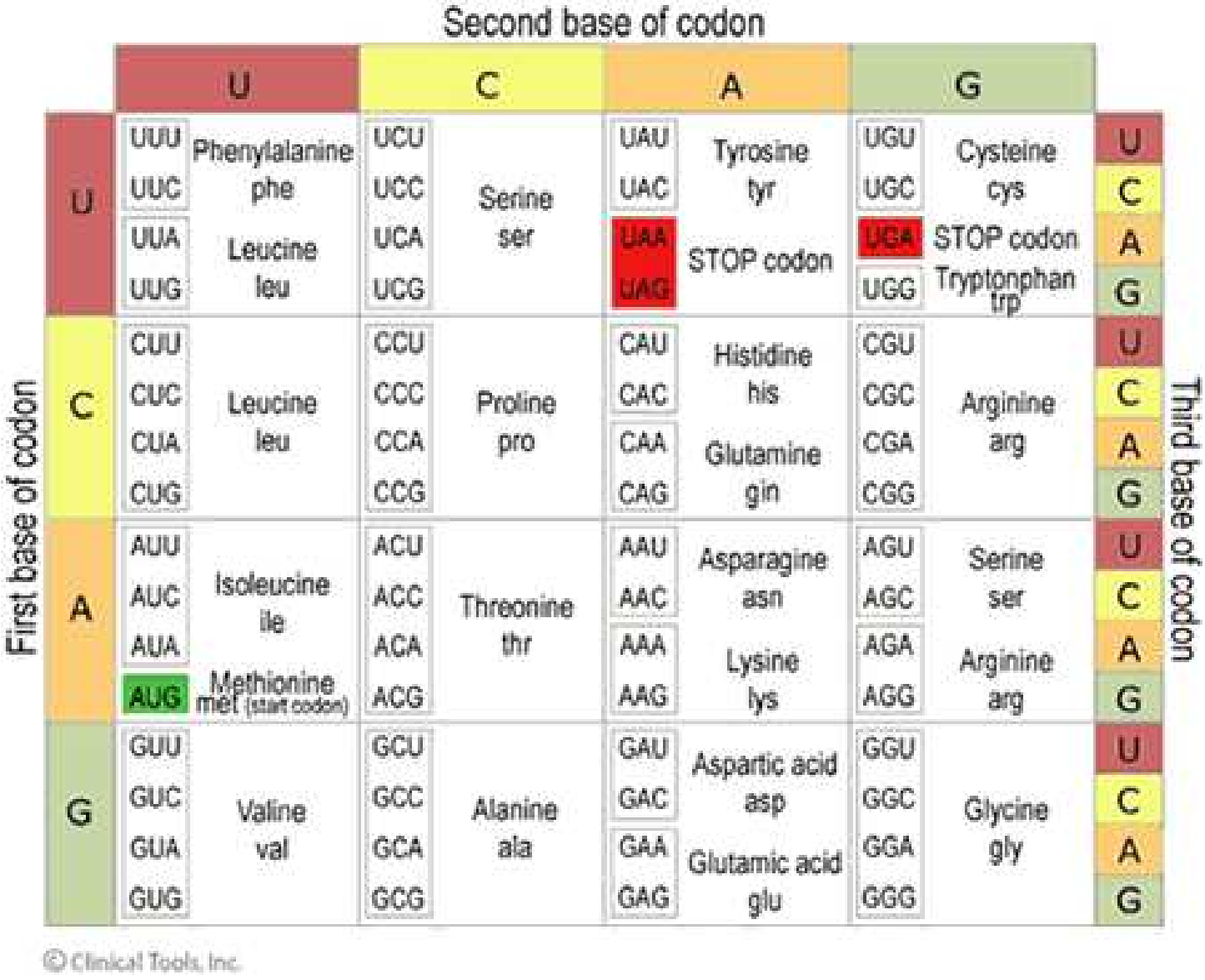
1. Three bases (codon) correspond to an amino acid or some other function.

2. Genes consist of many codons.



Structure of DNA. Phosphate groups connect adjacent sugar molecules at the 3' and 5' positions.

c. **Protein production** mediated by **m-RNA** (one strand) in which uracil (U) replaces thymine (T).



The triplet code is degenerate and universal. Shown here are the correspondences between m-RNA and amino acids – hence the U's for uracil.

- **Cell Theory.**

a. Basic structural and physiological units of organisms.

b. Exist as **independent organisms** and **building blocks** of multicellular life

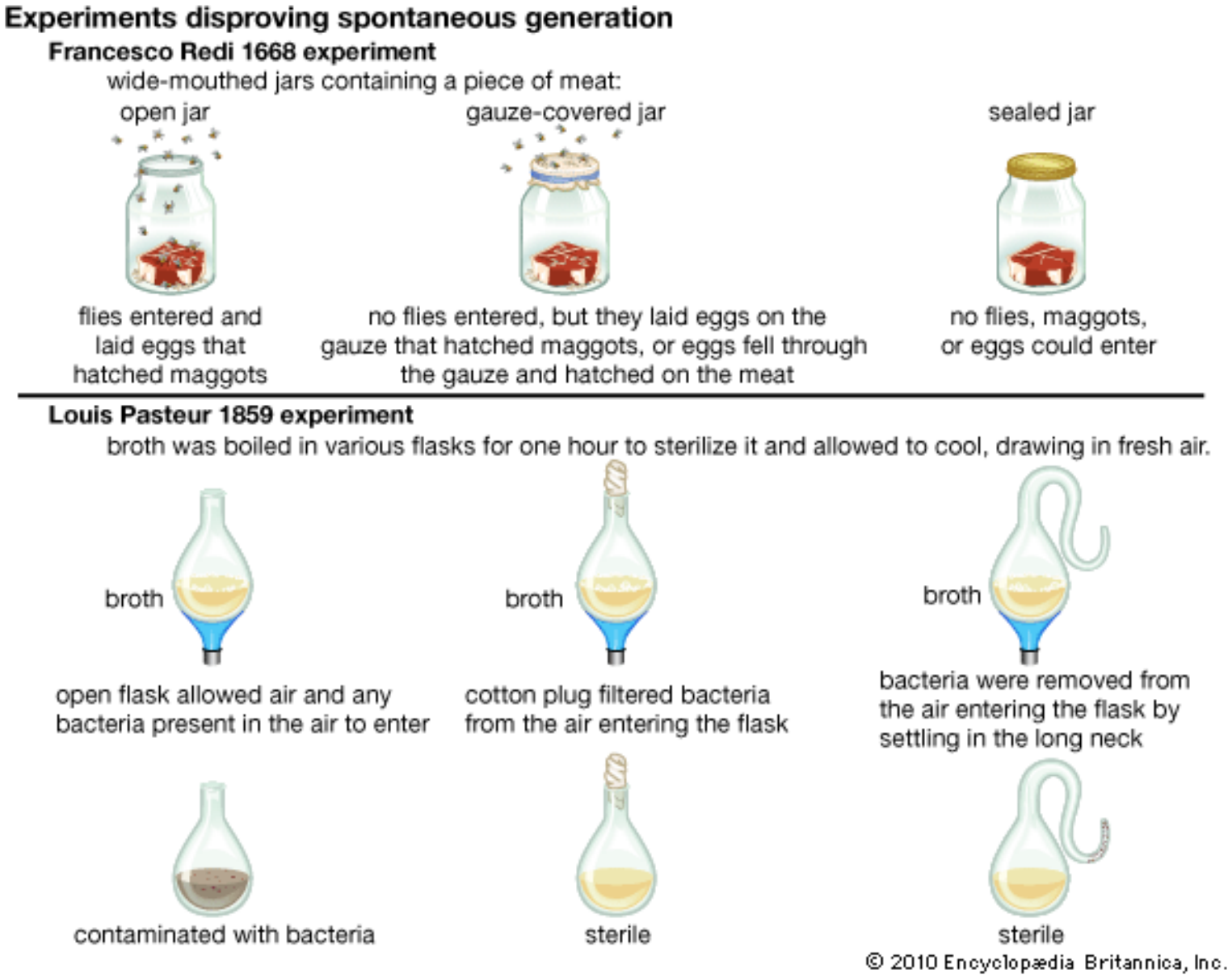
c. Duplication / specialization – general **developmental** and **evolutionary themes**.

d. **Cells from cells** – Pasteur's experiment (right) overthrew theory of "spontaneous generation."

e. **Complete sets** of genetic information replicated / passed on during cell replication.

f. **Viruses** lack cell structure but are dependent on cellular organisms.

Pasteur's Experiments.



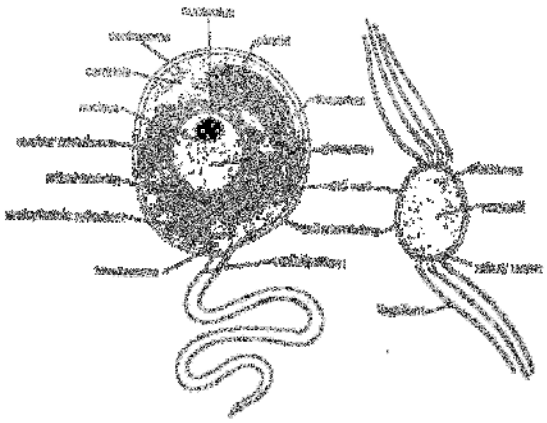
- **Not all Cells are the Same.**

a. *E.g.,* prokaryotes *vs*. eukaryotes.

b. Implies

   1. Cell structure has changed over time.

   2. The number of cell types has also increased since life first evolved.



Structure of eukaryotic (left) and prokaryotic (right) cells compared.

c. Multicellular organisms begin life as a single "totipotent" cell, which subsequently divides. As development proceeds,

   1. Cells differentiate.

   2. Totipotency lost – hence the interest in stem cells in treatment of degenerative disease.

- **Questions.**

15. If cells from cells, whence cometh the first cell? Give two possibilities.

16. Viruses lack most of the structure of even the simplest cells. Whence cometh viruses? Give two possibilities.

17. In unicellular organisms, the cell is the organism; in multicellular organisms, cells are building blocks. How might the first multicellular organisms have evolved?

18. If complete genomes are replicated when cells divide, how can one account for different cell types in multi-cellular organisms?

- **Descent with Modification – The Pattern.**

  a. Species related by ancestry.

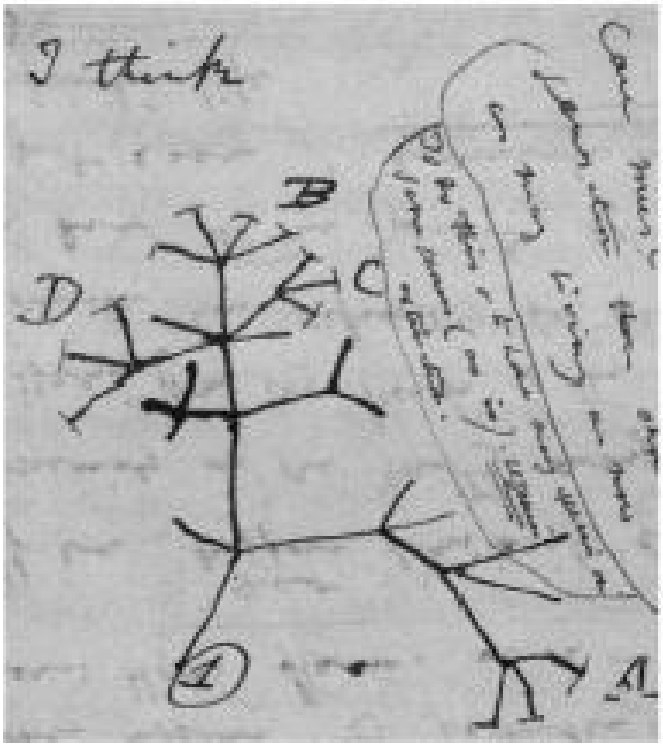
  b. Species have changed with time.

  "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. … Thus, from the war of nature, from famine and death, the most exalted object which we are capable of conceiving, namely, the production of the higher animals, directly follows. There is grandeur in this view of life, with its several powers, having been originally breathed by the Creator into a few forms or into one; and that, whilst this planet has gone circling on according to the fixed law of gravity, from so simple a beginning endless forms most beautiful and most wonderful have been, and are being evolved." [C. Darwin. Concluding paragraph of *The Origin of Species*.]

- **Question.**

19. Darwin and Alfred Wallace (co-discoverer of natural selection) both imagined phyletic descent as a branching tree – often referred to as the "tree of life." By this, we mean that any pair of living species trace to a unique common ancestor and, by extension, all living species to a universal common ancestor – Dar- Darwin imagined " one or a few."

    Does DWM necessitate a tree-like pattern of relatedness? Why or why not?



The famous 'branching tree" sketch from Notebook B (1837) was Darwin's first attempt at illustrating his theory. From Shu, 2005. *Guidance to Reading 'On the Origin of Species'.* Peking University Press.

- **Natural Selection (NS) – the Mechanism.**
  a. Superior variations replace inferior ones.

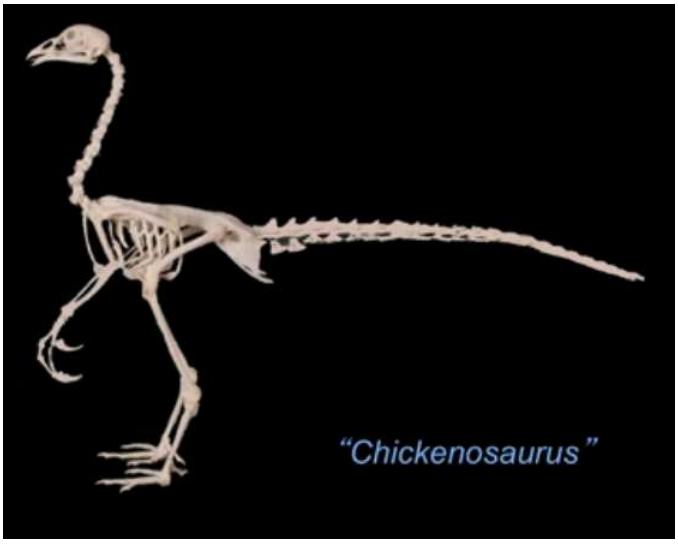
  b. NS requires:
     1. Individuals vary.

     2. Variations heritable.

     3. "Excess biotic potential" – More individuals produced than survive – Principle of Malthus.

  c. => "superior" varieties replace "inferior" ones.

  d. "Stuff" of evolution once assumed to be **point mutations** in structural proteins.



  e. Genes that **regulate development** now believed to be major players – see "Chickenosaurs" video at http://www.ted.com/talks/jack_horner_building_a_dinosaur_from_a_chicken.html).

- **Questions.**

20. With regard to natural selection, what is meant by "superior" variations?

21. Who was Thomas Malthus?

- **Fitness.**

  a. Criterion of evolutionary "superiority."

  b. Refers to relative contributions different individuals (genes) make to future generations.

  c. Sometimes increased fitness entails increased size / strength. **Usually not**.

  d. Except in special circumstances, traits do **not** evolve to benefit the species.

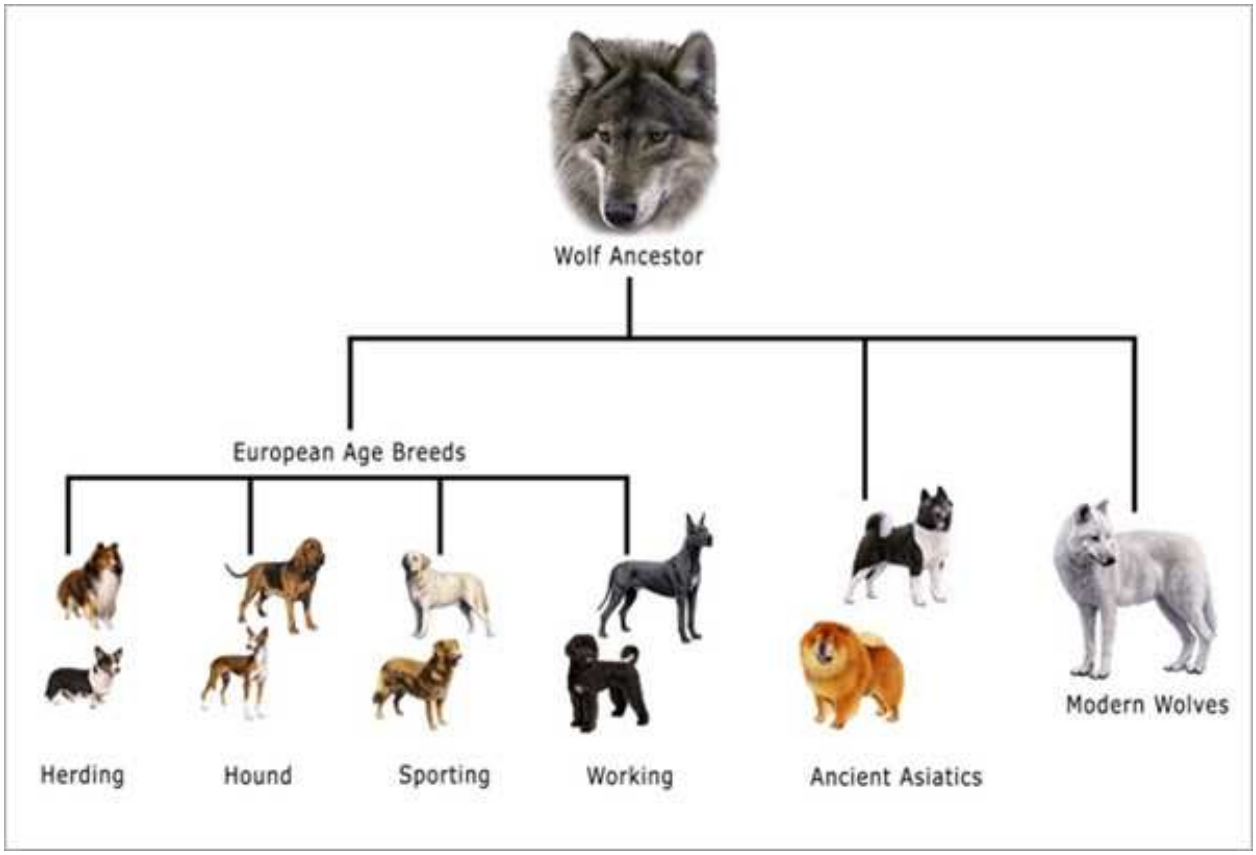
- **Question.**

22. If predators become sufficiently adept at detecting / catching / subduing / killing their prey, they will drive the latter to extinction. Give three or more reasons why this might not happen.

- **Artificial Selection (AS).**
  a. Darwin viewed AS as an analog of what transpires in nature.

  b. Wallace viewed products of domestication as "monstrosities."

  c. Breeds of domestic dogs exemplify the extent to which heritable variations can be selected for.



  d. **But** – most breeds are inter-fertile. Speciation additionally requires barriers to crossing.

Question:

23. What do you think Darwin and Wallace might each have had to say about the little "yappers" (below) that inhabit retirement communities?

"Real dogs" (**left**) and "rodent dogs" (**right**) share a common wolf-like ancestor.

- **Three Common Misconceptions and Three "Buts."**

1. **Claim:** Evolution is intrinsically progressive.

   Reality: Lots of examples of degeneration – many parasites, for example. **But**, evolution is *broadly* progressive – we don't find elephants in the Cambrian. The more interesting question is "Why?"

2. **Claim:** Characters acquired by organisms during their lifetimes are passed to their offspring.

   Reality: While, the inheritance of acquired characters (IAC) was widely accepted by Victorian biologists including Darwin, it has since passed into the dustbin of discarded ideas. **But**, recent advances in epigenetics may resurrect this idea.

3. **Claim:** High fitness implies increased size / strength / dominance.

   Reality: Often the meek (= the more efficient) inherit the earth. **But**, when individuals compete aggressively for a limited "resource," *e.g.*, males competing for females, such traits are selected for.

- **The Linnaean Classification.**

a. Kingdom, Phylum. Class, Order, Family, Genus, Species.

The Linnaean Classification for Man.	
Kingdom	Animalia
Phylum	Chordata
Class	Mammalia
Order	Primates
Family	Hominidae
Genus	*Homo*
Species	*sapiens*

b. Additional taxa *e.g.*, subspecies, sometimes added. Modern humans – *H. s. sapiens*; Neanderthals – *H. s. neanderthalensis*.

c. Linnaean system predates evolution. Linnaeus believed species created in their present form.

d. Contemporary systematics imagines all species descended from a single original form (so-called "Tree of Life") – but see below for discussion.

- **How Many Kingdoms?**

a. Traditionally two: **Animalia** and **Plantae** – both included unicells (single cell organisms).

b. **Fungi** assumed to be plants that had lost their chloroplasts.

c. With discovery of bacteria, prokaryotes (no nucleus) distinguished from eukaryotes (nucleus and other organelles).

d. Two kingdoms replaced by five:

1. **Monera** (prokaryotes)

2. **Protista** (unicellular eukaryotes)

3. **Plantae**

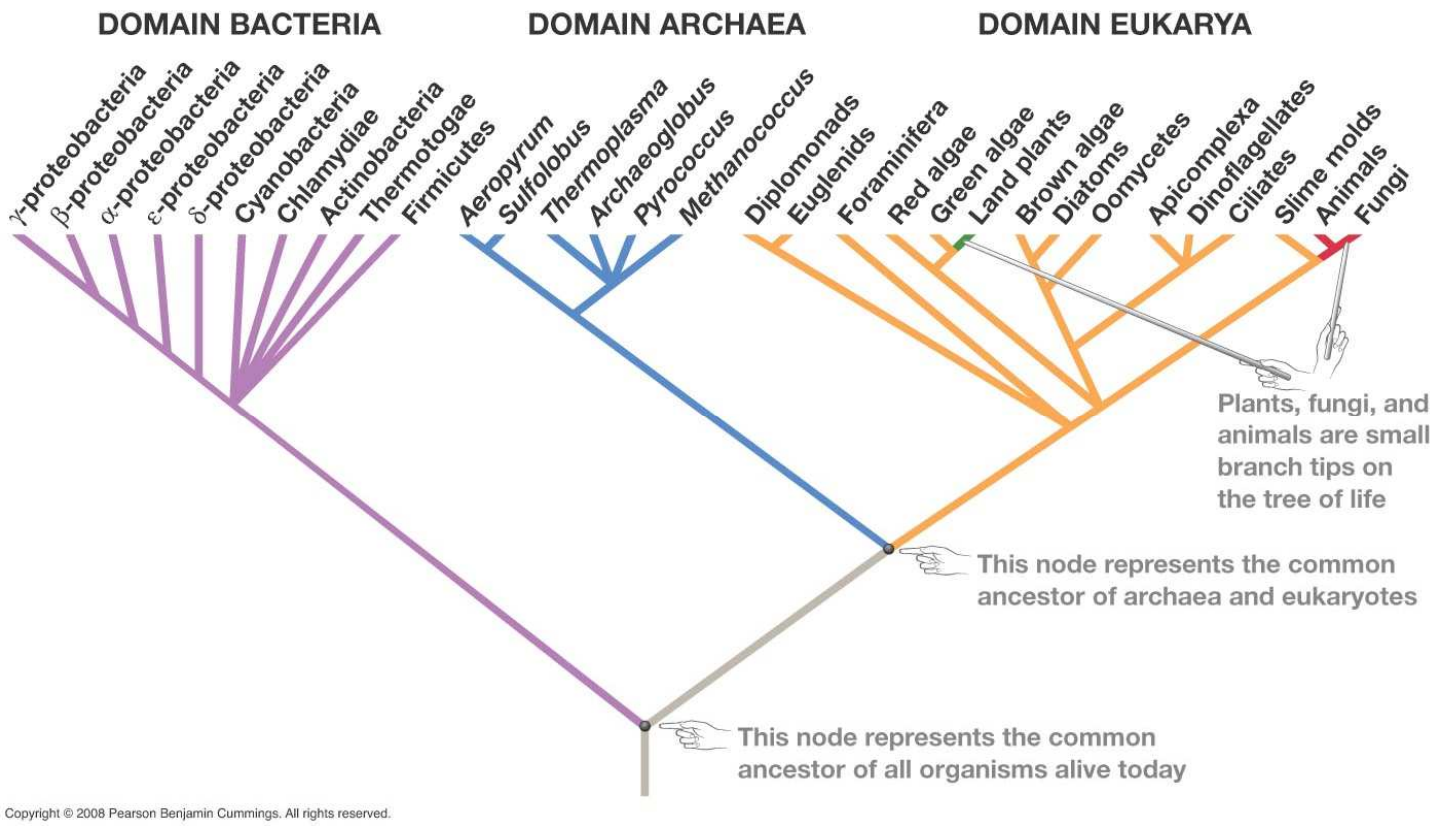
4. **Fungi**

5. **Animalia**

- **Three Domain Scheme.**

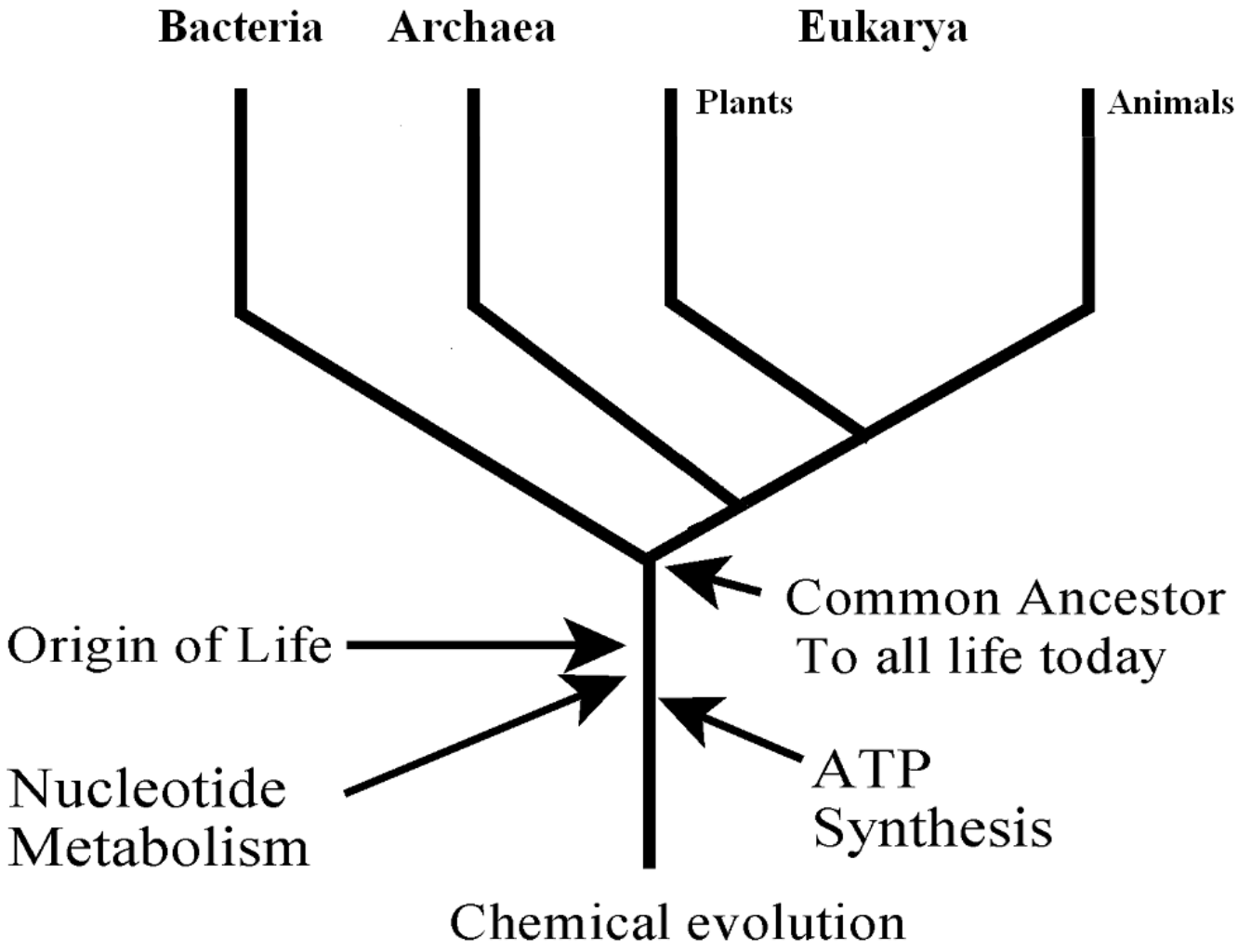
    a. Introduces "**domains**" (above kingdoms).
        1. **Bacteria** (= eubacteria)
        2. **Archaea** (= archaebacteria)
        3. **Eukarya** (= eukaryotes)

    b. Based on analysis of ribosomal RNA.

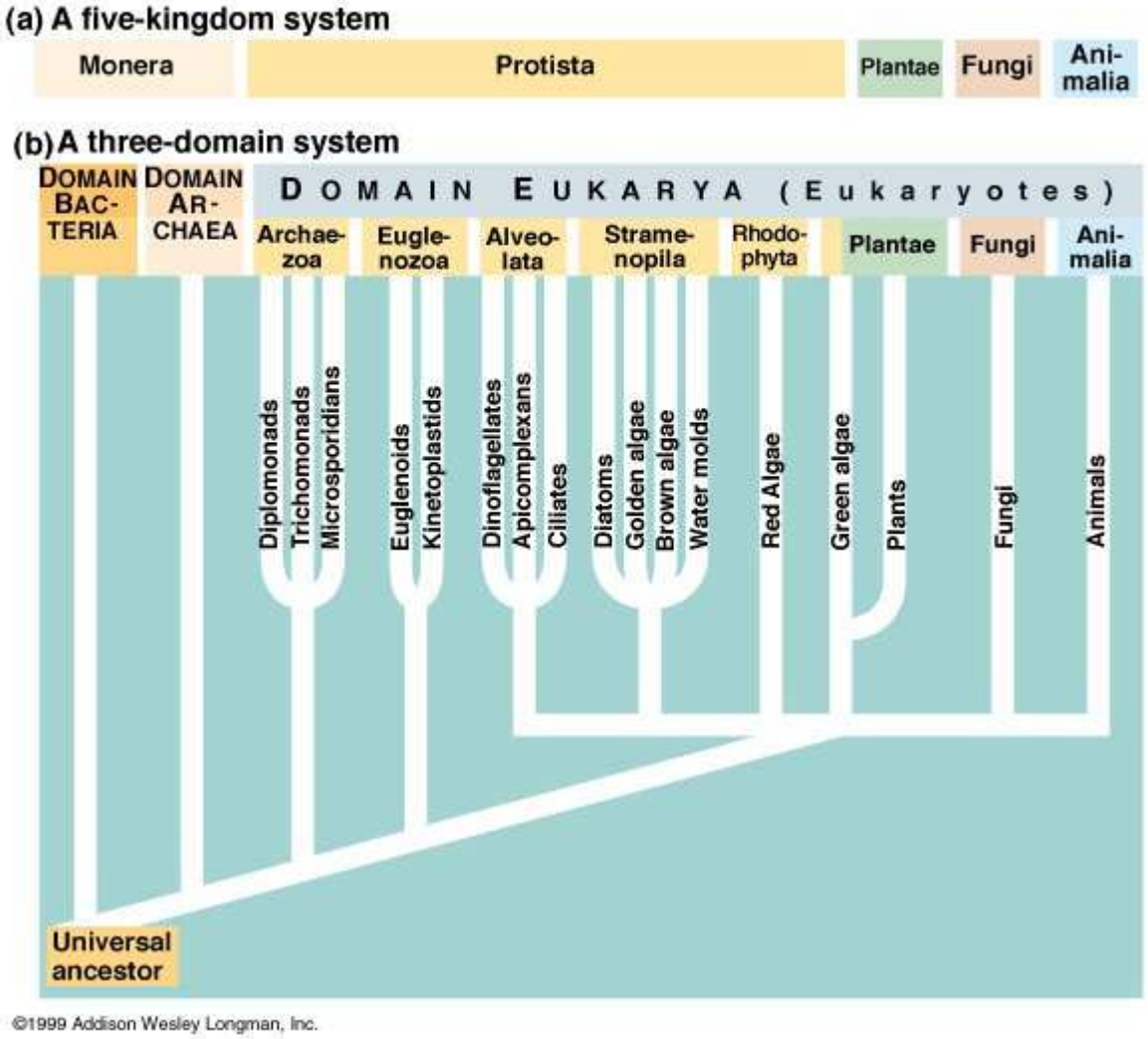


Three domain scheme as shown in many textbooks.

- **Simplified Version.**



- **Three Domains *vs*. Five Kingdoms.**

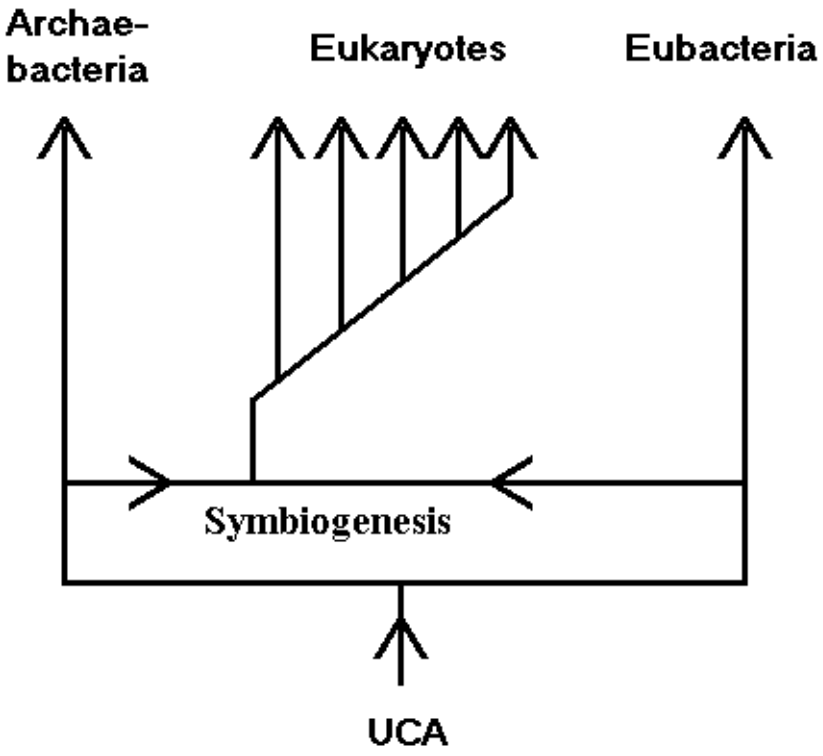


Five kingdom (a) and three domain (b) classifications compared.

But –

1. Eukaryotes may have resulted from the fusion of an archaebacterium and a eubacterium, a process called **symbiogenesis**.

2. If yes, the "tree" metaphor **fails** at its base.



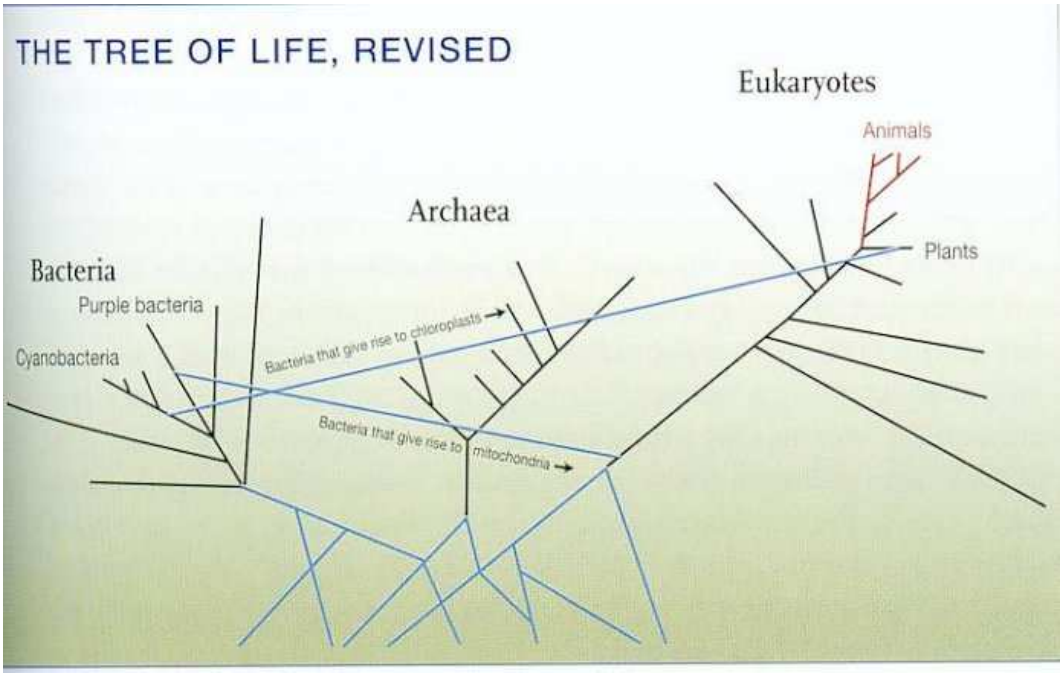
Symbiogenic origin of eukaryotes as proposed by Lynn Margulis and others. UCA stands for "universal common ancestor."

And –

a. Even if eukaryotic nucleus, endoplasmic reticulum (ER), *etc*., evolved *de novo*,

1. **Lateral gene transfer** common among prokaryotes

2. **Mitochondria** and **chloroplasts** almost certainly descended from free living bacteria.



b. Even among plants and animals, **gene trees** and **species trees** may not be the same.

- **Adaptation.**

  a. Regarding complex biological characters –

     1. How did they come to be?

     2. What are they good for, if anything?

  b. Before Darwin, the conventional answer to #1. was "**Design**" – the so-called "**teleological argument**" best known to us through the writings of William Paley.

  c. Rejected by contemporary biologists.

  d. Today's "plausible" possibilities:

     1. Response to selection for the character in question – adaptation.

     2. Correlated consequence of selection for / against some other character(s).

     3. Result of change absent selection.

- **Questions.**

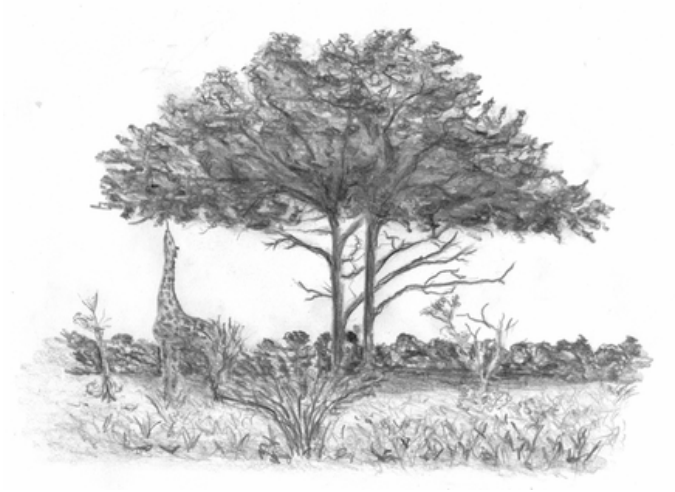
24. Who was William Paley?

25. What was the teleological argument?

26. What was Paley's iconic example?

- **The Giraffe's Neck.**

a. **Traditional hypothesis**: Long neck allows individuals to forage high in the canopy.

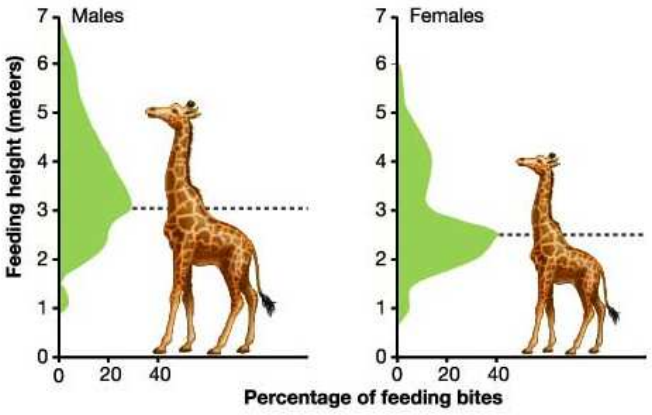


Giraffe feeding on acacia leaves with head fully extended. Below this level, the tree has been stripped. Note the 18" tongue.

b. **But**,

1. Giraffes often forage low down.

2. Males use their necks to fight with each other. Their necks are larger and more heavily muscled than those of females.



Foraging height frequency diagrams for male / female giraffes.

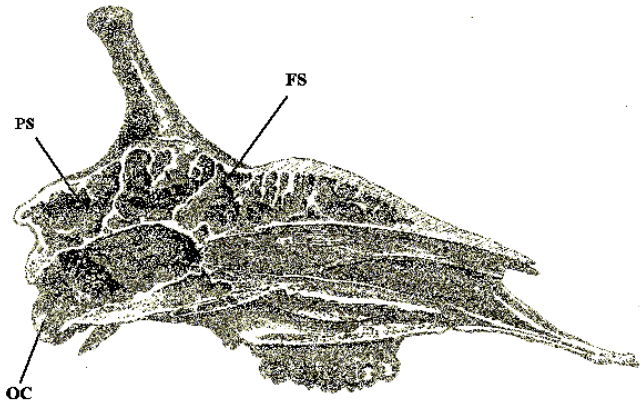
c. **New Hypothesis**: Long necks evolved in response to **sexual selection** – males contesting for females.

d. **Additional observations**:

1. Giraffe skull heavily armored – consistent with sexual selection hypothesis.

2. Skull-neck joint allows more complete extension of the head – consistent with foraging hypothesis.

3. Hypotheses are not mutually exclusive.

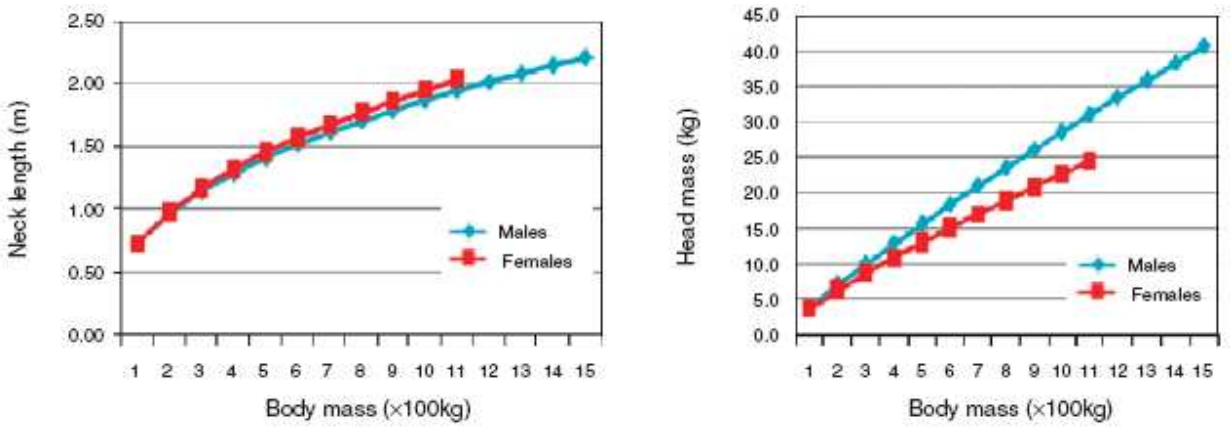


Skull of a Male Giraffe in section. Note the prominent frontal (FS) and parietal (PS) air sinuses within which are struts that support the skull roof while impeding transmission of blows from above to the brain and nasal cavities. The enlarged occipital condyle (OC) permits backwards rotation of the head so as to bring the anterior-posterior axis of the skull in line with the neck, thereby permitting fuller extension of the head.

e. Recent data

1. Supports selection for proportionally more massive skulls in males.

2. But not for longer necks.



Neck length and head mass plotted against body mass for male and female giraffes. Only head mass is proportionately larger in males. From Mitchell *et al*. 2009. *J. Zool.* **278** : 281–286.

- **Questions.**

Regarding giraffes:

27. How might you attempt to further assess the relative merits of the two hypotheses? Hint: Think okapi (right).

The ancestor of savanna-dwelling giraffes resembled the much smaller okapi that lives in forests.

28. Following publication (1996) of the paper in which it was first proposed, the sexual selection hypothesis quickly became a staple of introductory biology texts. What do you make of that?

29. As a general matter, what are some of the difficulties that attend determination of the adaptive significance of *any* character?

More generally:

30. The theory of natural selection says that the fit survive – more accurately, that the fittest individuals make the greatest contribution to succeeding gener-

ations. If we compare successive generations and find differences in gene frequencies, morphology, *etc*., what are we to conclude? According to NS, the changes are due to differential survival / reproduction. But this is circular: the fit survive and the survivors are the fittest. How do you break the circularity?

- **Science as the Modeler's Art.**

a. Scientific hypotheses are **models** that simplify reality.

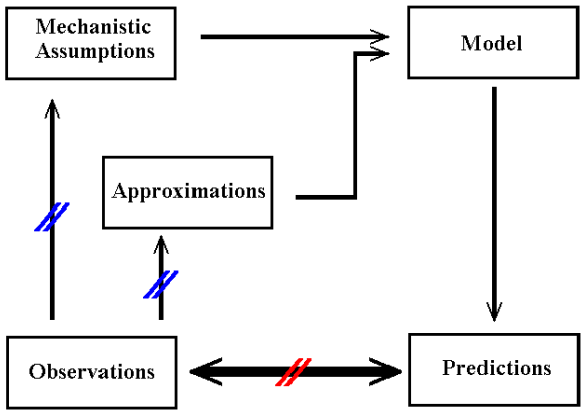
b. To be useful, a scientific theory must be **falsifiable**.

c. Prediction - observation mismatch necessitates model **revision**.

d. Models can fail due to

   1. Invalid assumptions.

   2. Inappropriate simplifications.



Science as modeler's art. Mechanistic assumptions and simplifying approximations inform the construction of a model that generates predictions. Falsification (red slashes) results when observation contradicts prediction, or when other advances invalidate the assumptions (blue slashes). Model revision is also required when simplifications are shown to be untenable.

e. Additionally:

1. Model must be **plausible**.

2. Predictions should be **non-trivial** – *i.e.*, not readily deducible from other considerations.

- **Questions.**

31. Search on "Ptolemaic epicycles." What were they?

32. Does a model's ability to predict guarantee its correctness?

33. What does a scientist do when his predictions are confirmed by experiment – *i.e.*, after publishing his results?

34. In physics, you study "laws" – Newton's, Kepler's, *etc*. What's a law?

35. As a scientist, how should you respond when someone tells you that such and such will happen because a computer model predicts it?