Lecture 27

Nature of Life on Earth

Outline of Lecture 27

- Hallmarks of life on Earth are *growth and reproduction*. On a molecular level, growth and reproduction are mediated by *proteins and nucleic acids (DNA and RNA)*.
- *Central dogma of molecular biology*:

  DNA → RNA → Proteins
- Many reactions of biological importance have to be driven "uphill," requiring an input of energy. The *universal energy currency* of all cells is ATP (adenosine triphosphate), which is generated by burning glucose, a simple sugar.

Physical Rather than Vitalistic Origin and Evolution of Life

- Champions of Physical View for Origin and Evolution of
  - Solar System:
    - Christiaan Huygens (1629-1695)
    - Pierre Laplace (1749-1827)
  - Earth:
    - James Hutton (1726-1797)
    - Charles Lyell (1797-1875)
    - Alfred Wegner (1880-1930)
  - Life:
    - Charles Darwin (1809-1882)
    - Alfred Wallace (1823-1913)
    - Gregor Mendel (1822-1884)
    - James Watson (1928-)
    - Francis Crick (1916-2004)

- Vitalism, discredited notion that forces outside of physics and chemistry are needed to understand the origin and maintenance of life on Earth
- Historical tenacity of vitalistic ideas concerning a sharp separation between
  - Organic and inorganic chemistry
  - Living and nonliving things
  - Thinking and nonthinking organisms

Life on Earth

Maintenance

- Growth (metabolism)
- Reproduction (self-replication)
- Growth and reproduction of living organisms have a molecular basis in biochemistry.
- *Vitalism is not needed* to explain the basic properties and processes of life.

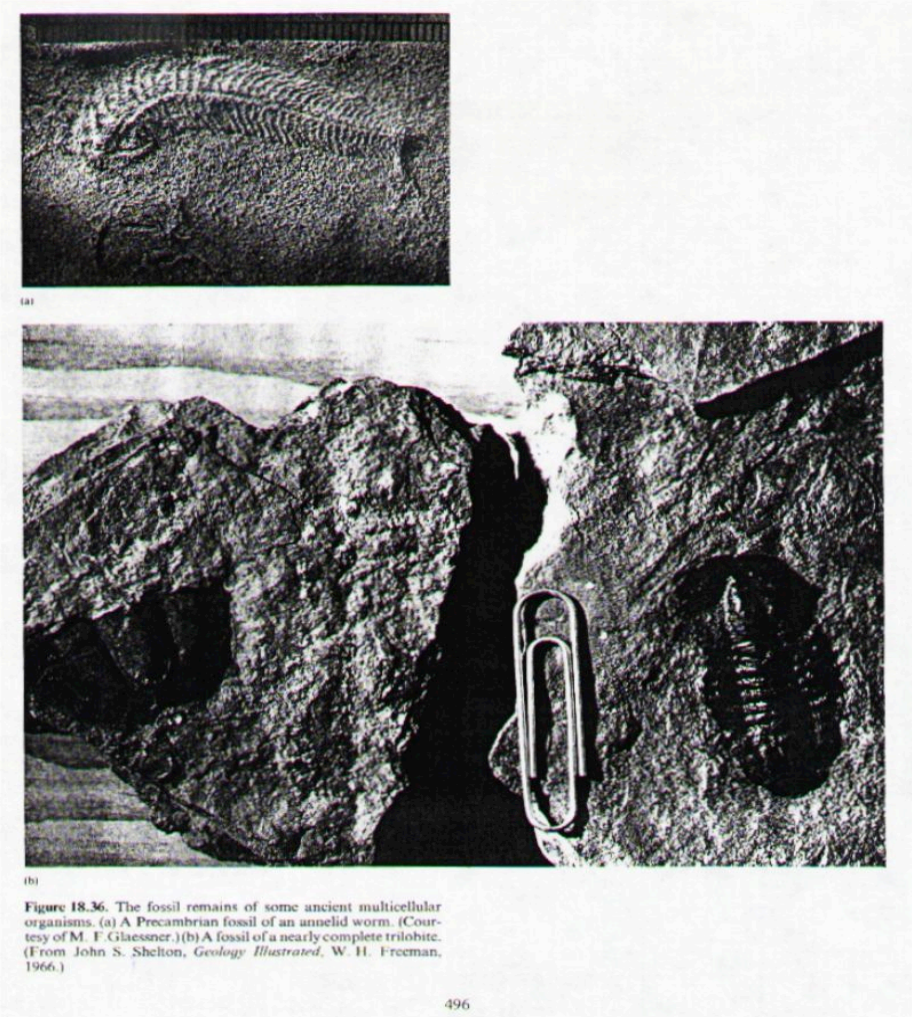
Evolution

- How did *complexity of present lifeforms* come to be?
- Darwin's answer: *Natural selection and evolution*.
- Modern basis of Darwinian theory – *genetics and molecular biology* (functional genomics).
- *Vitalism is not needed* to explain the creation of advanced lifeforms on Earth.

Changes of the Earth over Geological Time

- Hutton & Lyell: Long history (at least hundreds of millions of years) where landforms of Earth gradually changed.
- Sea shells found atop mountains (e.g., Appalachians): mountains raised from ancient sea beds.
- Wegner: Jigsaw fit of east coasts of Americas and west coasts of Europe and Africa suggests “continental drift” (plate tectonics) from “pangaea.”
- Empirical proof of ocean spreading in “magnetic stripes” at ocean rifts (dating from reversals of Earth’s magnetic field as calibrated in rock strata).

Fossil lifeforms recorded in rock:



(a)

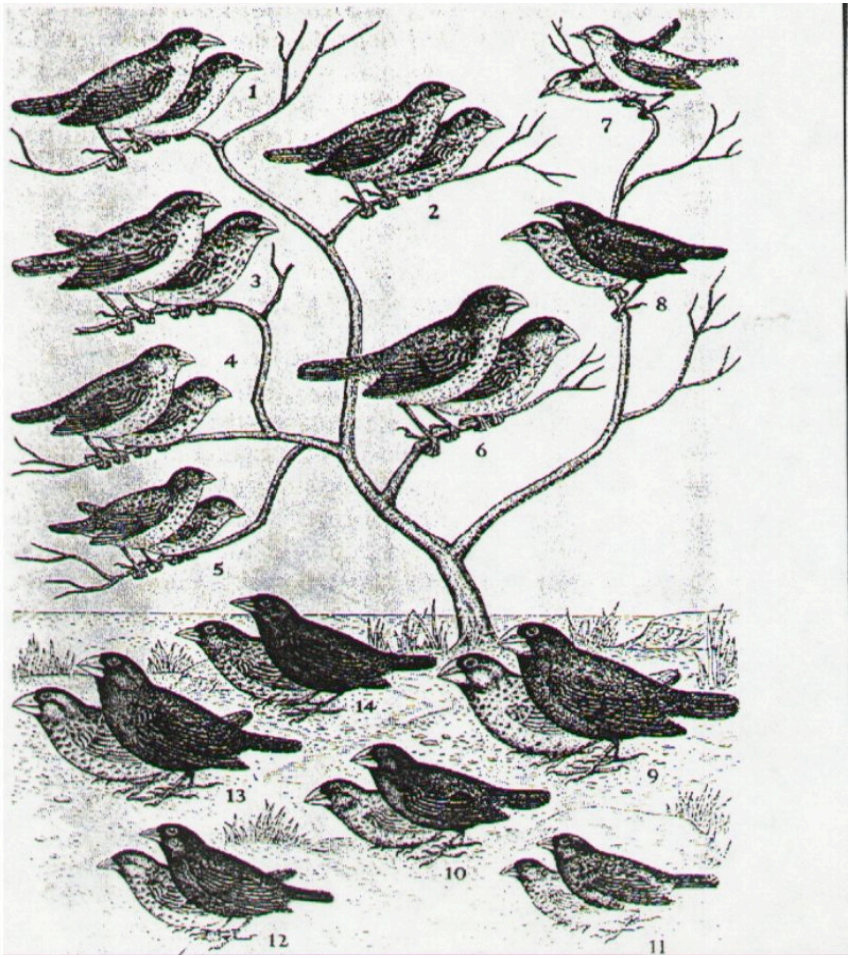
(b)

Figure 18.36. The fossil remains of some ancient multicellular organisms. (a) A Precambrian fossil of an annelid worm. (Courtesy of M. F. Glaessner.) (b) A fossil of a nearly complete trilobite. (From John S. Shelton, *Geology Illustrated*, W. H. Freeman, 1966.)

496

Darwin's Finches

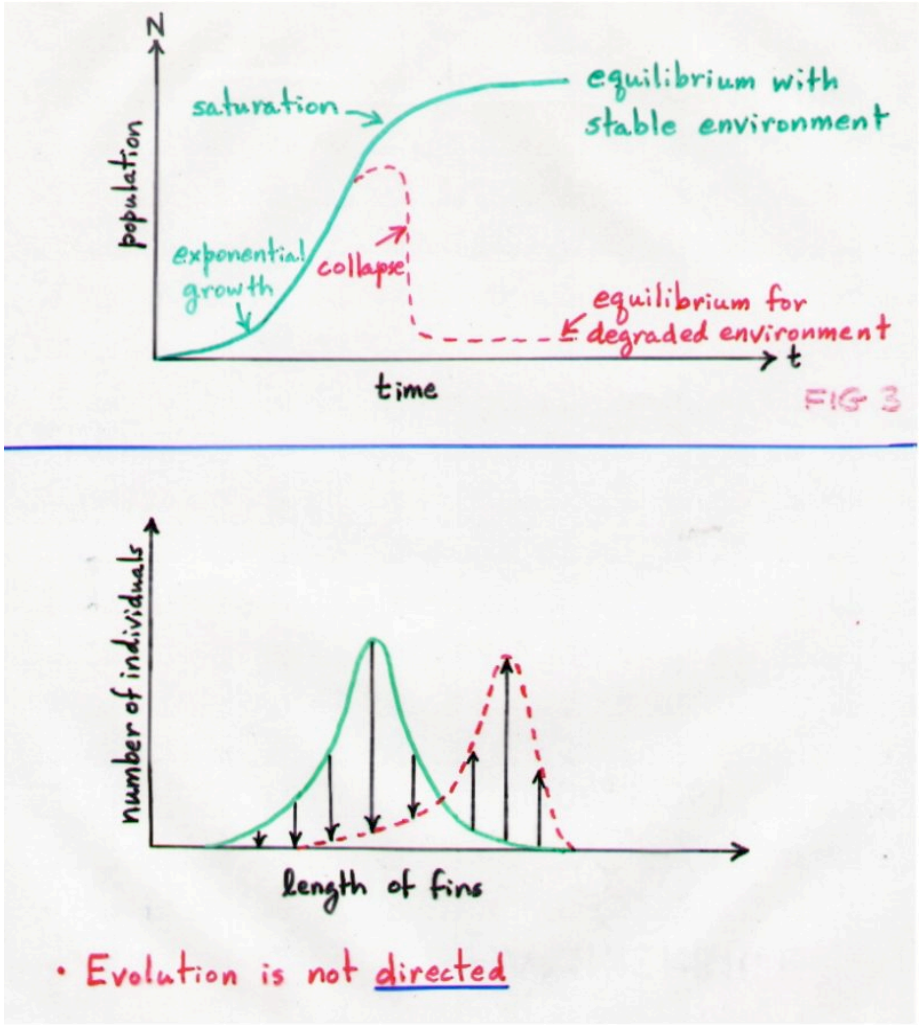
- Voyage of H. M. S. Beagle in 1831-1836
- Darwin signs on as naturalist (model for Doctor Maturin played by Paul Bettany in movie "Master and Commander")
- Brings aboard copies of Lyell's *Principles of Geology* and Malthus's *Essay on Population*
- On Galapagos Islands, find many varieties of tortoises and, especially, finches
- Surmises each variety has evolved from an original common form to adapt to local conditions of food sources on isolated islands: stout beaks to crack nuts or seeds, sharp beaks to drink nectar or peck for insects, etc.



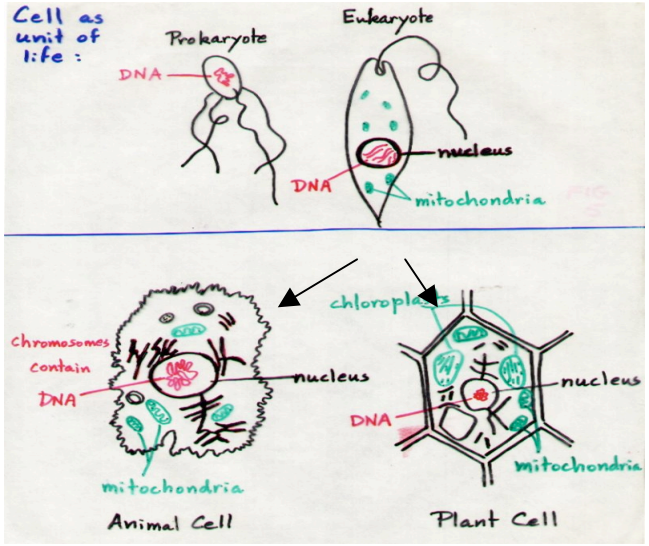
Scientific American

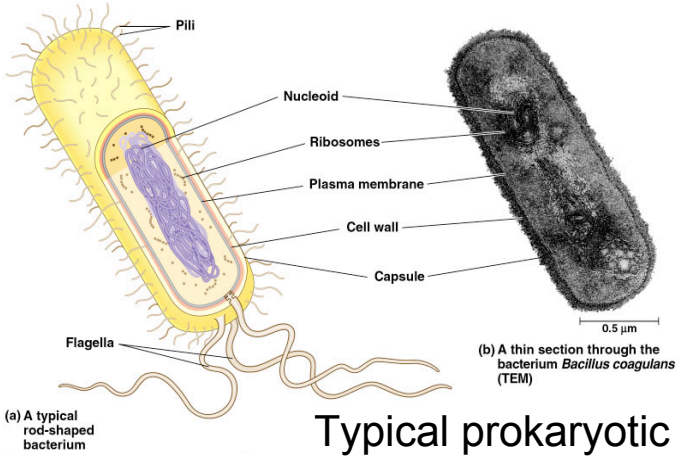
Pressure from Population Growth

- Adaptation is driven by environmental or population pressures.
- As competition for survival becomes fierce, those accidentally best adapted for the changing conditions preferentially survive and reproduce offsprings which are more likely to share the particular selective advantage ("survival of the fittest" = natural section).
- Over time, mean characteristics of species change = evolution.
- Example: how ocean creatures might have begun to colonize the land. *Evolution is not directed* toward this goal; it just happens through natural selection as ancient sea beds dry up because of continental drift and collisions.

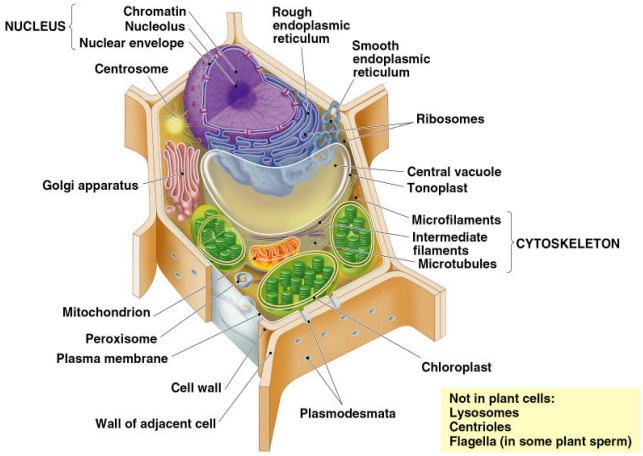


Cell as Unit of Life

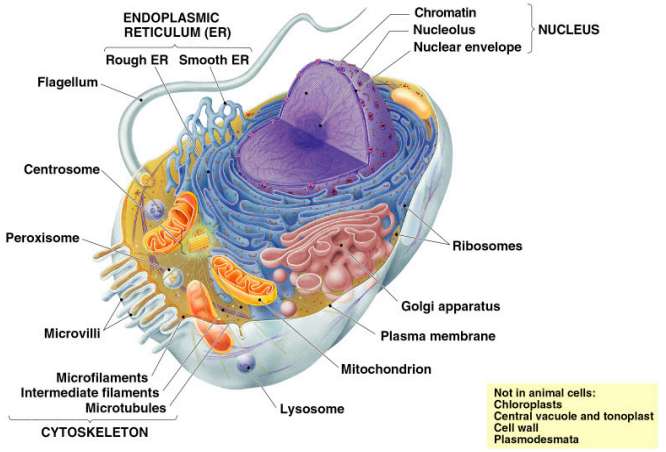




Typical prokaryotic cell



Typical plant cell

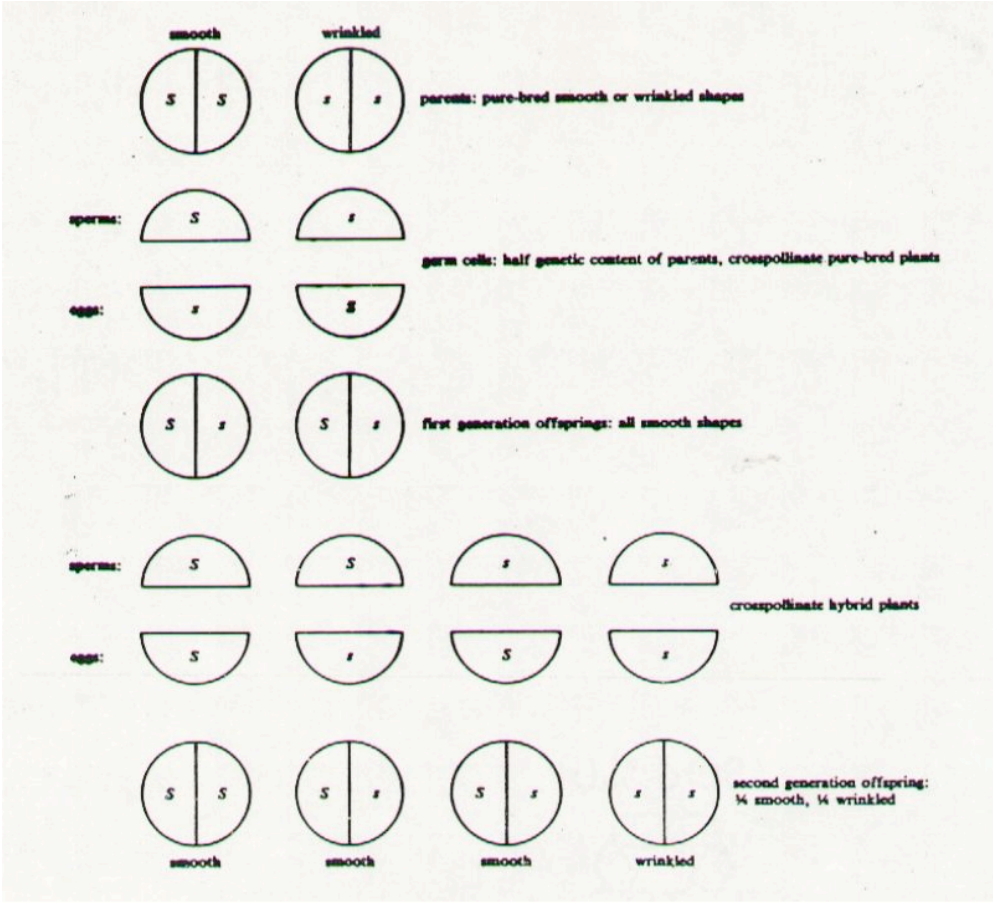


Typical animal cell

Gene as Unit of Heredity

Mendel's Experiments

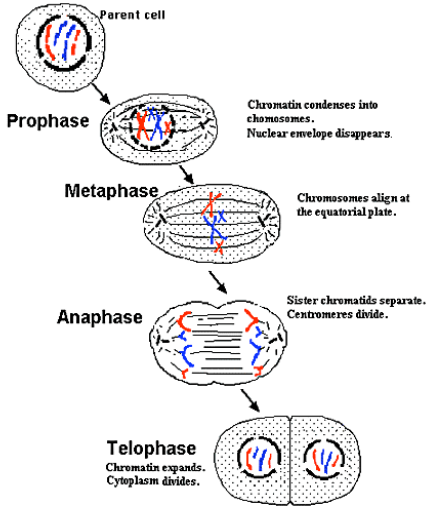
- Austrian monk who performed experiments on pea plants in 1857 to 1865
- Cross breed two varieties of pure-bred peas: smooth & wrinkled
  - First generation
    - All smooth
    - Suggests smooth dominant, wrinkled recessive
  - Second generation
    - 3/4 smooth, 1/4 wrinkled
    - Suggests model of paired genes



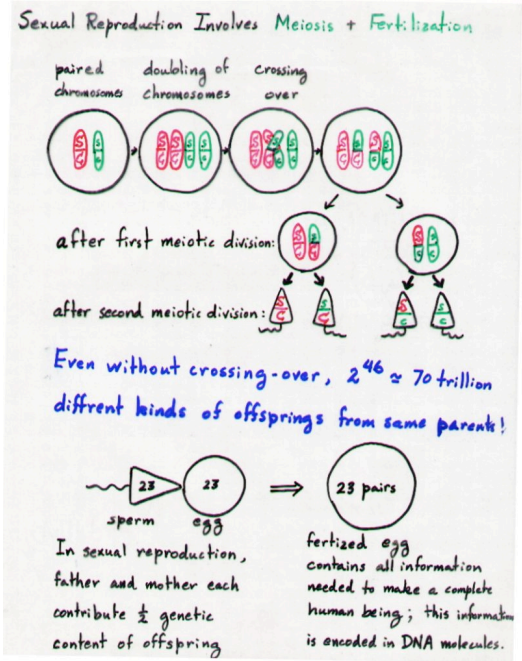
Should be true only statistically. Mendel's data set too small to yield results as precise as he claimed. A man of faith and reason, he may nevertheless have fudged his data partially to fit his theoretical model!

Growth & Reproduction

- Reproduction of simple unicellular organisms occurs by *mitosis* (simple cell division).
- Mitosis also underlies how cells of the human body (*somatic cells*) divide and reproduce.
- Growth in *multicellular organisms* → more cells, not individual cells getting larger.
- In 1879 Walther Flemming showed that genes of complex organisms are located on *paired chromosomes*, and in 1903 W. S. Sutton gave interpretation that justified Mendel's model on a cellular level:
  - Reproduction of complex organisms (unicellular and multicellular) occurs by *meiosis* (division into *germ cells – egg or sperm* in a *haploid state*, with a halving of *paired chromosomes*) – followed by the *fusion of germ cells* (*fertilization*) to give cells in a normal *diploid state*.
  - Cross-over during meiosis and fusion of haploid germ cells (sexual reproduction) add to variety of offsprings, which works to advantage of natural selection.



Mitosis



Meiosis

Germ Cells in Haploid State

Fertilization: Fusion of Germ Cells into Diploid State

Growth of Individual Cells

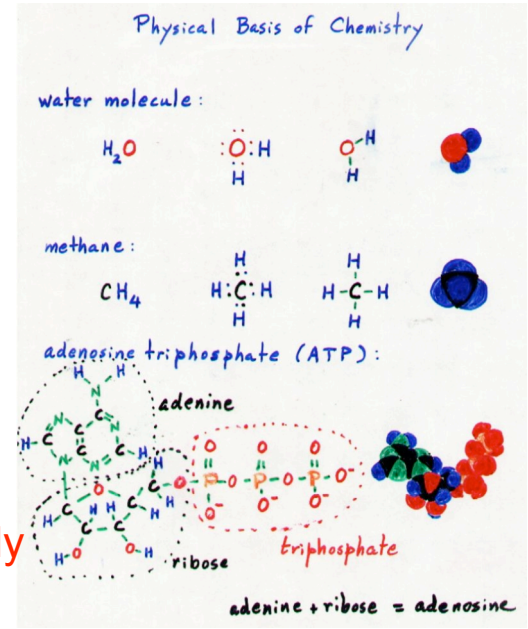
- A *cell is a chemical factory* which manufactures various compounds (lipids, carbohydrates, proteins, nucleic acids, etc.)
- Much of the manufacture involves assembling *small molecules into large ones (macromolecules): monomers → polymers*.
- Assembling amino acids into proteins and vice-versa is an especially important process. (Child eating Wheaties does not become Wheaties. Wheaties become child.)
- Blueprints for how to do this must be encoded in genes, but where are the genes located in a cell?
- In 1944, O. T. Avery shows that DNA introduced into pneumonia bacteria could alter the hereditary traits of progeny. Genes must be located in DNA.
- In 1953, Watson & Crick using the X-ray diffraction pictures taken by Rosalind Franklin and Maurice Wilkins show that DNA is a double helix.
- This discovery provided the crucial breakthrough for how cells grow and reproduce on a molecular level.
- The chemical factory has
  - designers with blueprints = DNA
  - workers = RNA
    - mRNA carries blueprint supplied by DNA
    - tRNA is assembly line worker
    - rRNA moves assembly line and provides scaffolding
- The RNA link small molecules called *amino acids into long chains called proteins*, which serve structural and other purposes.
- *Central dogma*: DNA → RNA → proteins (with a few exceptions).
- At temperatures not harmful to the cell, chemical reactions would proceed too slowly to be useful physiologically. To speed up chemical reactions, cells use *proteins as enzymes*.
- Many reactions of a cell have to be driven "uphill," requiring energy input to proceed. The *universal energy currency* of all cells is ATP.
- ATP is manufactured ultimately from *fermenting (without oxygen) or burning (with oxygen) glucose*, a simple sugar (monomer for carbohydrates).

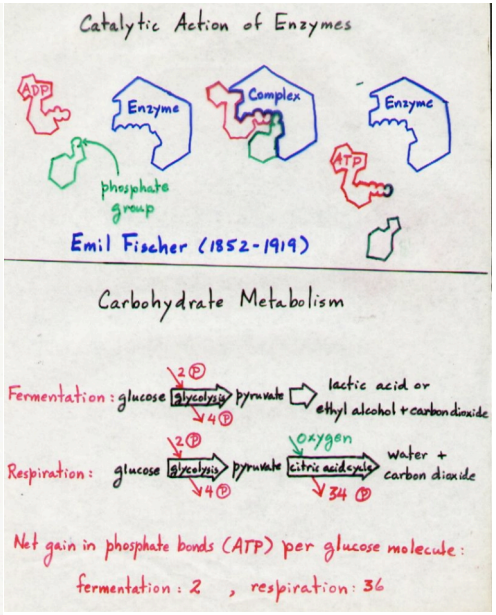
ATP and Catalytic Synthesis by Enzymes

Big molecules are made by sticking together small molecules.

Energy in ATP is contained in repulsion of PO_4^- groups, which become negatively charged when placed in water.

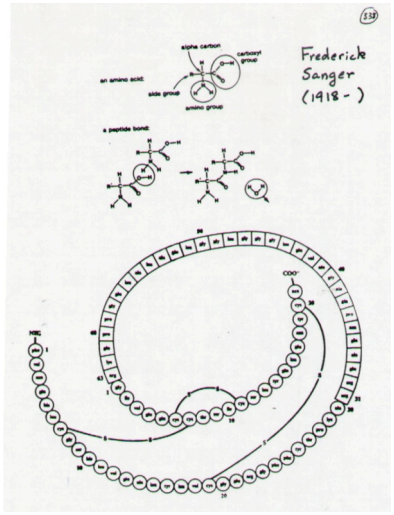
A protein is a linear chain of monomers (amino acids) strung together in a non-repeating polymer (polypeptide).

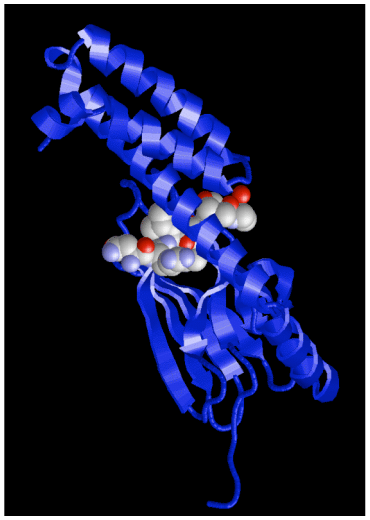




Short-range nature of chemical forces involving (nearly) neutral molecules requires "lock and key" relationship for enzymes to act as catalysts.

Energy-rich phosphate bonds in ATP are obtained in net by consuming carbohydrates with or without the presence of O.

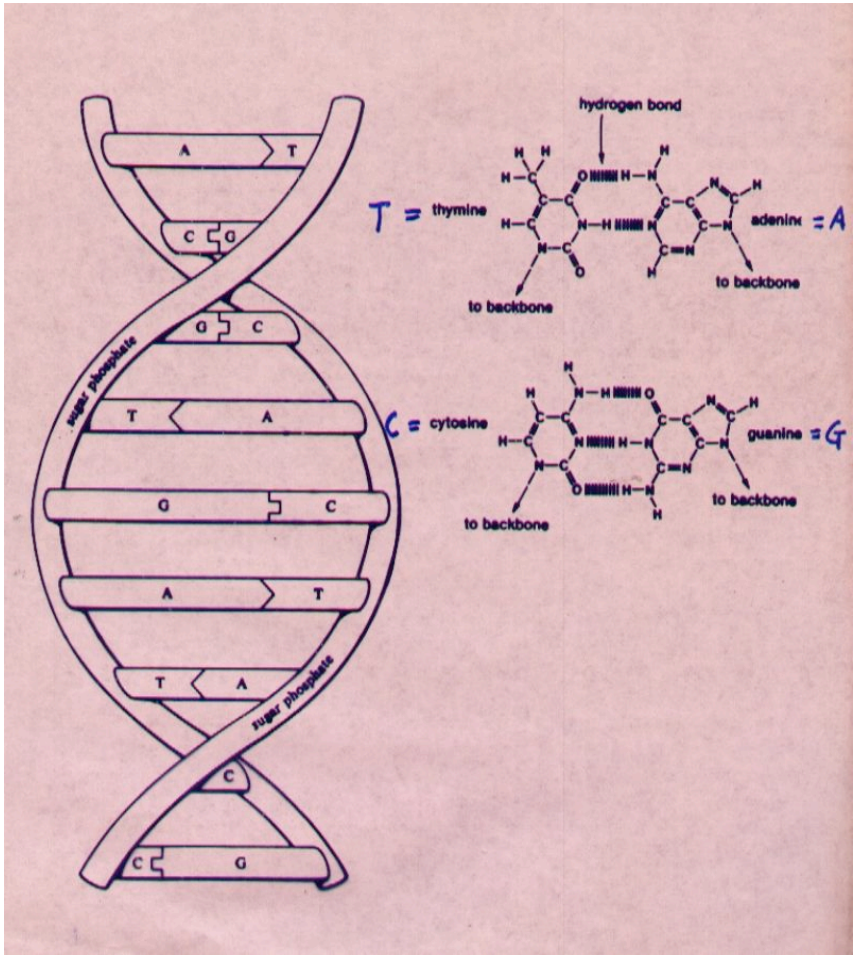




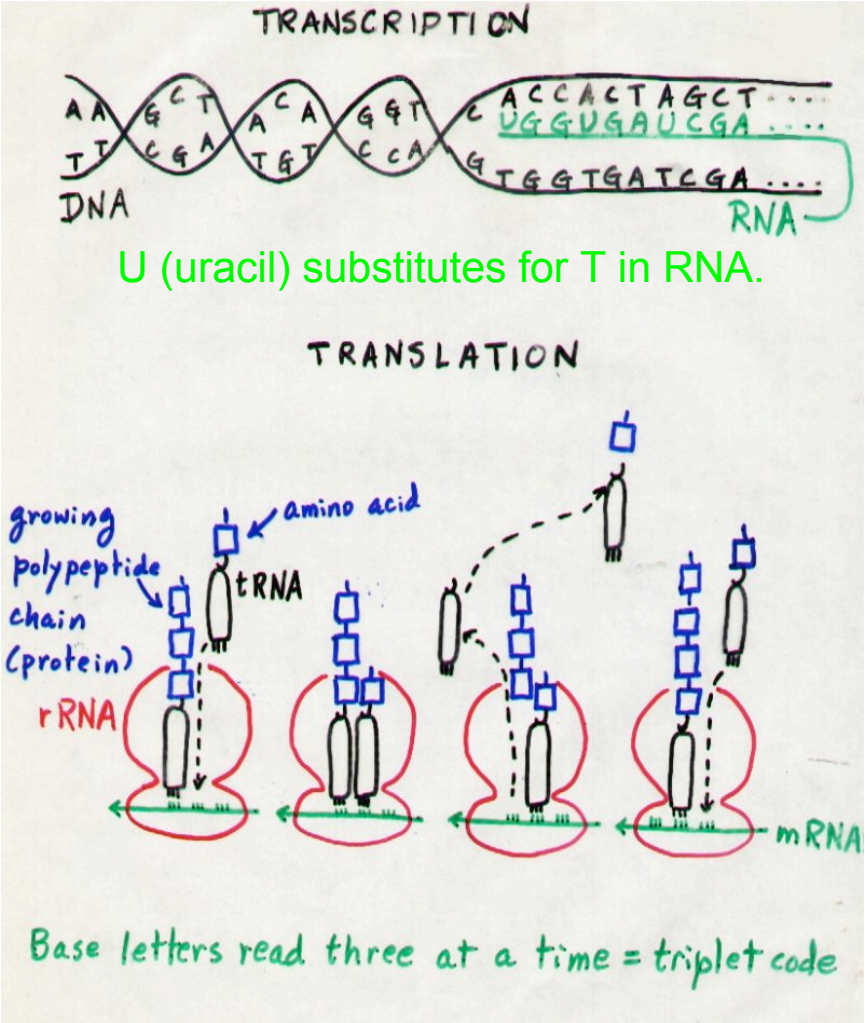
To achieve near-minimum energy states at the low temperatures inside cells, the linear sequences that are proteins fold into complex 3-D shapes. These shapes give enzymes their "lock and key" function as catalysts. How proteins fold is forefront research problem today in biophysics.

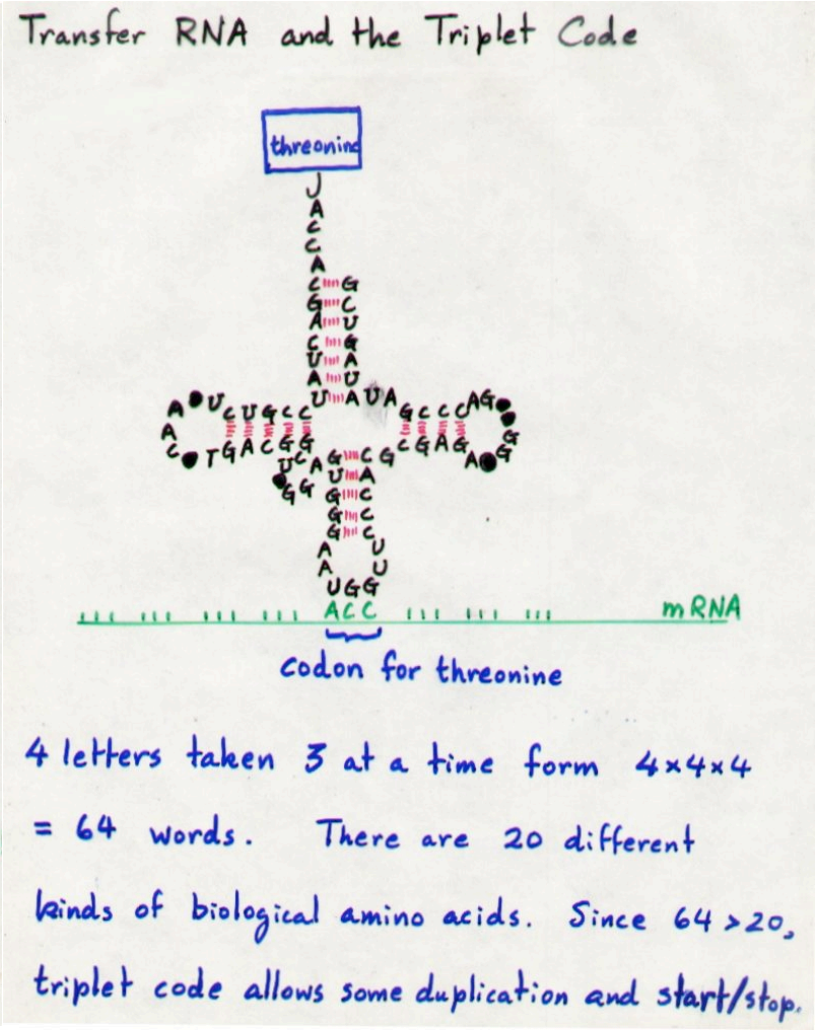
Watson and Crick: DNA as Double Helix with Specific Base Pairings

- Backbone is a spiral staircase of sugar-phosphates (things like ATP, CTP, GTP, or TTP).
- Steps of this twisted ladder are “base pairs,” A with T and G with C (Chargaff’s rule).
- The pairing occurs by hydrogen bonds (the ability of H to bind with more than one atom at a time), which gives “A with T and G and C. “
- A-T is of the same length as G-C, which energetically favors these combinations in the double helix of DNA.

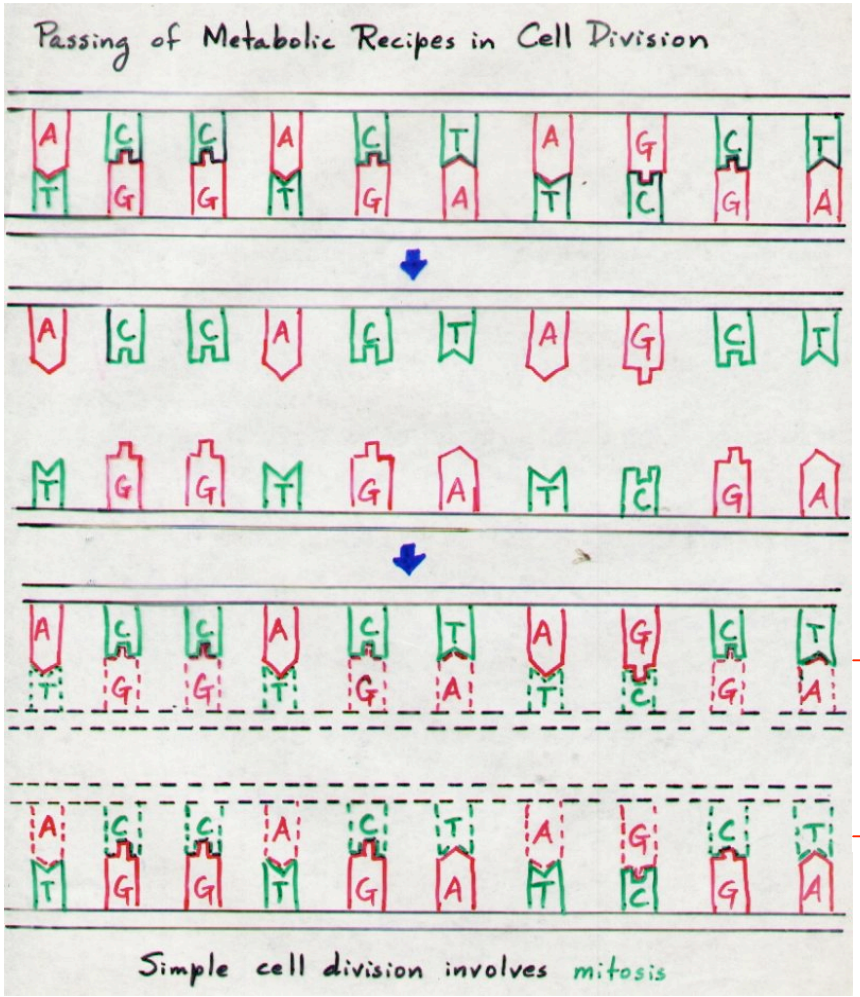


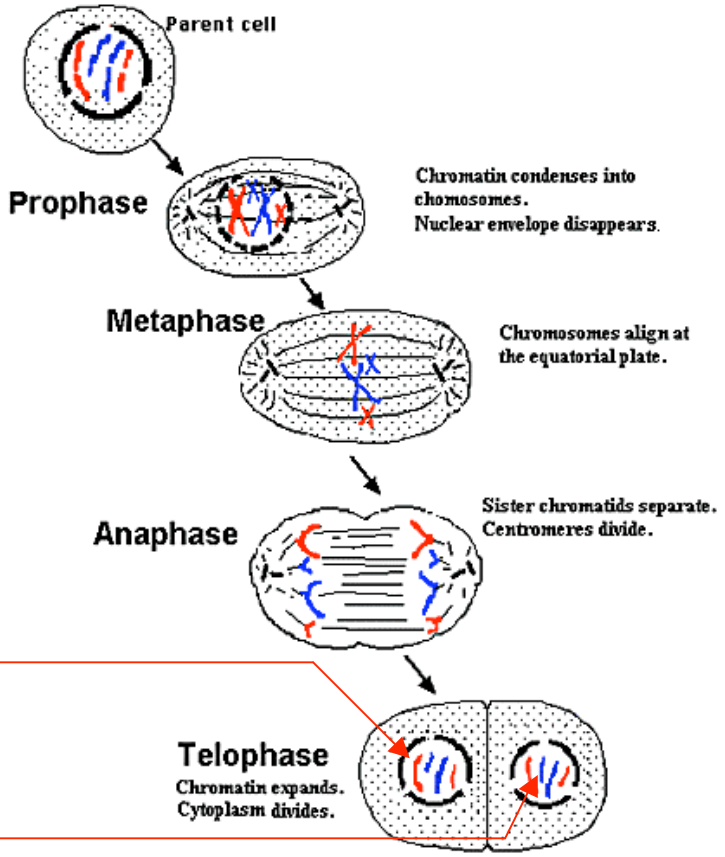
DNA Encodes "Three Letters at a Time" the Recipes in mRNA for Protein Synthesis





Replication of DNA During Mitosis

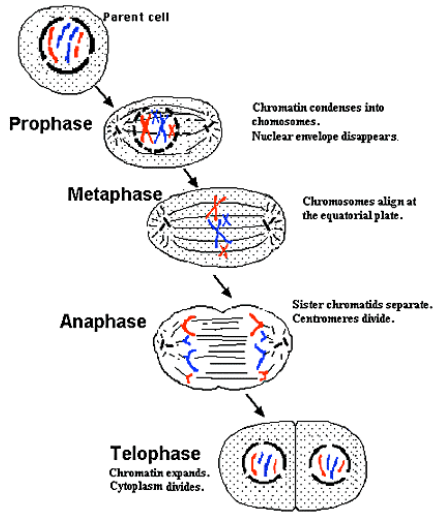




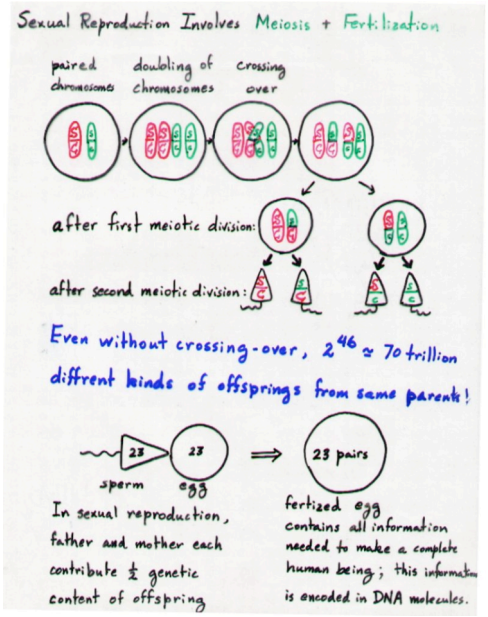
Mitosis: same blueprints or recipes are passed to both daughter cells.

Reprise: Growth & Reproduction

- Reproduction of simple unicellular organisms occurs by *mitosis* (simple cell division).
- Mitosis also underlies how cells of the human body (*somatic cells*) divide and reproduce.
- Growth in *multicellular organisms* → more cells, not individual cells getting larger.
- Genes of complex organisms are located on *paired chromosomes,* thereby justifying Mendel's model on a cellular level.
- Reproduction of complex organisms (unicellular and multicellular) occurs by *meiosis* (division into *germ cells – egg or sperm* in a *haploid state*, with a halving of *paired chromosomes*) – followed by the *fusion of germ cells* (*fertilization*) to give cells in a normal *diploid state*.
- Cross-over during meiosis and fusion of haploid germ cells (sexual reproduction) add to variety of offsprings, which works to advantage of natural selection.



Mitosis



Meiosis

Germ Cells in Haploid State

Fertilization: Fusion of Germ Cells into Diploid State

Cell Differentiation & Complex Organisms

- *Fertilization* of egg by sperm produces an *embryo*.
- In the further development of a complex organism, the embryo produces different kinds of cells (such as *embryonic stem cells*), which divide and *differentiate into more specialized forms*.
- Different cells combine to form *tissues*, different tissues combine to form *organs*, different organs combine to form *organ systems*, different organ systems combine to form the *organism*.
- Through natural selection, *populations* of different organisms come *under environmental stress*, *adapt or become extinct, and evolve into new species*.

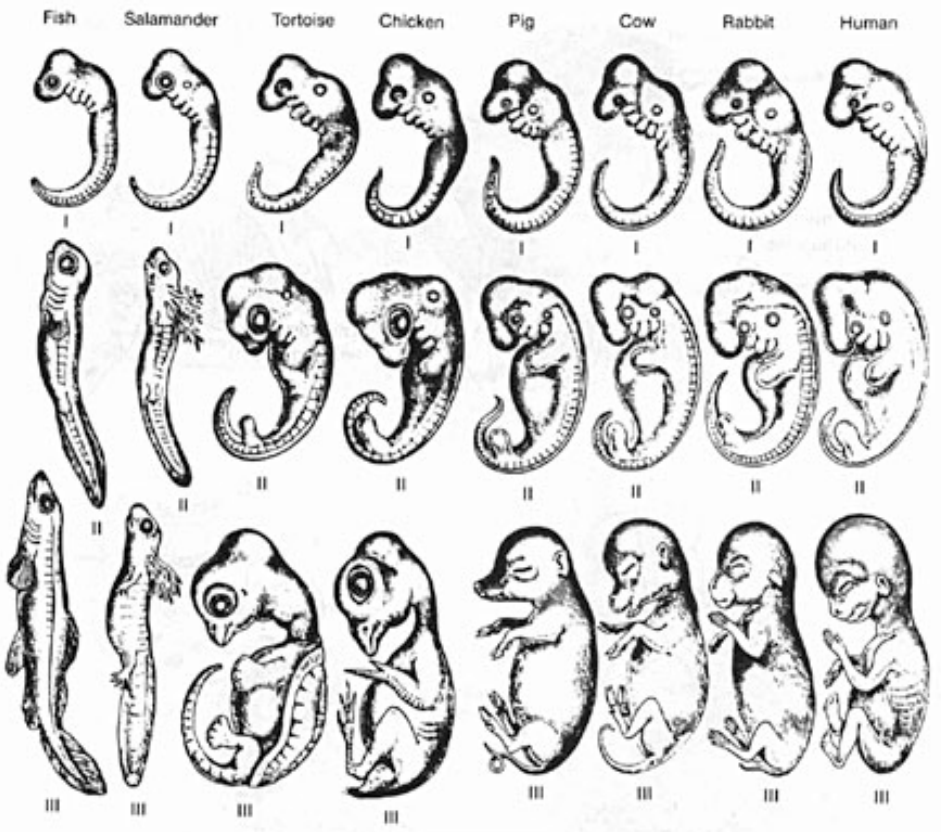


Figure 3–10

A series of embryos of different vertebrates at comparable stages of development. The earlier the stage of development, the more strikingly similar are the different groups. Note that each of the embryos begins with a similar number of gill arches (pouches below the head) and a similar vertebral column. In later stages of development, these and other structures are modified to yield the various different forms. (The embryos in the different groups have been scaled to the same approximate size so that comparisons can be made between them.) (From Romanes, adapted from Haeckel.)

Charles Darwin: “The Origin of Species” and the Tree of Life

“It is interesting to contemplate an entangled bank, clothed with many plants of many kinds, with birds singing on the bushes, with various insects flitting about, and with many worms crawling through the damp earth, and to reflect that these elaborately constructed forms, so different from each other, and dependent on each other in so complex a manner, have all been produced by laws acting around us. These laws, taken in the largest sense, being Growth and Reproduction; Inheritance, which is almost implied by Reproduction; Variability, from the direct and indirect external conditions of life, and from use and disuse; a Ratio of Increase so high as to lead to a Struggle for Life; and as a consequence to natural selection, entailing a Divergence of Character and the Extinction of less improved forms. 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 into a few forms, or into one; and that while this earth has gone cycling according to the fixed laws of gravity, from so simple a beginning, endless forms, most beautiful and wonderful, have been, and are being, evolved.”