Thinking about Thought

- Introduction
- Philosophy of Mind
- Cognitive Models
- Machine Intelligence
- Life and Organization
- Ecology
- The Brain
- Dreams and Emotions
- Language
- Modern Physics
- Consciousness

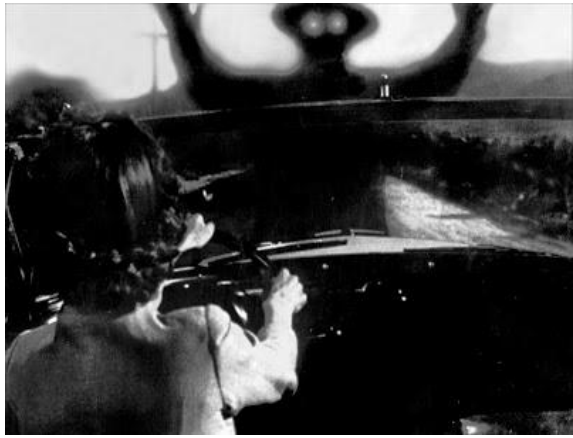
We are born naked, wet and hungry.
Then things get worse.
('One-liner' signature file found on the Internet)

Session Four:
Life and Organization

for Piero Scaruffi's class
"Thinking about Thought"
at UC Berkeley (2014)

- Roughly These Chapters of My Book "Nature of Consciousness":
  - 12. The Evolution Of Life: Of Designers And Designs
  - 13. The Physics Of Life

How will extraterrestrial life look like?
How will we recognize it as “life”?



Christian Nyby: The Thing From Another World (1951)
Edgar Ulmer: The Man from Planet X (1951)
Jack Arnold: It Came From Outer Space (1953)

Steven Spielberg: Close Encounters of the Third Kind (1977)
Steven Spielberg: E.T. (1982)
Tim Burton: Mars Attacks (1996)

The Fermi Paradox

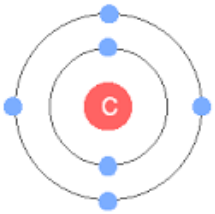
- Given the probability of exoplanets, the probability of life, the probability of sentient beings, the probability of high technology, etc, the Earth must have been visited many times by aliens
- "Where is everybody?" (Enrico Fermi, 1950)
- Giuseppe Cocconi and Philip Morrison: "Searching for Interstellar Communications“ (Nature, 1959)
- First Search for ExtraTerrestrial Intelligence (SETI) meeting (West Virginia, 1961)
- Frank Drake’s equation (1961): number of civilizations in our galaxy with which radio-communication shouldbe possible

$$N = R_* \cdot f_p \cdot n_e \cdot f_\ell \cdot f_i \cdot f_c \cdot L$$

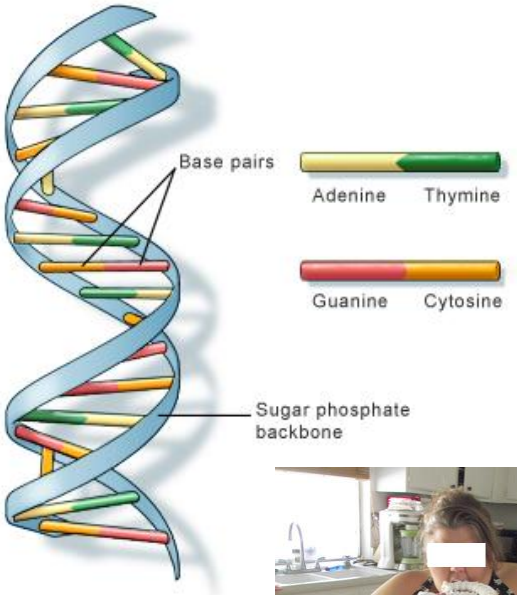
Unknown: $\cdot f_\ell \cdot f_i \cdot f_c \cdot L$

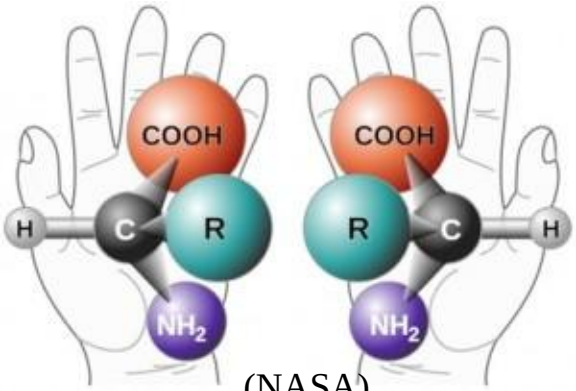
Life on Earth

- Carbon
- Left-handed
- DNA
- Reproduction
- Metabolism
- Homeostasis



A carbon atom has four electrons that can combine with other atoms, usually H, O, N

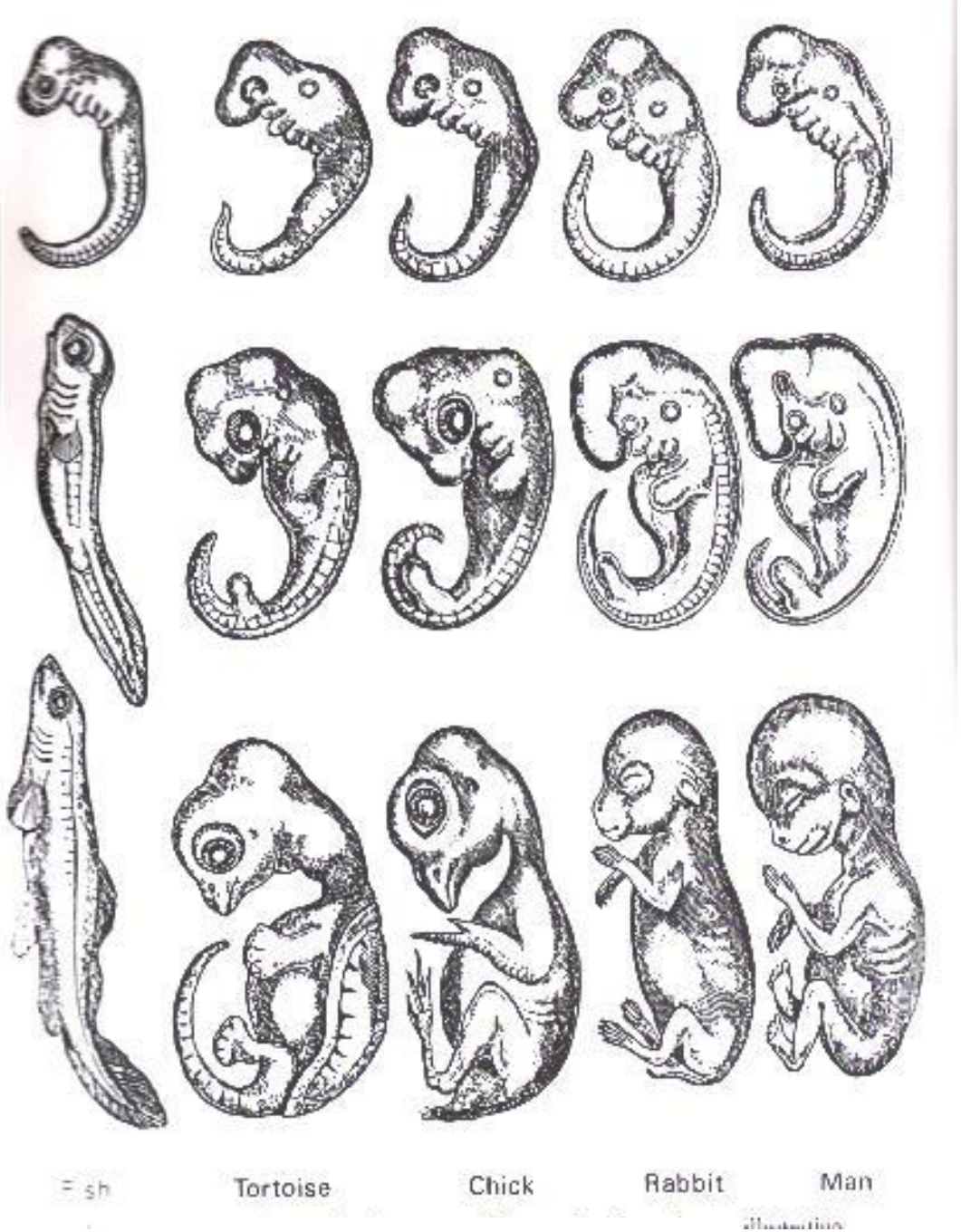




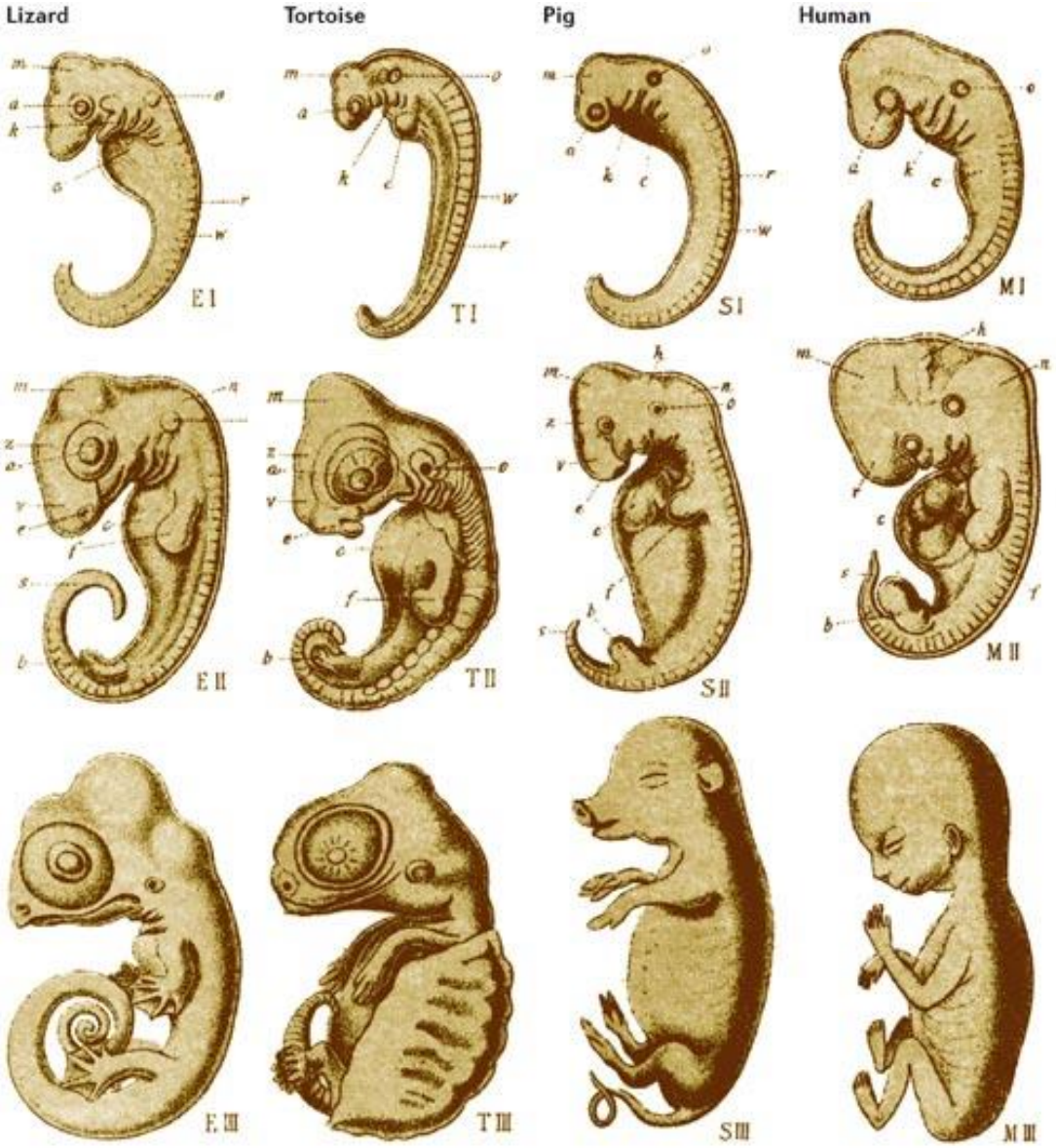
(NASA)

Human Life

Embryo’s development



Embryo’s development



Embryo's development

Life

- Only living beings can think
- Life is a natural phenomenon
- Life is governed by natural laws which differ from the natural laws of physics

Definition of life

- What is the difference between organic and inorganic matter?
- Living beings grow
- Living beings reproduce
- Living beings maintain their identity
- Replication + Metabolism + Homeostasis + …

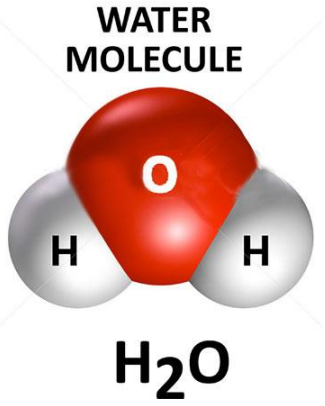
Definition of life

- Richard Dawkins:
  - Living beings have to work to keep from eventually merging into their surroundings
  - There is a natural tendency towards merging seamlessly with the rest of nature.
  - We have to work in order to maintain our identity.
  - When we stop working, we die: then we merge with our surroundings.
  - Living beings are never in equilibrium with their surroundings, unless they are dead

Definition of life

- Thought experiment
  - Aliens who speak and feel emotions but do not need to eat or go to the restrooms, and never change shape
  - They are born adults and they die adults
  - They do not even reproduce: they are born out of a mineral
  - Their cells do not contain genetic material
  - They do not make children
  - Would that still be “life”?

Definition of life



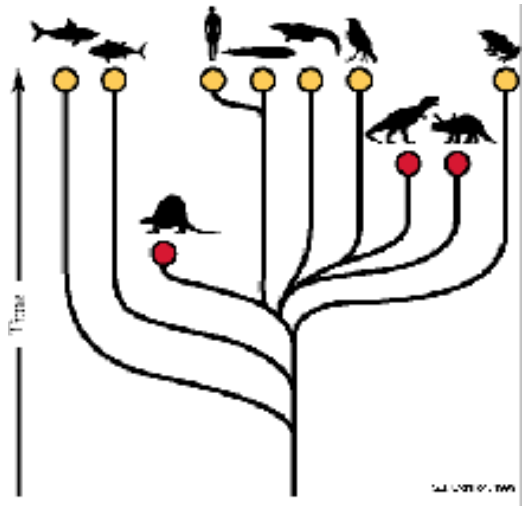
- What is life made of?
  - All living systems are made of the same fundamental constituents
  - These molecules cannot move and cannot grow
  - Still, when they are combined in systems, they grow and move.
  - New properties emerge.
  - The first new property is the ability to self-assemble
  - Eventually we get cells, tissues, organs, bodies, societies…

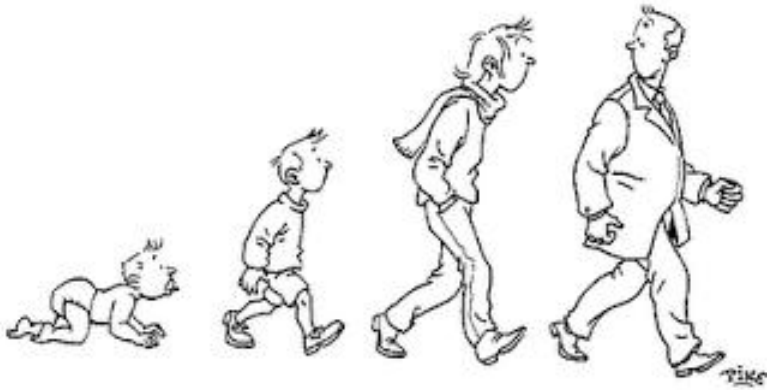
Definition of life

- Descartes
  - Animals are just machines
- La Mettrie
  - Humans are machines too

Definition of life

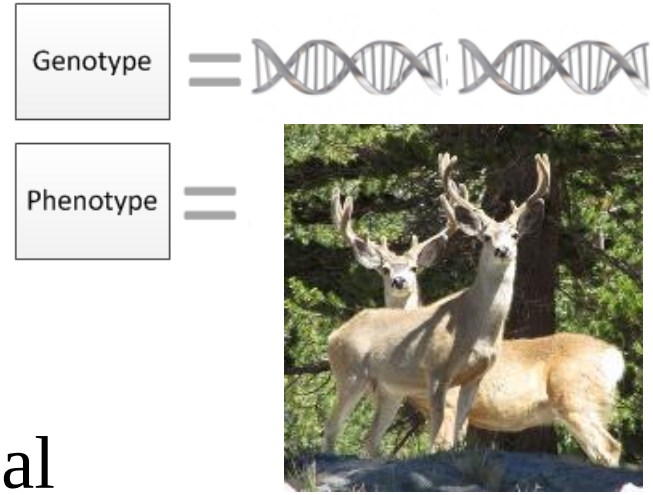
- Life occurs at three levels:
  - Phylogenetic: organisms evolve into other organisms
  - Ontogenetic: each organism changes (or grows) from birth till death
  - Epigenetic: the behavior of each organism changes during its lifetime (the organism “learns”)





Definition of life

- Life as information
  - Information that survives from one individual to another ("genotype")
  - Information about the individual ("phenotype")
  - When we say that "ants are alive" (vs stones) and "I am alive" (vs someone who is dead) we mean two different things



A brief history of Genetics

- 1859: Charles Darwin's theory of evolution
- 1865: Gregor Mendel's genes
- 1920s: Population Genetics (probabilities)
- 1940s: Modern Synthesis (variation=mutation)
- 1944: Oswald Avery discovers genes are made of DNA
- 1953: Francis Crick and James Watson discover the double helix of DNA
- 1961: Marshall Nirenberg and Heinrich Matthaei discover how the 4-letter genetic code gets translated into the 20-letter language of proteins
- 1965: Robert Holley discovers transfer RNA

Design Without a Designer

"This year was not marked by any of those striking discoveries which at once revolutionise science"

(Thomas Bell, president of the Linnean Society of London, summarizing the year 1858, the year in which Darwin had presented his theory of evolution to the Society)

Design Without a Designer

~~**DARWIN'S THEORY IS ABOUT SURVIVAL OF THE FITTEST**~~

DARWIN'S THEORY IS ABOUT DESIGN

Design Without a Designer

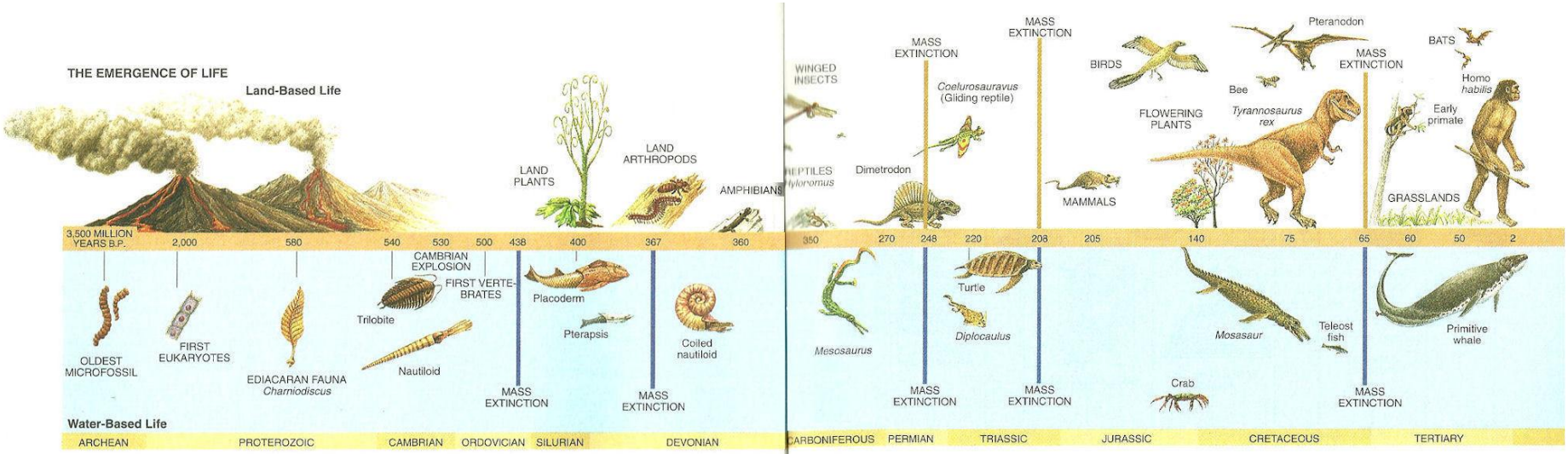
Charles Darwin (1858)

- Evolution=variation+selection
  - Variation is ubiquitous
  - Natural selection is the driving force of evolution
  - New species are created by the action of natural selection on variation
- Adaptation
  - New species are caused by the need to adapt to environmental changes
- Competition

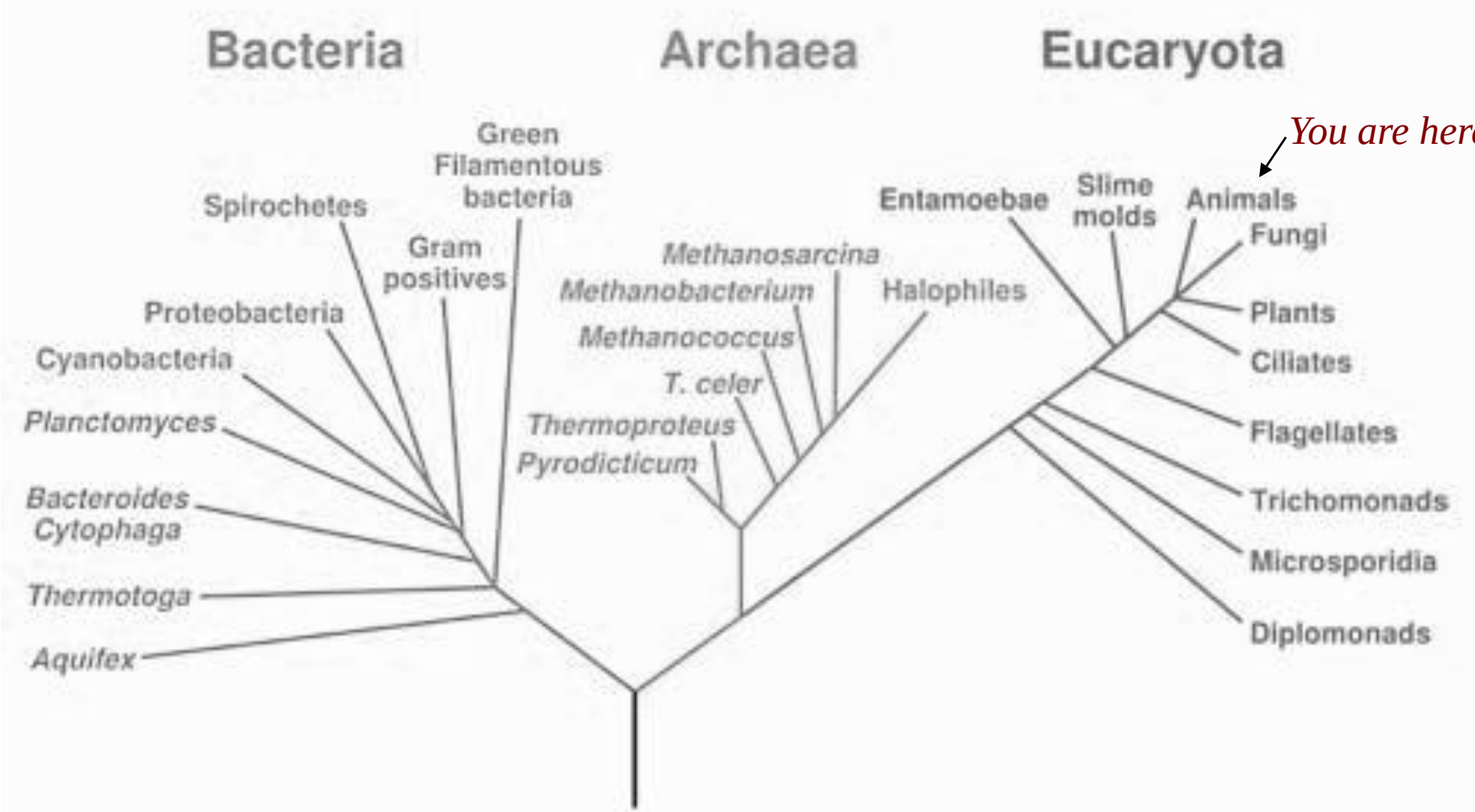
Design Without a Designer

Charles Darwin

- Evolution is the result of inherited differences that occur between one generation and the next
- All living beings are the descendants of a simple primeval form of life
- The diversity of life and extinct species are explained by evolution



Phylogenetic Tree of Life



Design Without a Designer

Charles Darwin

- Mystery of variation, that appears to be random
- Variation can only be treated as a statistical quantity and described statistically
- Populations, not individuals

Design Without a Designer

Charles Darwin

- Darwin's theory was three theories in one
  - A theory of natural selection (the environment selects species)
  - A theory of heredity (wrong - later replaced by Mendel's)
  - A theory of variation (randomness)

Design Without a Designer

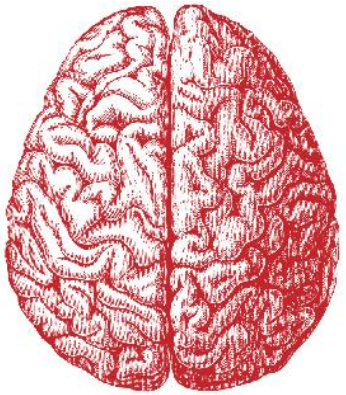
Charles Darwin

- Natural selection AND Sexual selection (competition for survival AND competition for reproduction)
- Sexual selection: males compete for females, females choose males
- Males were the first artists/musicians, females were the first art/music critics

Design Without a Designer

- Designing by trial and error
  - The offspring is never an exact copy of the parents
  - The environment (e.g., natural selection) indirectly “selects” which variations (which individuals) survive
  - Nobody programs the changes in the species
  - Design emerges spontaneously
  - Selection = environment
  - Variation = randomness

Design Without a Designer



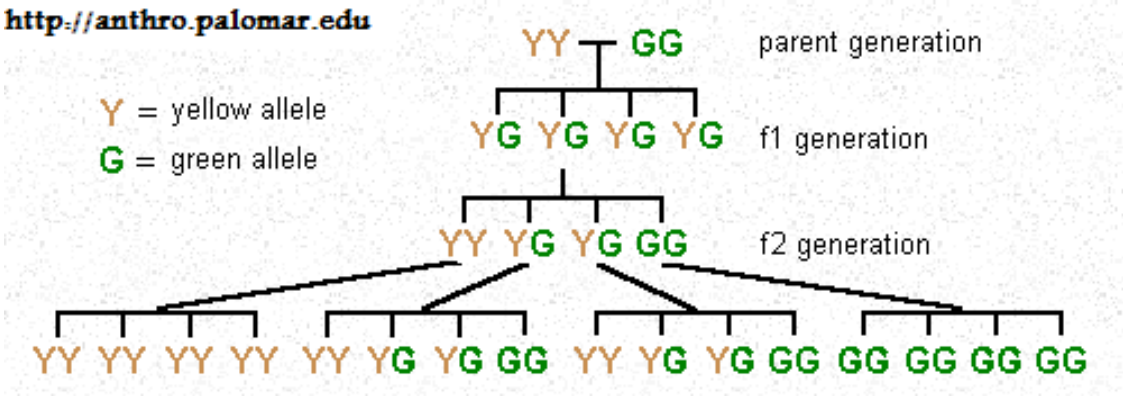
- Designing by trial and error
  - The environment (e.g., natural selection) indirectly "selects" which variations (which connections) survive
  - Nobody programs the changes in the connections
  - Design emerges spontaneously
  - Selection = environment
  - Variation = randomness

Design Without a Designer

- Designing by trial and error
  - Natural selection has never produced a clock or even a wheel; but it has produced eyes and brains
  - Humans can easily manufacture clocks, but not eyes or brains
  - Very complex design can emerge spontaneously via an algorithmic process

Design Without a Designer

- Gregor Mendel (1865)
  - Traits are inherited as units, not as "blends“
  - Each trait is represented by a "unit" of transmission, by a "gene“
  - Traits are passed on to the offspring in a completely random manner: any offspring can have any combination of the traits of the parents.
  - There is a unit of inheritance, later named “gene”



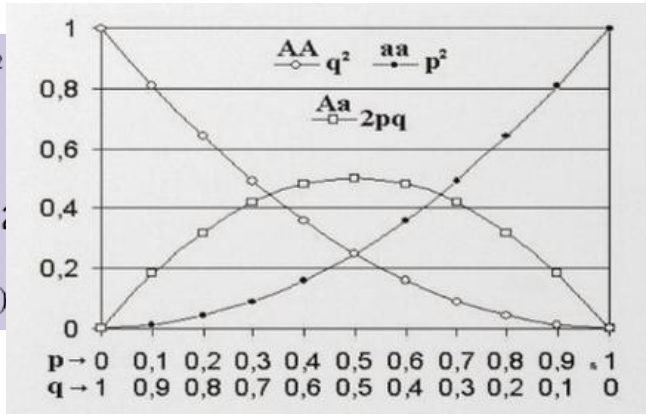
Design Without a Designer

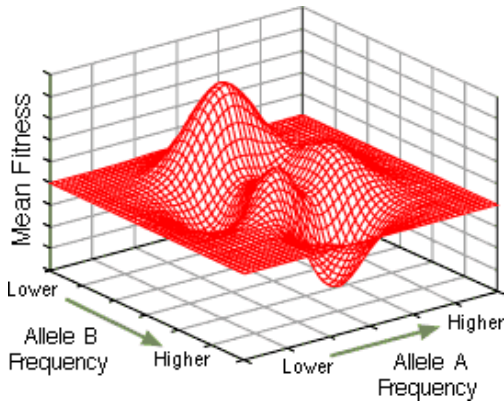
- Sewall Wright and Ronald Fisher: population genetics (1920s)
  - Darwinism turned into a stochastic theory
  - Evolution = a shift in gene frequencies within a population over time
  - Unification of Darwin and Mendel

Frequency of A_1/A_1: $u''=(u'+\frac{1}{2}v')^2 = (p_1^2+p_1p_2)^2$

Frequency of A_1/A_2: $v''= 2(u'+\frac{1}{2}v')(\frac{1}{2}v'+w')$
$= 2(p_1^2+p_1p_2)(p_2^2+p_1p_2)=$

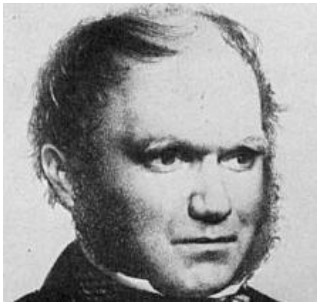
Frequency of A_2/A_2: $w''=(\frac{1}{2}v'+w')^2 = (p_2^2 + p_1p_2)$





Design Without a Designer

- "Modern synthesis" (1940s)
  - The synthetic theory of evolution merged a theory of inheritance (Mendel's genetics) and a theory of species (Darwin's evolutionary biology)



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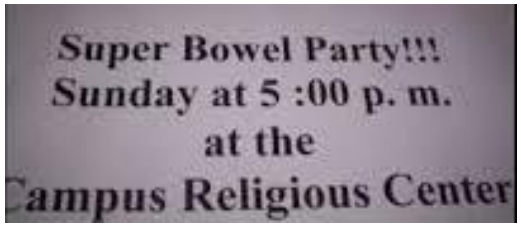
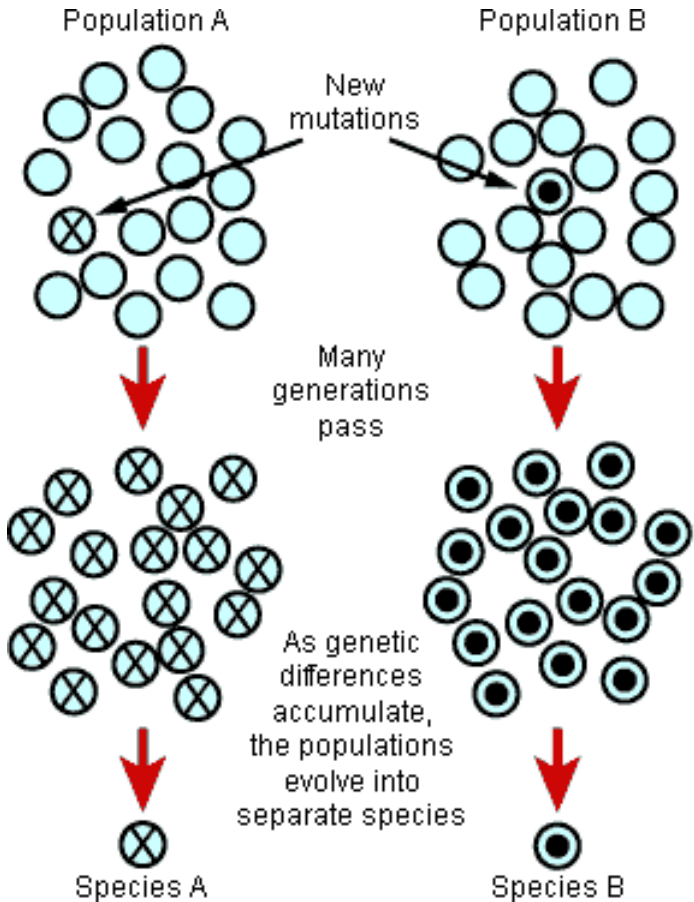
Design Without a Designer

- "Modern synthesis" (1940s)
  - Variation is due to mutation: when copying genes, nature is prone to making typographical errors that yield variation in a population



Design Without a Designer

- "Modern synthesis"
  - Theodosius Dobzhansky (1937): what makes a species a species is sex

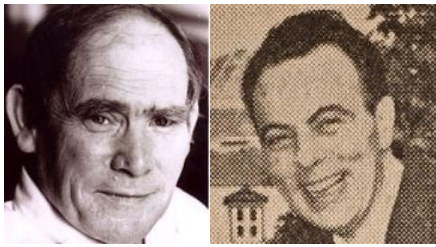


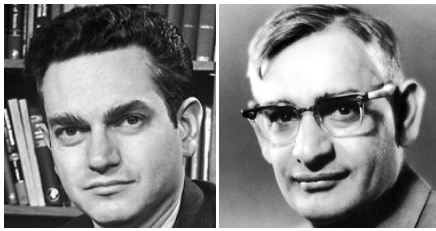
Design Without a Designer

- Oswald Avery (1944) identifies the the substance that genes are made of, the bearer of genetic information: the deoxyribonucleic acid (DNA)
- Francis Crick and James Watson (1953) discover the double-helix structure of the DNA molecule
- Genetic information is encoded in a mathematical form, the “genetic code”
- DNA is made of four kinds of nucleotides, proteins are made of twenty types of aminoacids
- Francis Crick (1957) concludes that information must flow only from the nucleid acids to proteins, never the other way around.

Design Without a Designer

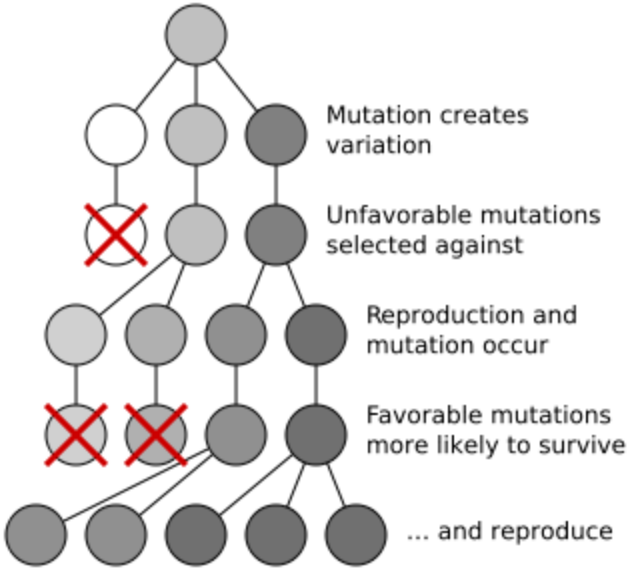
- Sydney Brenner and Francois Jacob (1961) discover that cells of ribonucleic acid (messenger RNA) carry the genetic instructions from the DNA to the ribosomes, the sites within a cell that manufacture proteins.
- Francois Jacob and Jacques Monod (1961) discover the mechanism of gene regulation: genes are organized in a network.
- Marshall Nirenberg and Har Gobind Khorana (1961) crack the "genetic code“: how the 4-letter language of DNA is translated into the 20-letter language of proteins
- Robert Holley discovers transfer RNA (1965), that mediates the translation of the RNA alphabet into the protein alphabet





Design Without a Designer

- Evolution as pattern theory
  - Reproduction. Copies are made of the pattern.
  - Variation. Random errors appear in the copies and yield variants.
  - Selection. The environment selects which variants survive.
- Each generation copes better with the environment.
- Other factors may accelerate evolution: sex, learning, …?



Origins

- The birth of the first cell is just statistically impossible
- Graham Cairns-Smith calculated the probability of all the events required to create a DNA molecule and concluded that there wasn’t enough matter or time in the universe to achieve it

Origins

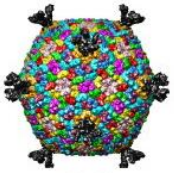

- Primordial Soup (Stanley Miller, 1953)
- Panspermia (Svante Arrhenius, 1903 - John Oro, 1961)


- Autocatalytic Loop (Manfred Eigen, 1971)
- Chance (Jacques Monod, 1971)
- Crystals (Graham Cairns-Smith, 1982)
- Thermosynthesis (Anthonie Muller, 1983)
- Surface Metabolism (Gunter Waechtershauser, 1988)


- Necessity (Harold Morowitz, 1992)
- Self-organization (Stuart Kauffman, 1993)
- CHNOPS (Christian DeDuve, 1995)
- Heat bath (Jeremy England, 2013)


Origins

1. An organism became capable of generating another organism of the same type
2. Two organisms engaged in sexual reproduction to generate an organism of the same type
3. Organisms became complex assemblies of cells
4. Some of those cells developed into specialized organs
5. A central nervous system developed to direct the organs
6. Mind and consciousness appeared
7. (Next?)



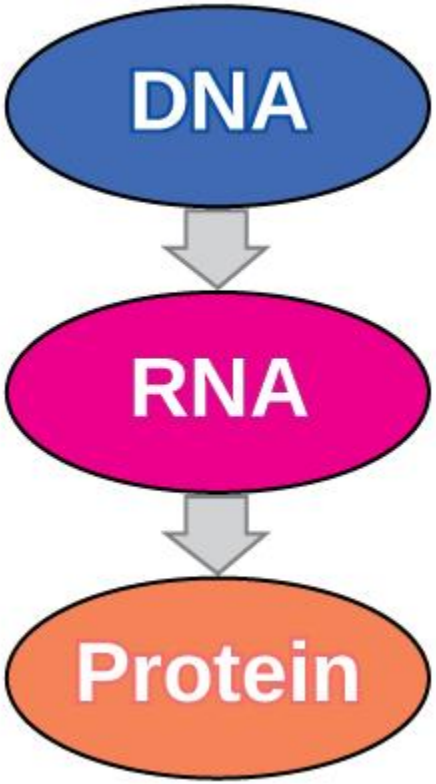
Origins

Louis Pasteur (19th century)

- Living systems prefer molecules with a certain handedness (all proteins are made of L-aminoacids and genetic material is made of D-sugars)
- This molecular asymmetry is the only difference between the chemistry of living and of inanimate matter

Chemistry of Life

- The “central dogma”

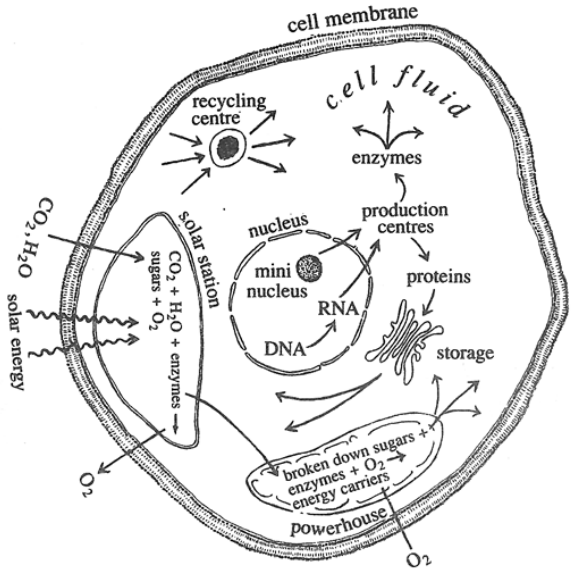


Chemistry of Life

- The genetic code
  - An organism is a set of cells
  - Every cell of an individual contains the DNA molecule for that individual, or its "genome“
  - Bodies are made of proteins
  - A protein is made of aminoacids
  - There are 20 kinds of aminoacids

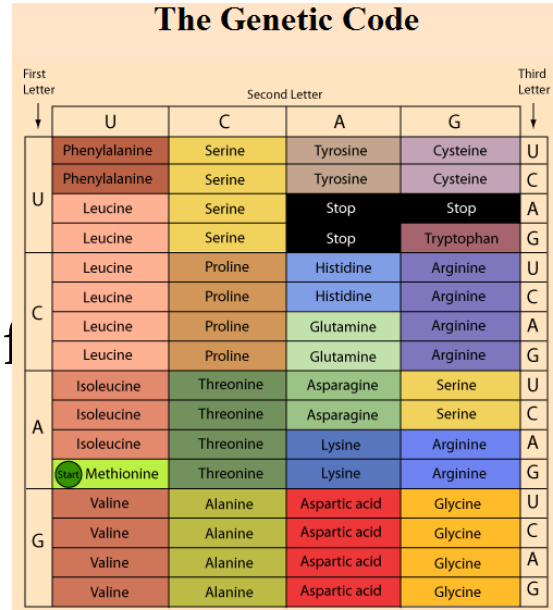
Chemistry of Life

- The genetic code
  - From genes to aminoacids?



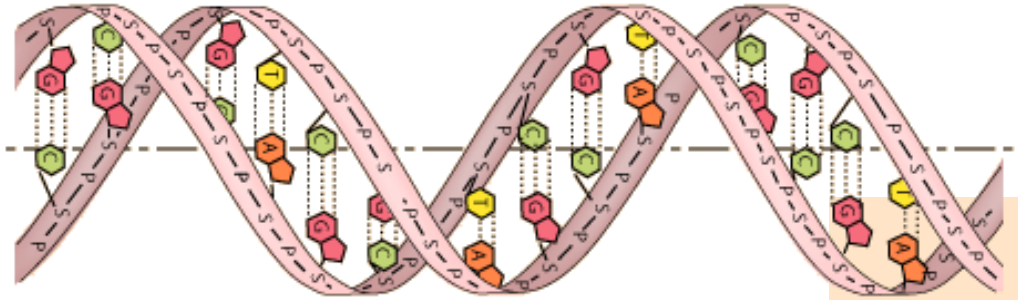
Chemistry of Life

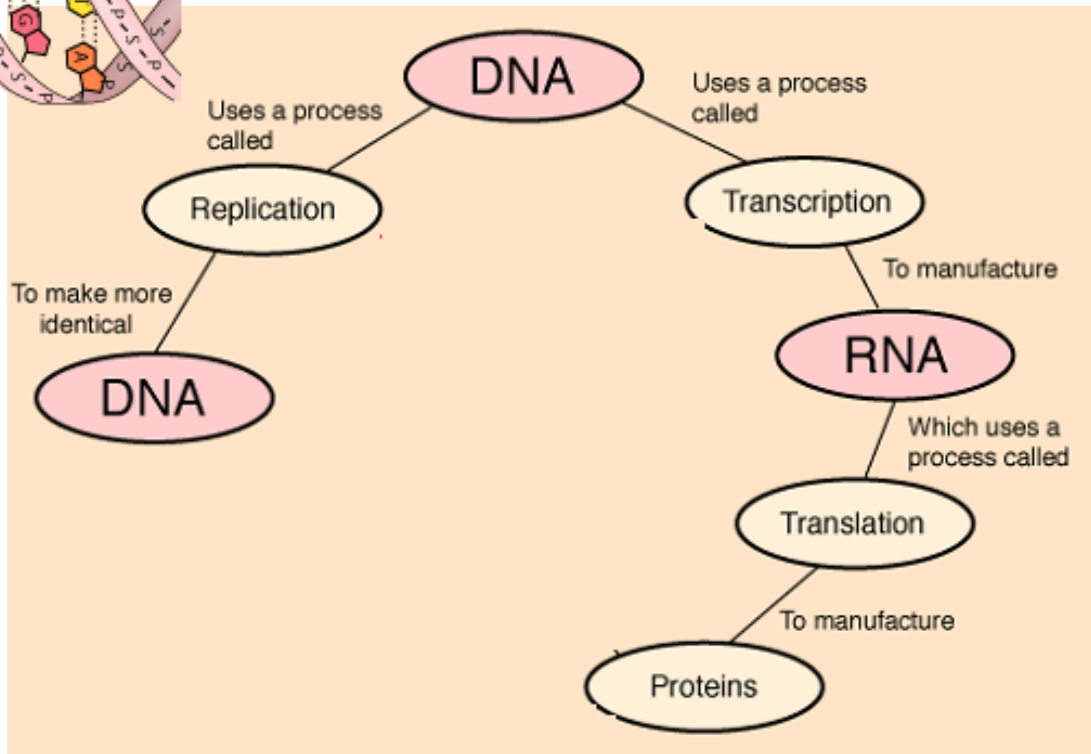
- The genetic code
  - A DNA molecule is made of two strings, or "strands", each one the mirror image of the other ("double helix")
  - Each string is a sequence of "nucleotides" or "bases", which come in four kinds (adenine, guanine, cytosine, thymine)
  - Nucleotides are the elementary unit of the "genetic code"
  - These four chemical units constitute the alphabet of the genetic code
  - The genetic code: translating the 4-letter alphabet of DNA into the 20-letter alphabet of proteins (bases into amino acids)



Chemistry of Life

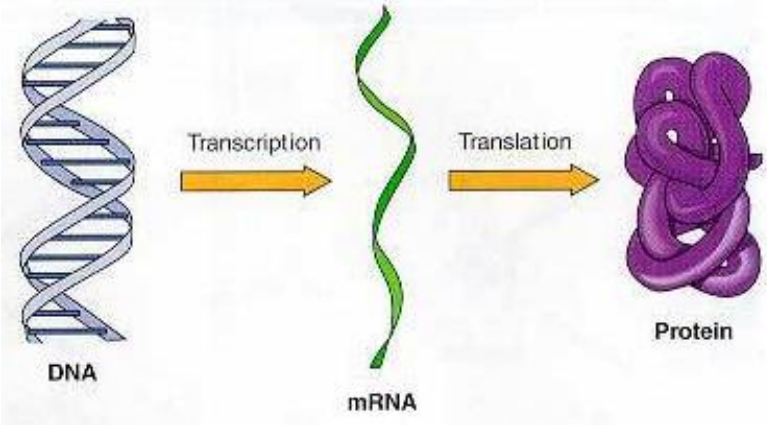
- The genetic code
  - DNA is the master blueprint for the production of proteins and for the replication of itself

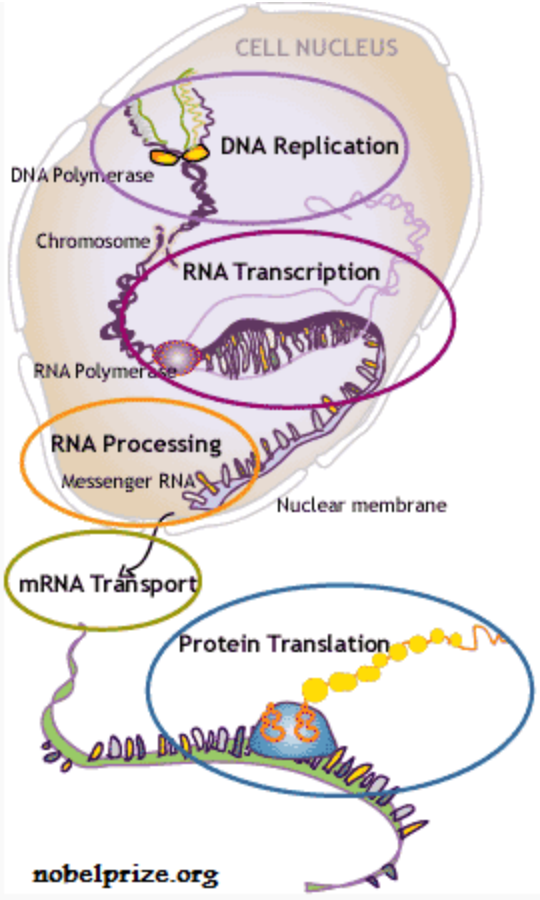




Chemistry of Life

- **DNA-RNA-Protein**
  - Transcription: the synthesis of RNA under the direction of DNA
  - Translation: the synthesis of a protein occurs under the direction of mRNA
  - RNA polymerase: an enzyme which reads DNA and makes messenger RNA (mRNA) during transcription
  - mRNA: the product of transcription
  - Ribosome: the site where the mRNA is read and protein synthesis occurs





Chemistry of Life

- DNA-RNA-Protein
  - The one-dimensional string of instructions of the DNA is used to determine the three-dimensional shape of a protein.

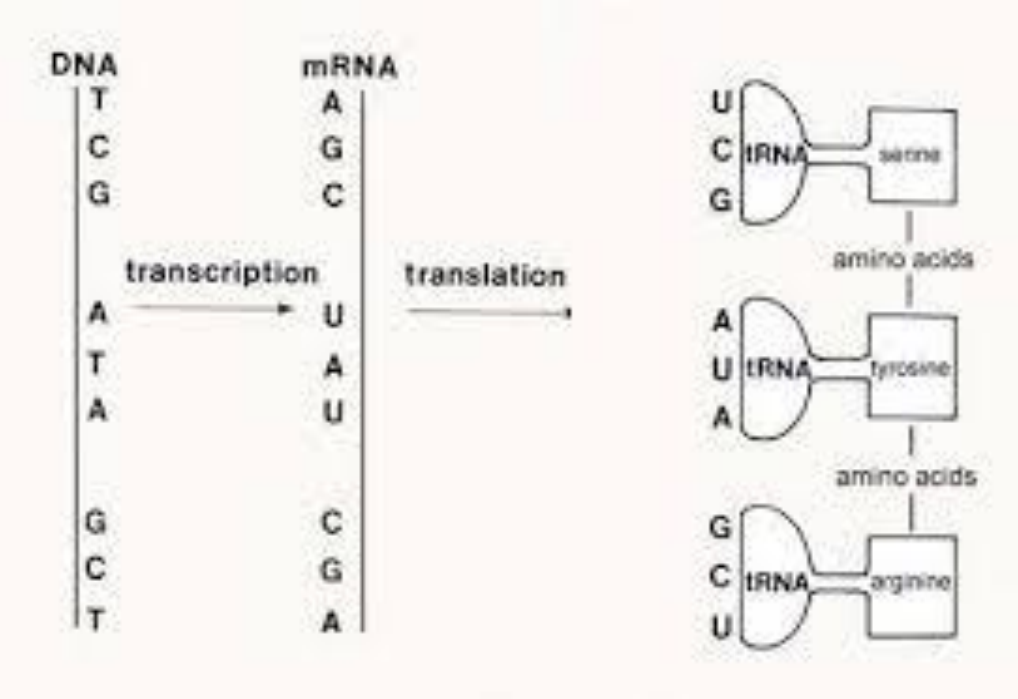
ACCTTCAATCTCTTCAGCACAGAGGACTCATCTGCTGCTTCGGAACAGAGCCTCCTA

Chemistry of Life

- Footnote: why a double helix?
  - Why double helix?
  - “Redundancy is a familiar stratagem to designers of error-detecting and error-correcting codes. If a portion of one strand of the DNA helix were damaged, the information in that portion could be retrieved from the complementary strand” (Bob Haynes and Phil Hanawalt, 1967)

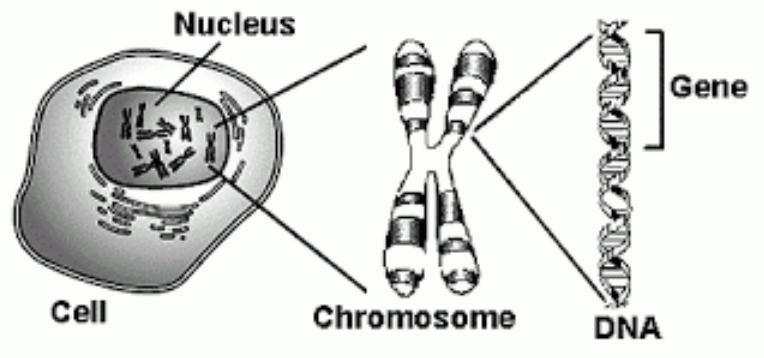
Chemistry of Life

- mRNA
  - 4 nucleotides arranged in trios (codons) each corresponding to an aminoacid



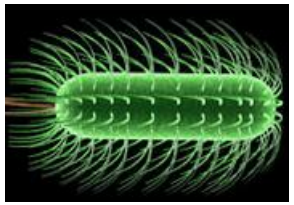
Chemistry of Life

- The genome
  - The genome is organized into chromosomes (23 pairs in the case of the human race)
  - Chromosomes are organized into genes
  - A gene is a section of the DNA molecule which instructs the cell to manufacture proteins (indirectly, a gene determines a specific trait of the individual)
  - Genes vary in size, from 500 bases long to more than two million bases



Chemistry of Life

- The genome
  - Humans have about 20,000 genes, only six times more than the Escherichia Coli bacterium
  - Chimpanzees share 98.6% of the human genome
  - 98% of the human genome contains the same DNA found in most other vertebrates
  - Our genome has only 20,000 genes, but our body has 100,000,000,000,000 (100 trillion) cells.



Chemistry of Life

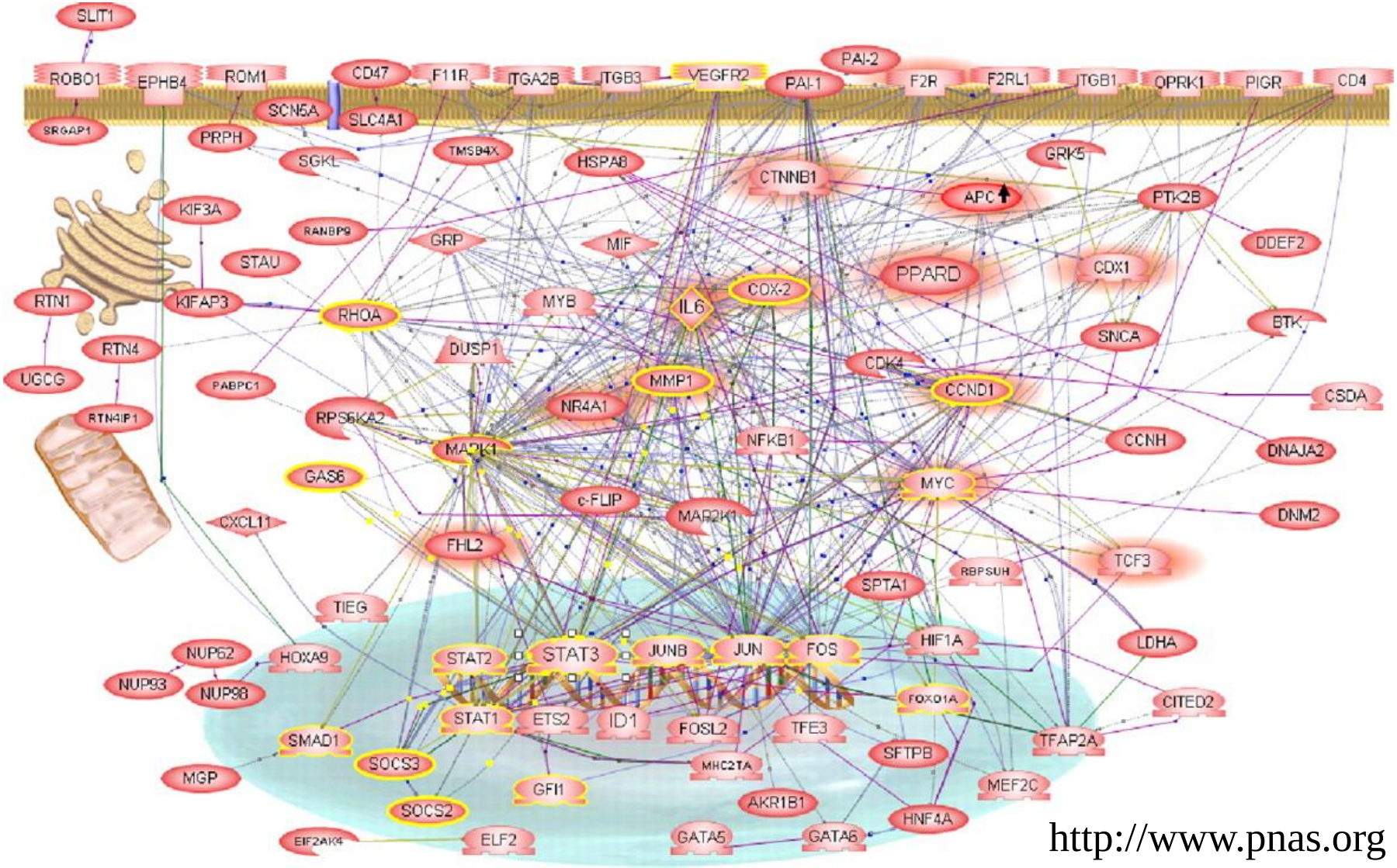
- Trivia: estimates of human genes over the years
  - 1960s: 2 million genes
  - 1999: 100,000
  - 2001: 30,000
  - 2004: 24,500
  - 2007: 20,500
  - 2014: 19,000
- While it takes a lot of neurons to create the complexity of the brain, it takes very few genes to create the complexity of the body

Chemistry of Life

- The genome
  - The genome is not a sequential program, that is executed mechanically one gene after the other. It is more like a network of genes that "regulate" each other.
  - The genetic "program" behaves more like a network of switches.

Chemistry of Life

- Network of genes



http://www.pnas.org

Chemistry of Life

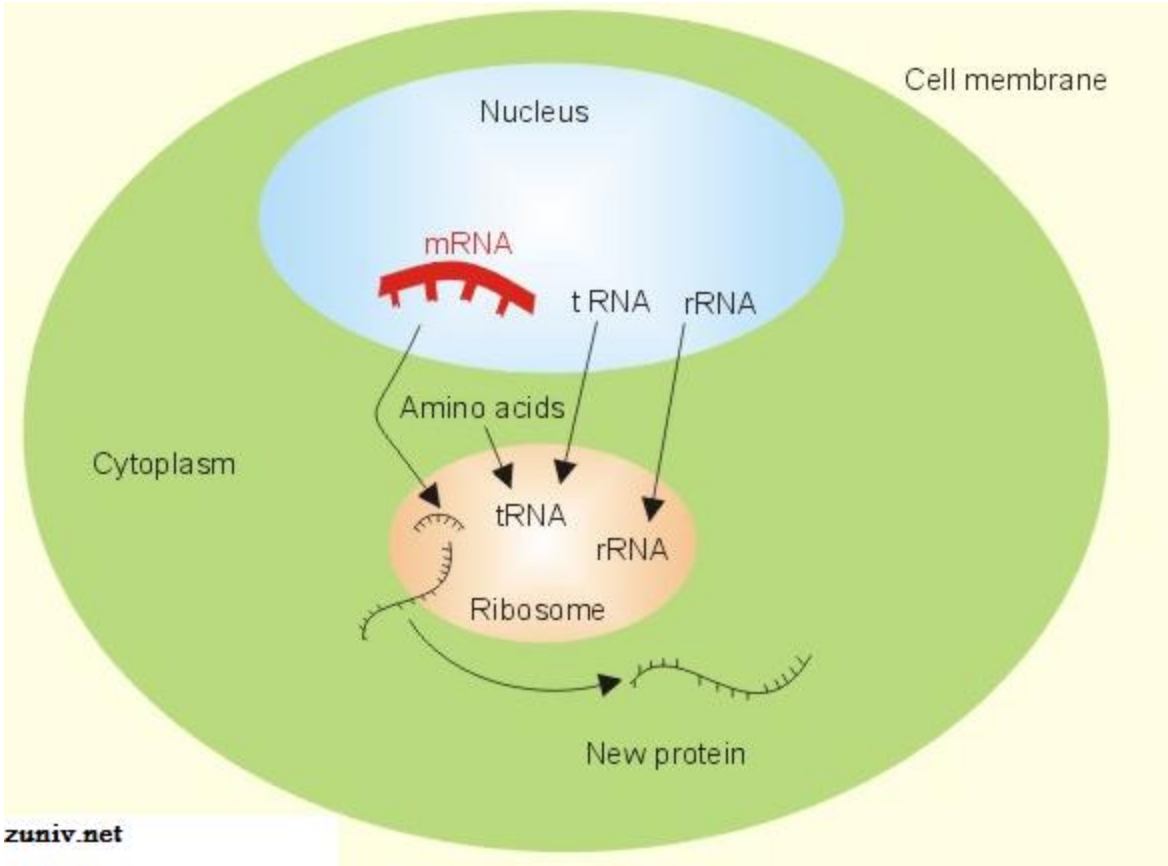
- The genome
  - All living organisms use DNA to store hereditary information and they use the exact same code (the "genetic" code) to write such information in DNA
  - The smallest genome that is known is the genome of the Mycoplasma Genitalium: 470 genes
  - Highest number of genes: Daphnia Pulex, 31,000 genes
  - Longest genomes: Amoeba Dubia (200 times longer than the human genome), Paris Japonica (50 times)

Chemistry of Life

- The genome
  - Genotype is the "genetic makeup" of the organism. The organism itself is the “phenotype”.
  - The phenotype is the physical manifestation of the genotype (the "body").

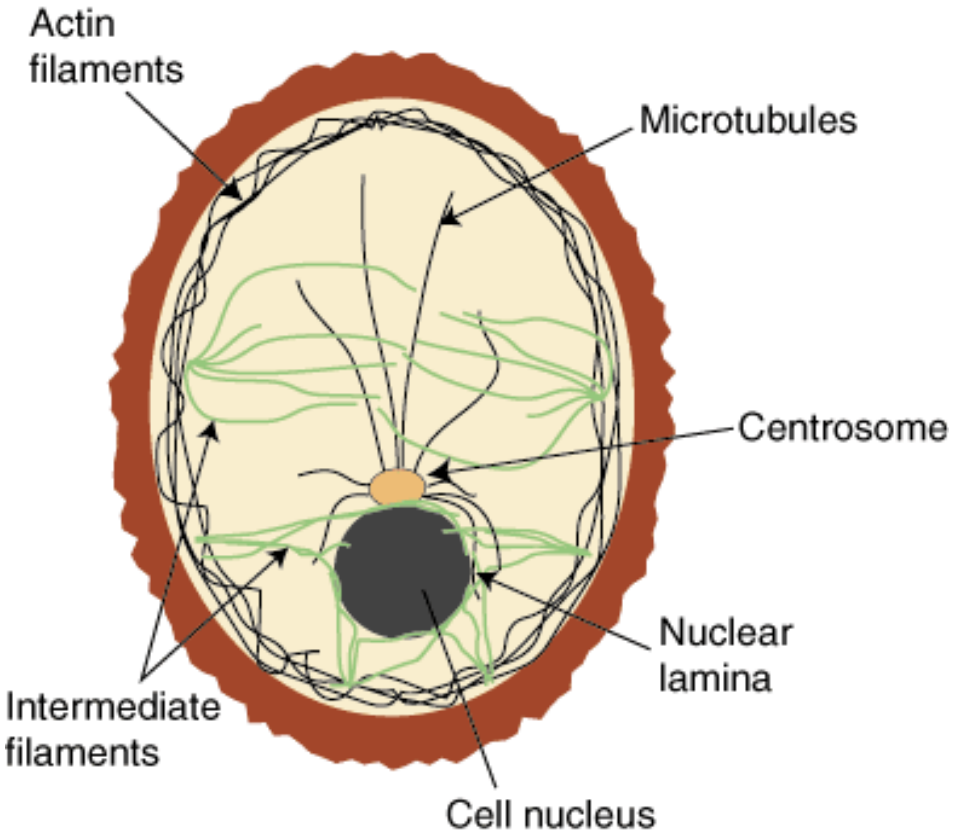
Chemistry of Life

- The cell
  - Cell membrane
  - Nucleus: site where DNA is transcribed into RNA
  - Ribosome: site where creation of proteins takes place (a Turing machine!)
  - Cytoplasm



Chemistry of Life

- The cell
  - The cell's cytoskeleton is made of "tubulin", which forms cylinders called "microtubules"



Chemistry of Life

- The cell

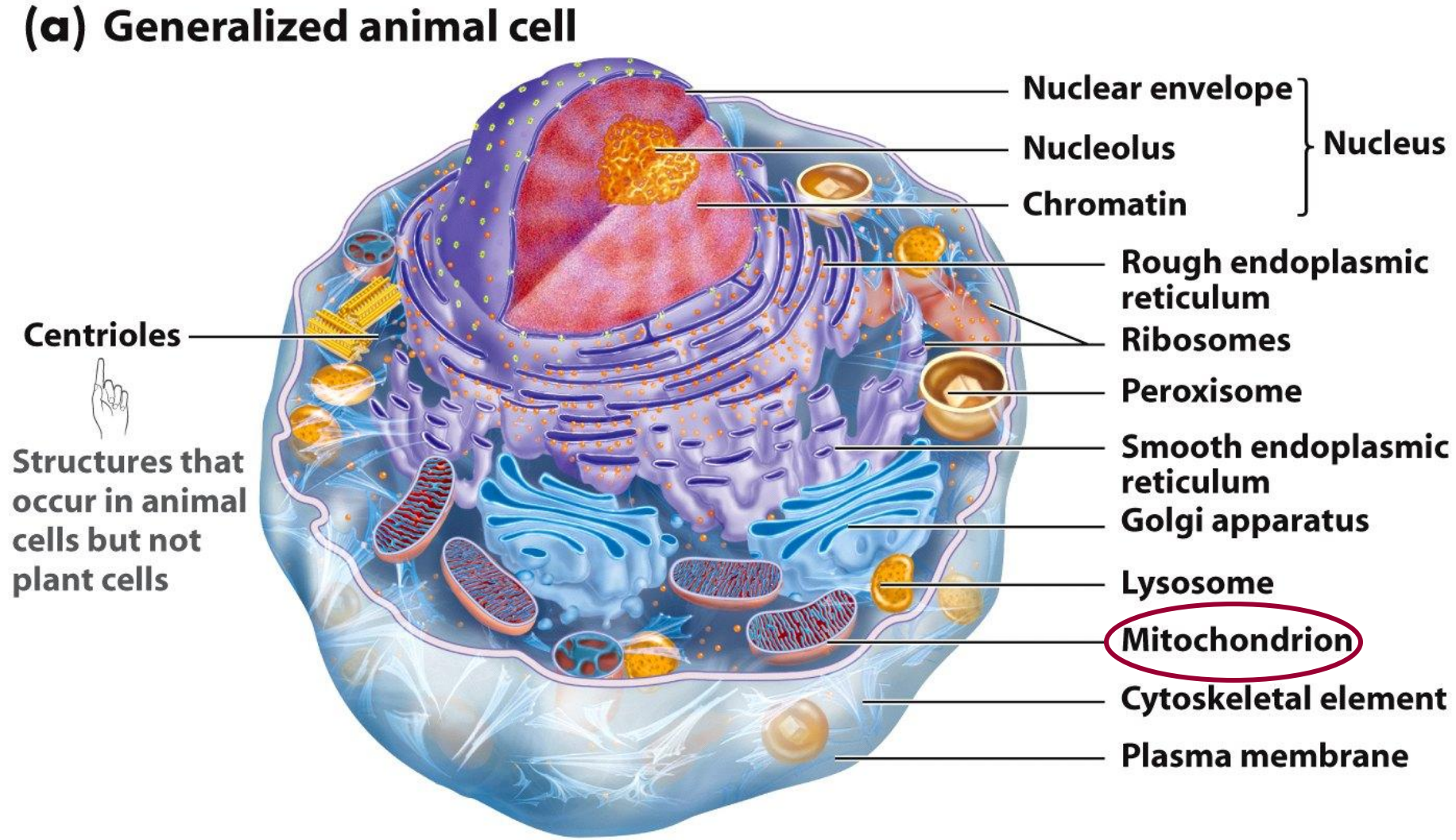


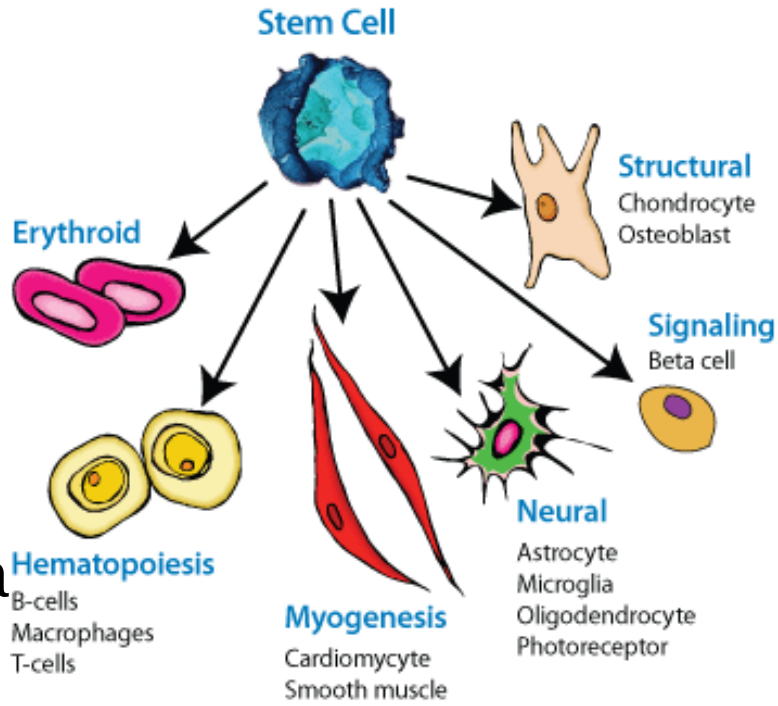
Figure 7-6a Biological Science, 2/e

Chemistry of Life

- The cell
  - Mitochondria provide most of the cell's energy source in the form adenosine triphosphate (ATP)
  - Mitochondria have their own genome, which is more similar to the genomes of bacteria than to the genome of the hosting cell

Chemistry of Life

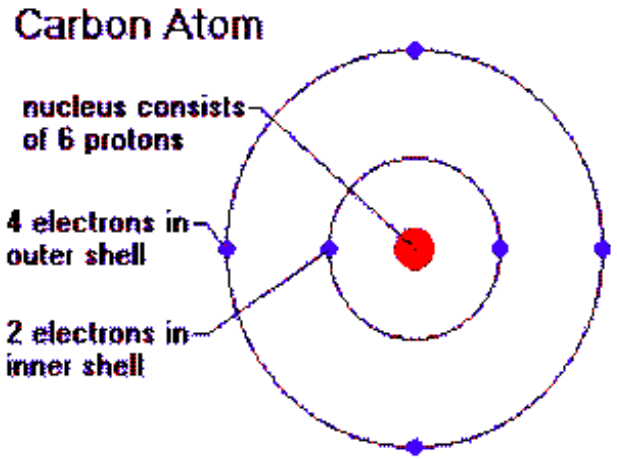
- The cell
  - "Cell differentiation": each cell "expresses" only some of the genes in the genome
  - The human body has about 265 different cell types.
  - Differentiation regulated by topology: depending on where a cell is, it exchanges energy (which is information) with some cells rather than others.



The cells of the 3- to 5-day-old embryo (blastocyst) generate all the specialized cell types (heart, lungs, skin, etc)

Chemistry of Life

- The matter of life
  - Life on Earth is based on the element carbon.
  - Carbon can bond with oxygen, hydrogen and nitrogen because of its four valence electrons
  - Both proteins and nucleic acids (DNA, RNA) are made of carbon
  - Energy is stored in the form of carbohydrates



Chemistry of Life

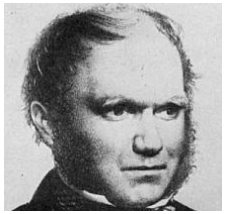
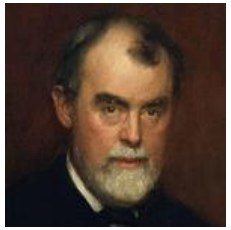
- Life on Earth uses carbon-based molecules and a base-4 genetic code
- Is it possible for a living being from another planet to be made of something else and be encoded in a different kind of code?
- Humans have built robots made mostly of metal and copper that are capable of reproducing, growing, communicating, exploring Mars, driving on the highway…

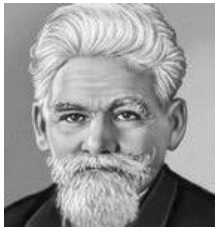
Chemistry of Life

- Fritz Lipmann (1941)
  - Adenosine Triphosphate (ATP), a high-energy phosphate and therefore a source of readily available energy, constitutes the main fuel for many biochemical processes and, in particular, is the main energy carrier in cells.
  - ATP is the connection between the metabolism and the physics of biological systems, i.e. the chemical process that makes life possible
  - Organic molecules are based on carbon, and energy transactions are based on phosphorus.
  - The meeting of (pervasive) oxidation-reduction energy and (relatively rare) phosphate-bond energy was a momentous event in the history of life

Theories of Evolution

- Jean-Baptiste Lamarck (hereditarity of acquired characters, 1809)
- Charles Darwin (differential rate of reproduction, 1858)
- Samuel Butler (life's free will, 1879)
- James-Mark Baldwin (Baldwin effect, 1896)
- Lev Berg (directed mass mutation, 1922)



Theories of Evolution

- Stephen Jay Gould (punctuated equilibrium, 1972)
- Stuart Kauffman (order succeeds despite natural selection, 1993)
- Michael Behe (irreducible complexity, 1996)

Theories of Evolution

- John Maynard-Smith & Eors Szathmary (1993)
  - The increase in the complexity of life originates from very few “major transitions” whose goal was not to increase complexity
  - A set of identical organisms differentiated into functionally specialized organisms
    - The RNA-only world decayed into a world of DNA + proteins
    - The monolithic cells of prokaryotes evolved into the combination of nucleus, cytoplasm and organelles of the eukaryotes.
    - A world of hermaphrodites morphed into a world of sexual organisms.

Theories of Evolution

- John Maynard-Smith & Eors Szathmary (1993)
  - In each major transition, sets of identical biological units were replaced by sets of specialized units that needed to cooperate in order to survive and replicate
  - These transitions involve a change in the language that encodes information and a change in the medium that expresses that language
  - They are about the way in which information is stored and transmitted.
  - A world of multifunctional self-sufficient biological entities evolved into a society of specialized entities

Theories of Evolution

- John Maynard-Smith & Eors Szathmary (1993)
  - Evolution was accelerated by changes in the nature of biological replicators
  - Each of the transitions "invented" a new way of coding, storing and transmitting information.
  - New kinds of coding methods made possible new kinds of organisms

Theories of Evolution

- John Maynard-Smith & Eors Szathmary (1993)
  - The first replicators were made of RNA.
  - The cell with DNA and the genetic code
  - Monocellular organisms (prokaryotes) evolved into multicellular organisms (eukaryotes) and the new mechanism of gene regulation arose
  - Asexual cloning evolved into sex that shuffles the genetic information before transmitting it
  - The living world split into animals, plants and fungi that have different information-transmission techniques.
  - Individuals formed colonies, that developed other means of transmitting information, namely "culture”
  - Social behavior led to language

Theories of Evolution

- Gary Cziko (1995)
  - There is a universal process of Darwinian evolution that is responsible for knowledge at all levels, and not only at the biological level.
  - The same behavior does not yield the same outcome unless the environment remains exactly the same
  - Two kinds of fitness: adaptation to the environment at birth, and lifetime adaptations to changes in the environment

Theories of Evolution

- Gary Cziko
  - Examples of "ontogenetic" adaptation: muscles that get bigger the more they are used; synapses get stronger with use; the immune system "learns" what antibodies to make based on which ones are "used" to fight antigens
  - “Functional shifts“: parts that evolved for a purpose but then ended up being used for a different purpose, simply because it worked ("exaptation")
  - Even cultural knowledge obeys a process of blind variation and selective retention

Theories of Evolution

- Why we have sex
  - Sex increases variation and therefore the chances of surviving changes in the environment (August Weismann, 1889)
  - Basically, sex accounts for faster rates of adaptation
  - Sex is a trade-off: a genome sacrifices a part of its genes to team up with another genome and increase its chances of survival in the environment
  - Lynn Margulis: once upon a time "eating and mating were the same"

Theories of Evolution

- Why we have to die
  - A stable immutable form of life would have scant chances of surviving the continuous changes in the environment
  - A form of life that continuously reshapes itself has a chance to “evolve” with the environment
  - Lynn Margulis: "death was the first sexually-transmitted disease“

Identity

- There are ~100 trillion cells in your body (of which 100 billion neurons)
- Cells reproduce by dividing - they produce clones of themselves (mitosis)
- Cellular longevity cap: the "Hayflick limit“: human cells can only double ~50 times before they stop reproducing (Leonard Hayflick & Paul Moorhead, 1961)
- Yes, the Hayflick limit keep us from living forever

Identity

- Programmed cell death (apoptosis) is a clockwork process of replacement of cells for the good of the organism (John Kerr, Alastair Currie & Andrew Wyllie, 1972)
- Apoptosis is the main deterrent against cancer (“immortality” of cells would increase the chances of cancer)

Identity

- The intelligence of the body: It builds itself from 1 cell into 100 trillion cells in 9 months, and it rebuilds 98% of itself in less than a year
- Your body is younger than you think: the average age of all the cells in an adult's body is 7 to 10 years (Jonas Frisen, 2005)
- Every year about 98% of the atoms in your body are replaced

Identity

- You are physically someone else…
- Good news: neurons in the cerebral cortex are not replaced - your neurons are the oldest cells in your body
- Bad news: many neurons die and are never replaced, hence you have fewer neurons than when you were a child.
- Replace a neuron with a computer chip?

Identity

- There are 10 times more bacterial cells in your body than human cells (bacteria are far smaller than human cells) - 500 species in the intestine alone (Human Microbiome Project, 2012)
- Where they came from: your mother's uterus, your mother’s milk, natural water, food, air…
- What they do: help your immune systems and your digestion (“commensal bacteria”)
- “Human bodies are an assemblage of life-forms living together” (David Relman, Stanford, 2012)

Break

"Nature has all the answers, so what is your question?"
(Howard Odum)

Physics of Life

"God is a comedian playing to an audience too afraid to laugh"
(Voltaire)

Physics of Life

- Second law of Thermodynamics
  - Entropy: a measure of disorder
  - Disorder must always increase. Physical systems decay.
- But…
  - Life creates order: biological systems appear from nowhere, organize themselves, grow, reproduce
- Two arrows of time:
  - Physical systems decay
  - Biological systems grow and evolve

Physics of Life

- Negentropy (Erwin Schrodinger, 1944)
  - Living systems exist in a flux of energy
  - The existence of a living organism depends on increasing the entropy of the rest of the universe.

Physics of Life

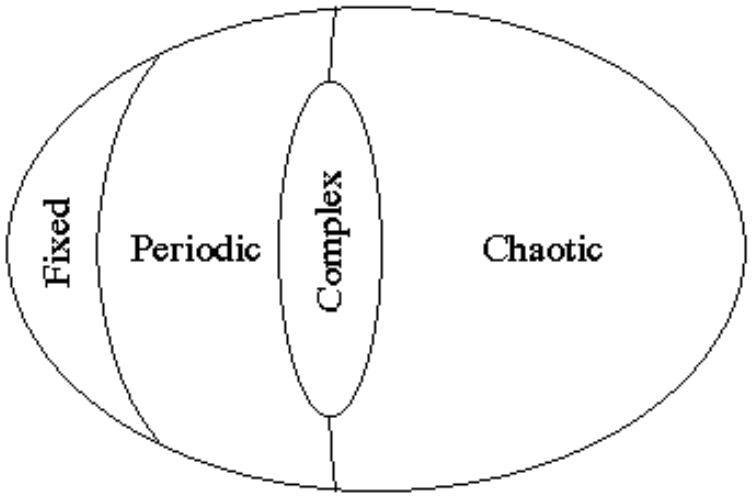
- Non-equilibrium dissipative systems (Ilya Prigogine, 1960s)
  - "Dissipative structures" form as patterns in the energy flow and have the capacity for self-organization
  - They maintain their structure by continuously dissipating energy
  - Dissipative structures reside permanently in states of non-equilibrium, unlike inanimate matter
  - The flow of matter and energy "through" the body of the living organisms is what makes it possible for the organism to maintain a (relatively) stable form
  - Equilibrium is death, non-equilibrium is life

Physics of Life

- Non-equilibrium dissipative systems (Ilya Prigogine, 1960s)
  - In order to stay alive, they have to be always in this state far from equilibrium.
  - An organism "lives" because it absorbs energy from the external world and processes it to generate an internal state of lower entropy.
  - An organism "lives" as long as it can avoid falling in the equilibrium state (maximum entropy)
  - Equilibrium is death, non-equilibrium is life.

Physics of Life

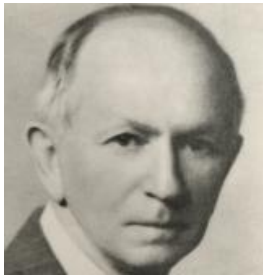
- Non-equilibrium dissipative systems



Information dynamics

Physics of Life

- Alfred Lotka (1920s)
  - Ecosystems are networks of energy flows
- Eugene Odum (1953)
  - The entire Earth is a set of interconnected ecosystems
- Harold Morowitz (1968)
  - Flows of energy organize systems
- Jeffrey Wicken (1987)
  - “Thermodynamics is above all the science of spontaneous processes”



Physics of Life

- Eric Schneider (1992)
  - Life is a way to optimize and accelerate (not just carry out) the production of entropy mandated by the second law of Thermodynamics
  - Living systems are the most efficient way ever devised by Nature to destroy order
  - Nature will create complex systems whenever it can: it will use any means available to achieve equilibrium (maximum entropy)

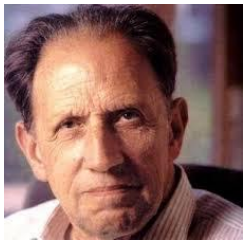
Physics of Life

- Eric Schneider
  - Exergy is a measure of how far from equilibrium a system is
  - Nature is building more and more complex systems in order to erase exergy ever more efficiently
  - Nature created animals because they are the most efficient way to erase the exergy of plants, and it created plants because they are the most efficient way to erase the exergy of sunlight, and so on.
  - Evolution has been progressing towards more and more efficient systems to destroy exergy
  - Genetic information is simply information about how to destroy exergy

Physics of Life

- Eric Schneider
  - A system pushed away from its attractor by a gradient, will tend to return to the attractor
  - The stronger the push, the stronger the reaction, the reaction being some form of self-organization
  - When the gradient pushing the system is particularly strong, the system may self-organize in ever more complex structures
  - Non-living complex systems play the same role that living systems play: they too spontaneously organize due to the energy flow caused by a gradient. They are just a bit less efficient.
  - “Nature abhors a gradient”

Physics of Life



- Bio-information theories
  - Ecosystem = cybernetic system (Ramon Margalef, 1968)
  - Life = a combination of metabolism and information control (Tibor Ganti, 1971)
  - Life = pattern (Gregory Bateson, 1979)
  - In living systems the manipulation of information prevails over the manipulation of energy (Chris Langton, 1989)
  - Biosystem = information processor (Lionel Johnson, 1998)

Physics of Life

- Ronald Fox (1988)
  - Life is, ultimately, a process about storing, transducing and using energy
  - Life evolved because the original (phosphate) structures inevitably evolved ways to regulate and to store energy
  - The evolution of life is due not only to natural selection but also to the evolution of more and more sophisticated forms of transducing and storing energy

Physics of Life

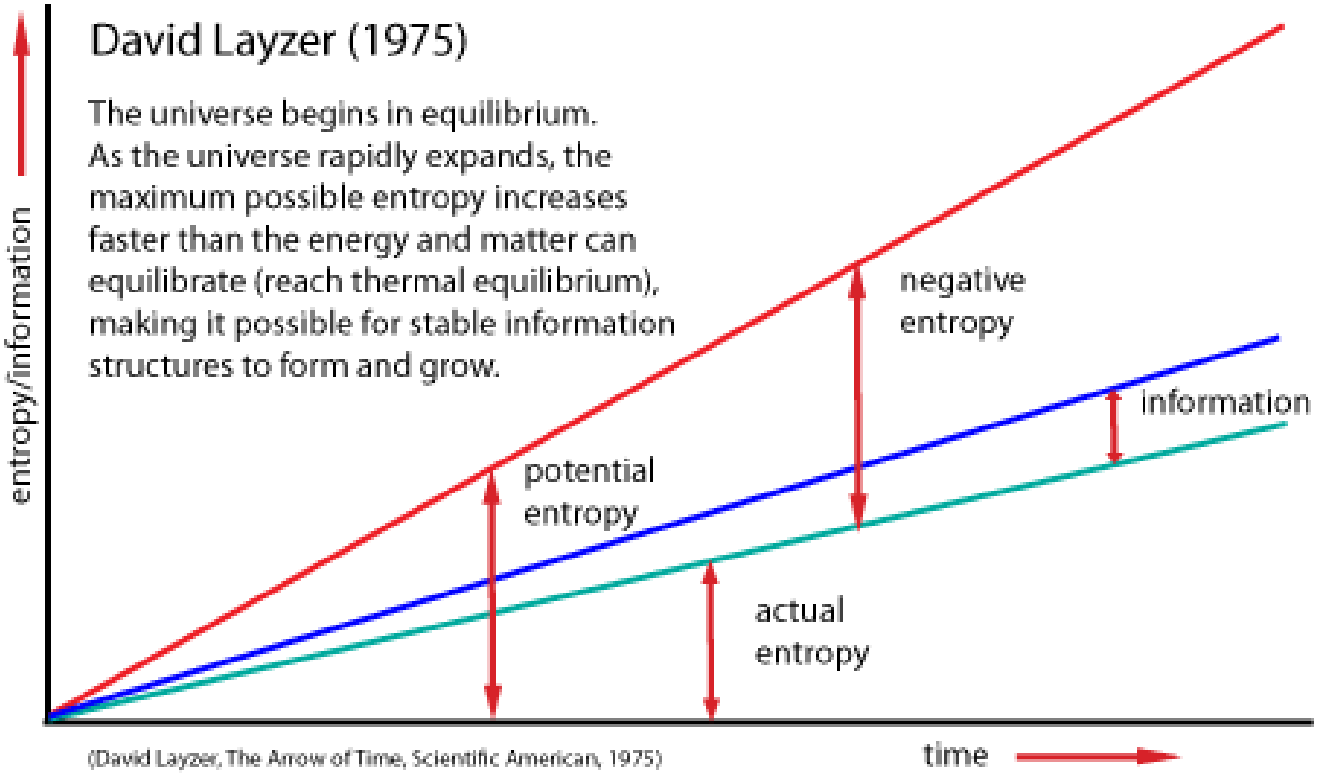
- Ronald Fox (1988)
  - For example, the emergence of phosphagens for energy storage enabled the evolution of muscles and motility in general.
  - Once muscles existed, it was important for the organism to predict the effect of a muscle movement on the environment…
  - … hence the nervous system, enabled by the evolution of creatine phosphate

Physics of Life

- Ronald Fox (1988)
  - The interaction between organism and environment as well as the interaction among organisms are nonlinear in nature
  - The nervous system is not only capable of predicting the outcome of linear situations, but also of predicting the much more important outcome of nonlinear situations
  - The reason is that the nervous system allows the organism to rapidly simulate the outcome of nonlinear events

Physics of Life

- David Layzer (1968)
  - In an expanding universe the potential entropy increases faster than energy and matter can "use", making room for the growth of order



Physics of Life

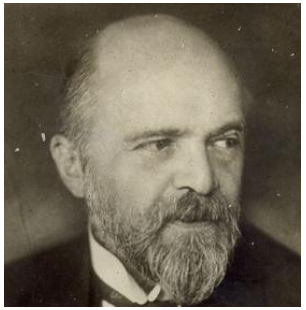
- David Layzer (1968)
  - If entropy in the environment increases more than the entropy of the system, then the system becomes more ordered in that environment
  - The expanding universe creates both entropy and order
  - Entropy and order increase together because the realization of structure lags behind the expansion of phase space
  - Biological systems behave like expanding phase space systems

Physics of Life

- Daniel Brooks and Edward Wiley (1988)
  - "Dollo's law" states the irreversibility of biological evolution: evolution never repeats itself
  - Living systems, unlike physical systems, owe their order and organization to their genetic information
  - Their relevant phase space is genetic, an ever increasing genetic phase space.
  - Dollo's law is the biological manifestation of the second law of Thermodynamics
  - Evolution may occur without any environmental pressure

Origin of Form

- August Weismann (1890s)
  - A piece of the living organism's machine is designed to reproduce and another piece is designed to achieve form
  - There is reproduction and "soma" (form), genetics and morphogenesis
- Hans Driesch (1890s)
  - A mutilated embryo still develops into a fully-functioning living organism
  - There is “life force”, or “entelechy”



Origin of Form

- Morphogenesis
  - During development, cells split and split and split
  - Every time a cell splits, the new cells inherit (almost) exactly the same genes
  - But then some cells become blood cells and some cells become bone cells and some cells become …
  - If they run the same program, how come that two cells become two different things?
  - And how do they know the position where those two things have to be?

Origin of Form

- Morphogenesis
  - Zebras have black and white stripes: how do those cells know that they have to be white or black?
  - A body is shaped by the orderly movement of billions of cells to the locations that specify their role

Origin of Form

- Morphogenesis
  - What determines which genes are switched on and off in a given cell?
  - How do "regulatory" genes know that a cell has to become part of a hair rather than a liver?

Origin of Form

- D'Arcy Thompson (1917)
  - The form of an object is a resultant of forces
  - Form is due to the action of the environment (natural forces) and to mathematical laws
  - Living organisms owe their form to a combination of internal forces of molecular cohesion, electrical or chemical interaction with adjacent matter, and global forces like gravity

Origin of Form


- Vitalism
  - Paul Weiss (1939) and Hans Speman (1938): "organizing fields" help organisms take their shape
  - Conrad Waddington (1957): "chreodes“ (a mathematical formalization of organizing fields) and the "epigenetic landscape“
  - Ralph Abraham (1976): "macrons“ (collective vibrational patterns) are ubiquitous in nature (in solids, liquids, gases)
  - Paul Davies (1999): the “life force” is a kind of software program (information is traded by “informational” forces the same way that matter is traded by physical forces)



Origin of Form

- Vitalism
  - Rupert Sheldrake (1981)
    - Memory is inherent in Nature
    - Natural systems inherit a collective and cumulative memory from all previous systems of their kind, : the “morphic field”
    - Not only genes are inherited, but also habits, which include development habits such as the growth of form
    - Each natural system has its own morphic field that shapes its behavior.
    - Nature is essentially "habit-forming
    - Genes do not carry all the information needed to shape an organism
    - Memory is not only in the brain

Origin of Form

- Vitalism
  - Donald Ingber (1993)
    - “Tensegrity" structures share the property of optimizing structural stability
    - Living systems, at all hierarchical levels, stabilize through the interplay of two forces, one which is tensional and one which is compressive
    - Buckminster Fuller ‘s geodesic dome: the geometry of the components constrains the Physics of the components, thereby immobilizing the whole structure
    - Tensegrity structures abound in nature, from the cytoskeleton to carbon atoms

Origin of Form

- Vitalism
  - Susan Oyama (1985)
    - Information (e.g., from the genome) develops
    - The form of an organism cannot be transmitted in genes or contained in the environment
    - Form is the result of interactive construction, not the outcome of a preexisting plan
    - An organism inherits its environment, as much as it inherits its genotype
    - It inherits some competence, but also the stimuli that make that competence significant

Cosmology

- Freeman Dyson (1988)
  - Life and intelligence are immortal, because sources of memory will grow
- Frank Tipler(1995)
  - A rigorous mathematical proof of the existence of an omnipresent, omniscient and omnipotent god
  - The “omega point” is the final singularity of the history of a closed universe, the point of infinite information, which is neither space nor time nor matter
  - Virtual reality is no less real than actual reality
  - We may well be just simulations inside a computer

Summary

- From Bioenergetics to the Brain
  - Life is about flows of energy
  - Thermodynamics is the discipline that studies energy
  - Life requires a new kind of Thermodynamics: non-equilibrium Thermodynamics
  - Non-equilibrium Thermodynamics has to do with non-linear systems
  - Survival requires the ability to predict what will happen to the system
  - If the system is non-linear, no mathematical prediction is possible: the only way to predict is to simulate the system at a higher speed
  - The brain is a simulation machine of nonlinear systems

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Life

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"No amount of study of present forms [of life] would permit us to infer [the existence of] dinosaurs" (Max Delbruck)

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