
The Cosmos
Planets & Life
PHYS 214
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Please start all class related emails with "214:"

Today's Lecture

- Biochemistry and DNA
  - Chemical basis of life
  - Alternative chemistries
  - Sugars to DNA

LAWKI

- In the rest of the course we will frequently refer to life similar to that on Earth
  - Carbon based, water solvent
- To save time, we'll refer to this as "Life as we know it" or LAWKI

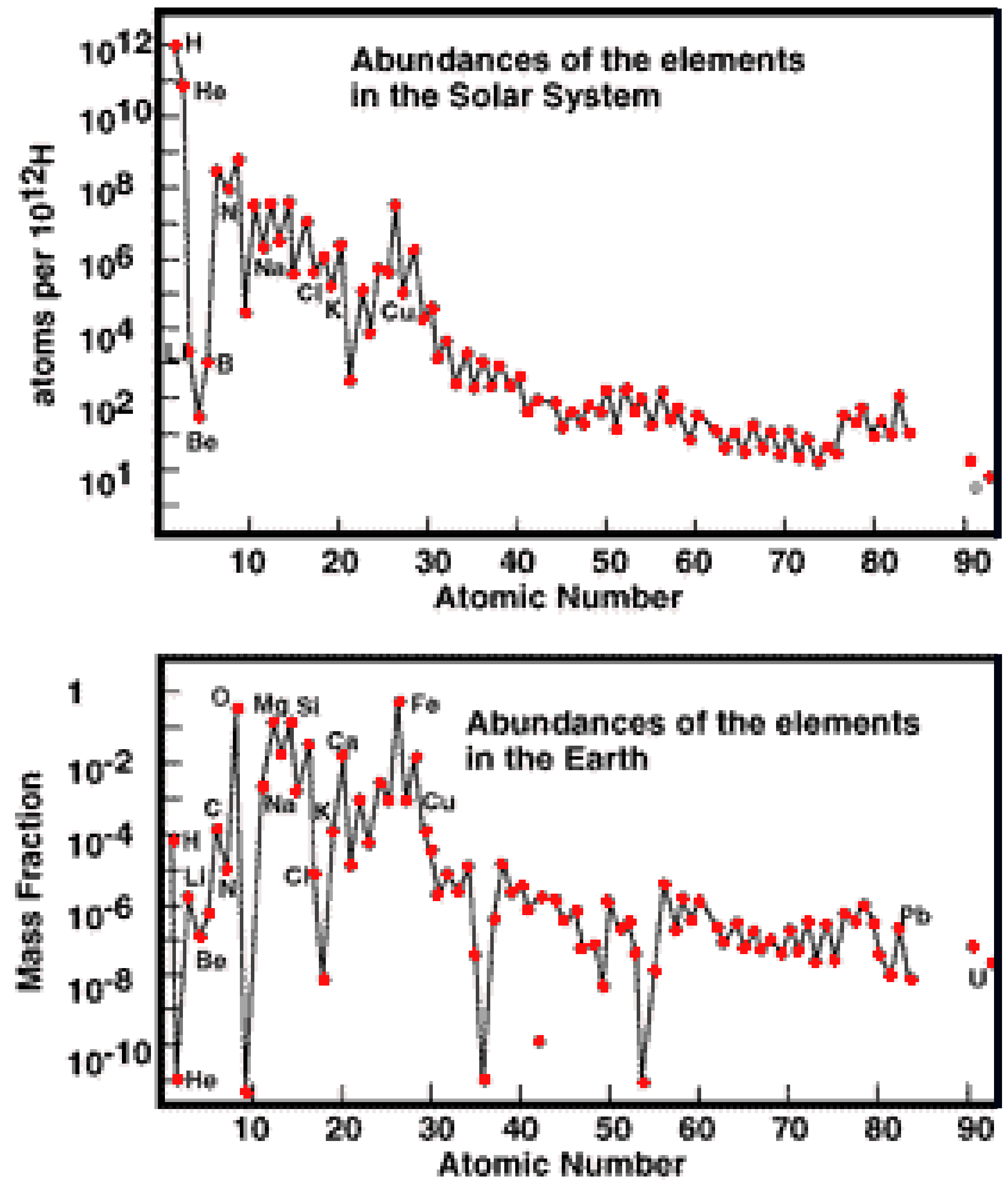
The elements: in life, on Earth, and in the universe

- Table 1.1 from Gilmour & Sephton (G&S from here on) shows the elemental abundances of the Universe, Earth (total), crust, ocean, and human beings
- Human beings have a very different proportion than their terrestrial environs
- The implications are:
  - The chemistry of life is innate and not simply a result of what chemicals are available
    - There is, for example, something special about carbon chain chemistry, water as a solvent…
      - Beware, it was thought at one point that oxygen based chemistry was *required*
  - The chemicals in LAWKI are to be found though out the universe, so the *potential* for life elsewhere is great

In the solar system H & He are the predominant elements

In the Earth (as a whole), O is the most abundant, closely followed by Fe.

The Earth's crust has comparatively low amount of Fe, but much higher amounts of Si and Al

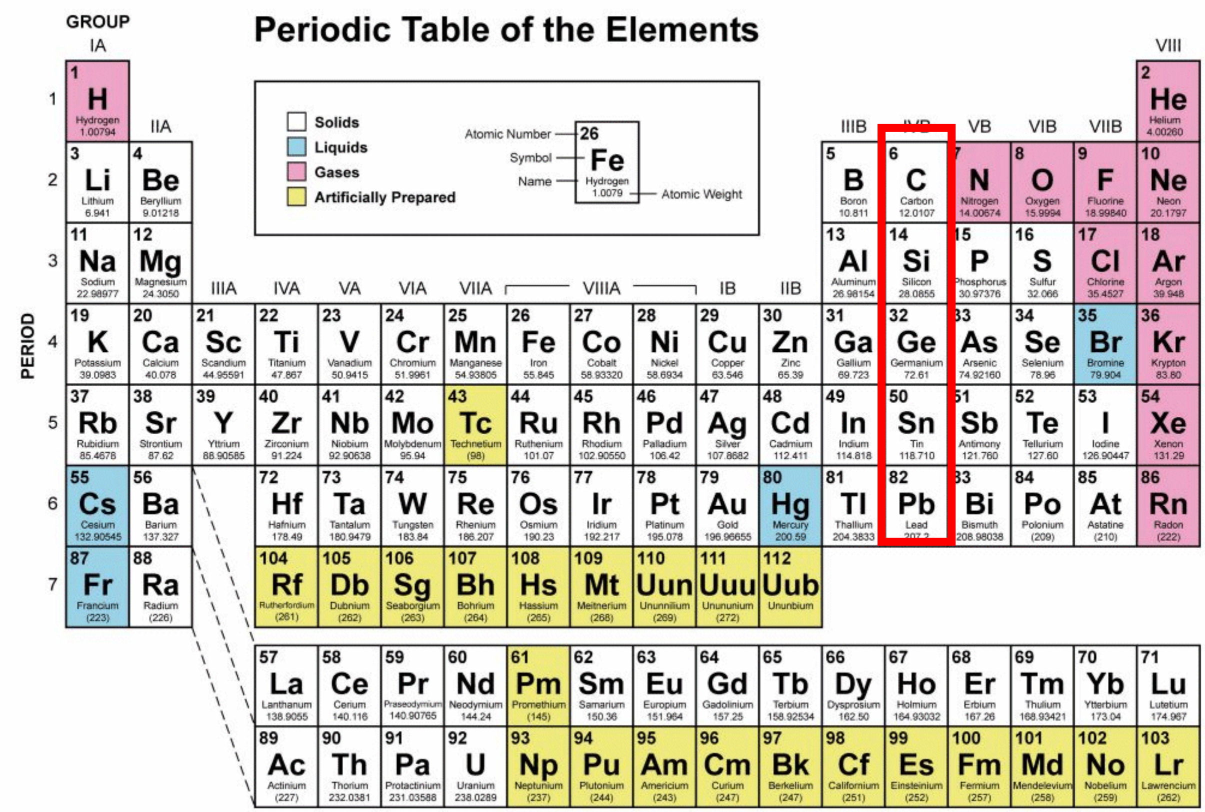


Organic Chemistry

- Originally organic chemistry referred to the molecules to be found only in and via life
  - Until urea synthesized by Wohler in 1824 (“organic” molecule synthesized from “inorganic” materials)
- Now we think of organic chemistry as the complex chemistry of the carbon atom
  - Biologically, carbon tends to form molecules with H, O and N -- and to a lesser extent P (nucleic acids) and S (aminos) [collectively called CHONPS].
- Carbon chemistry gives rise to a large variety of stable, but not inert, molecules
  - Potential for information storage and many reactions
- In many cases smaller molecules *monomers* can be chained (polymerized) together to form longer molecules, *polymers*

What about alternatives to carbon?

- Carbon's versatility due partly to its 4 valence electrons. Next obvious choice would be Silicon, also 4 valence electrons



Carbon vs Silicon

- Chemistry of Si much **less flexible** than C
  - C can form **double bonds**, Si can't: **less variety**
  - though Si **can** form **polymers** (*e.g.* silicones with Si,O)
- C-C bonds **twice as strong** as Si-Si bonds: carbon chains **more stable** (*silanes* Si_nH_{2n+2} compared to *alkanes* C_nH_{2n+2})
- Silicon reacts **very strongly** with oxygen to form a protective layer that is unstable only above temps > 940 K
  - *e.g.* silane (SiH_4) only forms when T > 1000K. SiH_4 **very unstable:** decomposes into SiO_2 in presence of oxygen or water vapour
  - Compare to CH_4, which is much more stable
  - Jupiter: H_2O, CH_4, NH_3, PH_3, but **no** SiH_4

Life based on Si seems improbable

- SiO_2 (silicon equivalent of CO_2) is not helpful:

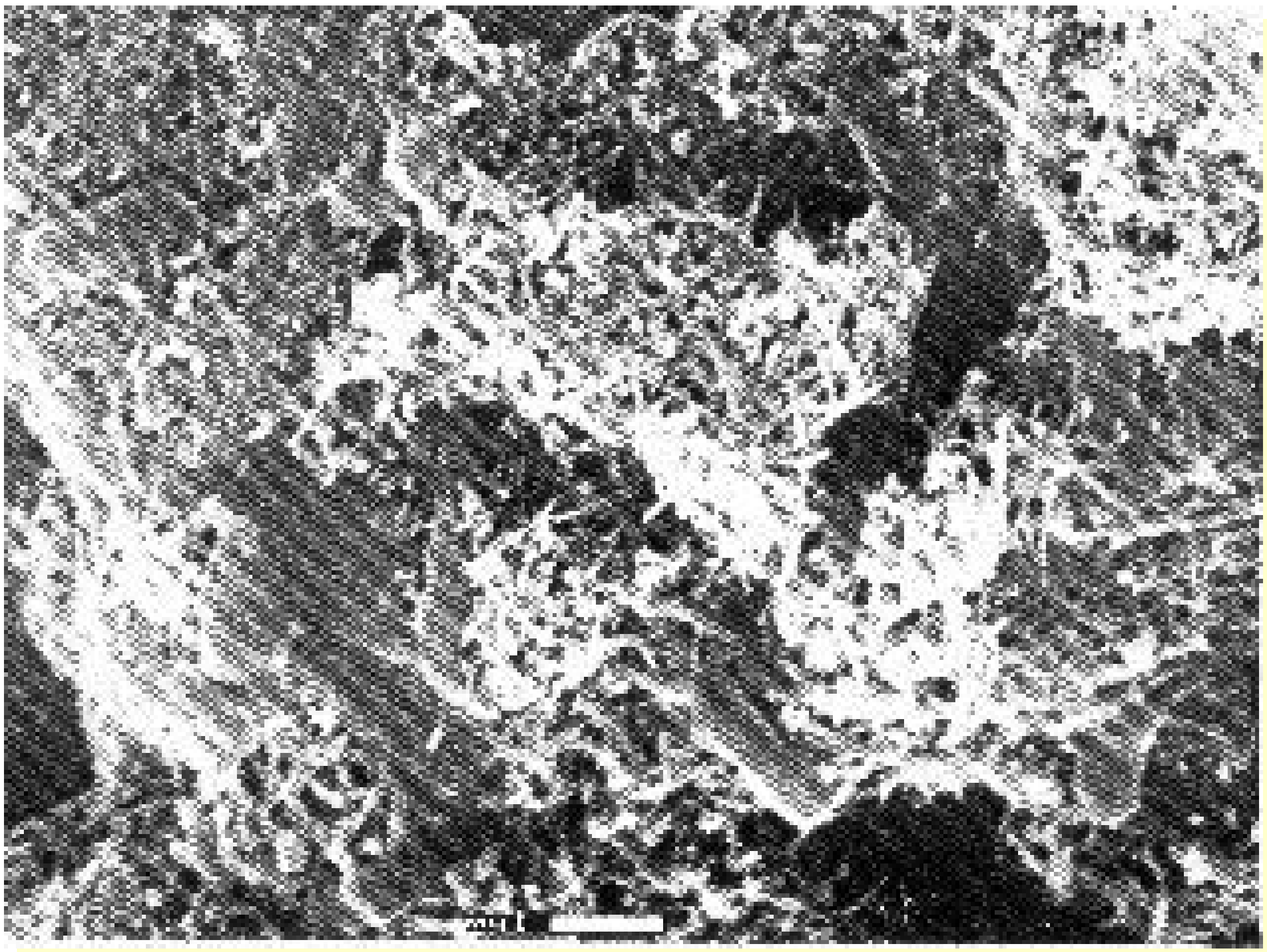
- solid below 2000 C (too high for stable polymers). A Si-based organism would exhale sand!

- **very insoluble** except in hydrofluoric acid
  - cf. CO_2, which easily dissolves in water, and remains a gas down to -75 C. This means that Si will stay **locked up** in SiO_2, and not available for "organic" uses.

- On the Earth, Si is ~600 times more abundant than C, but life is carbon-based not silicon-based. No silanes/silicones in comets, meteorites, or interstellar clouds

"Devil in the Dark"

Life stranger than fiction?



- *Shewanella oneidensis*
- Discovered in 1988
- Energy source is hydrogen or formaldehyde
- Breathes rocks! Mn oxides or Iron oxides

Solvents

- **Solvents are important for:**
- ***dissolving*** chemical compounds, to allow transport of nutrients and carrying off of waste.
- as a ***medium*** in which chemical reactions can take place
- to ***regulate temperatures*** in organisms
- solvents need to ***remain liquid*** for a large range of temperature and pressure

Comparison of possible solvents

Solvent	Liquid temperature range / C	Heat Capacity/ J K^{-1} g^{-1}	Heat of vapourization/ kJ g^{-1}
Water	-50 to 110	4.2	2.5
Ammonia	-78 to -33	5.1	1.3
Methyl Alcohol	-94 to 65	2.5	1.2

Note water can be supercooled down to -42 C at atmospheric pressure. You need very pure water and the container to be very still though. Once motion begins and a crystal nucleus is formed the rest of the water will crystallize almost immediately.

Ammonia – liquid at temperatures that are too low for promoting rapid reactions
Methyl alcohol, can be very reactive, latent heat of vapourization quite low too

Water as a solvent

- It is a good **solvent**: dissolves things well
- Has a high **heat capacity** and **latent heat of vaporization**
  - latter **twice** that of ammonia and methyl alcohol
  - water environment **more stable** against temperature changes
  - water is an excellent **temperature regulator** (can absorb large amounts of heat); important for maintaining **reaction rates**
    - *e.g.* sweating twice as efficient
- Since H_2O is a polar molecule it will tend to dissolve polar solvents by forming weak hydrogen bonds
  - Molecules that can be dissolved in water are dubbed hydrophyllic
  - Molecules that have a low affinity and are relatively insoluble in water are hydrophobic
  - Non-polar solvents required for dissolving non-polar molecules

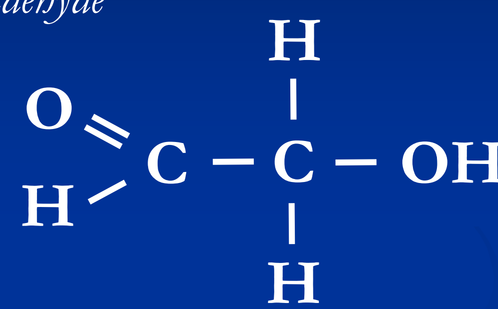
More about water

- Water has unique property: it **expands when it freezes**
  - ice layer on top with liquid water underneath
  - also means that ice can burst cells!
  - ammonia-based life forms could have advantage for interstellar travel
- Water has very high surface tension, important for creating **membranes**
- Water also provides **UV shielding**, via dissociation of H_2O and formation of O_3
- So it looks like water is really our best bet

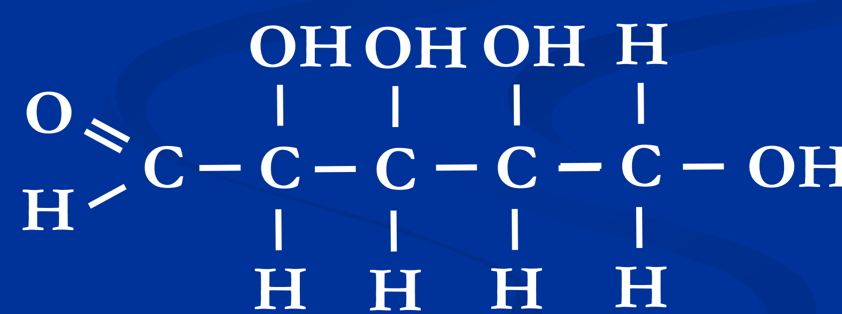
Sugars and Carbohydrates

- The most abundant single class of organic substances.
- Made of carbon, oxygen, hydrogen (H to O ratio of about 2 to 1 as in water)
- Sugars form ring like structures in water
- Monomers of sugar are linked into carbohydrate polymers
  - Water is lost in the process
- In animals the chief carb is glycogen
  - This is a polymer of glucose (see Fig 1.5 G&S).
- Plants are chiefly cellulose (making up the cell walls, also polymer of glucose)
  - Cellulose is the most common bio-organic substance making up about 50% of biologic carbon if we ignore the possibility of a major contribution from the 'deep hot biosphere'

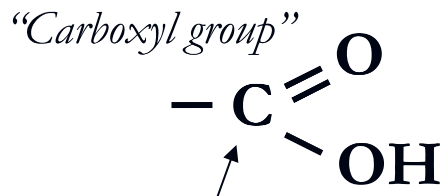
Glycolaldehyde



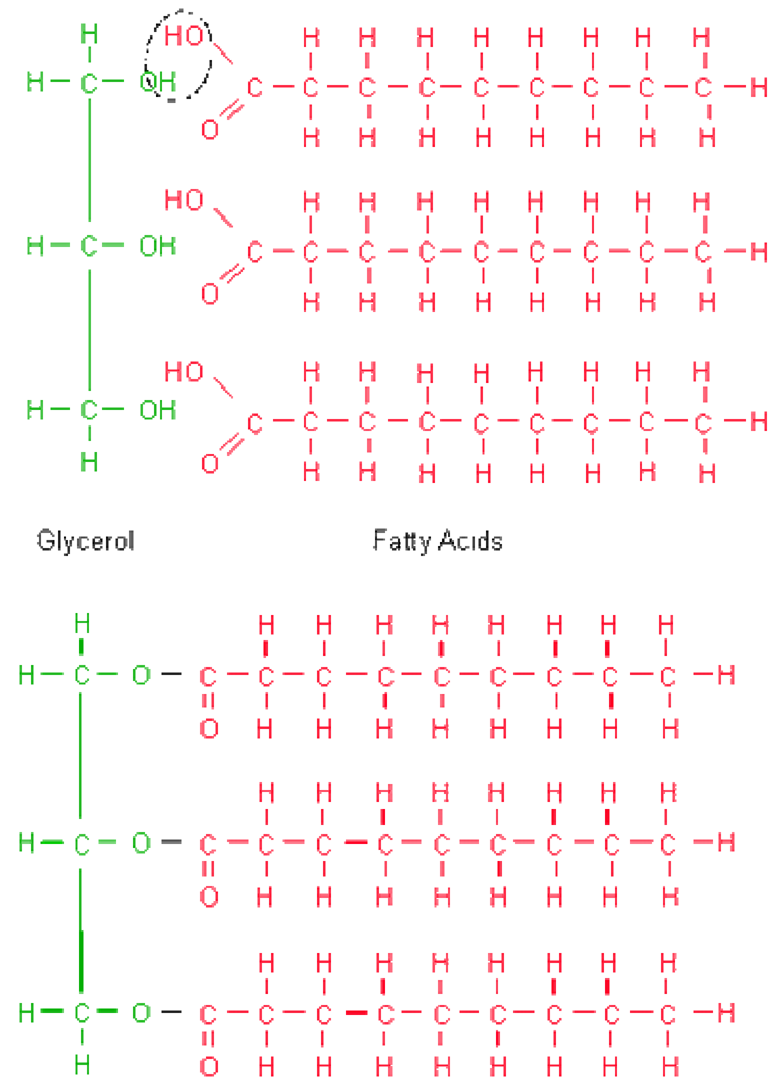
D-ribose



OH = *hydroxyl group*



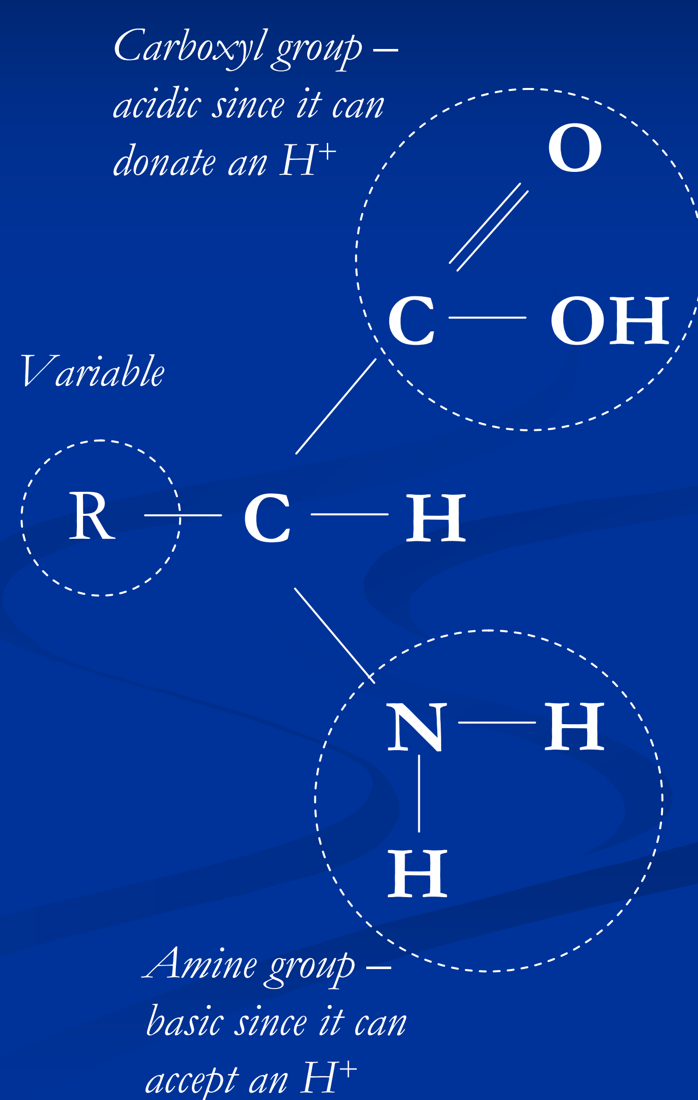
Lipids



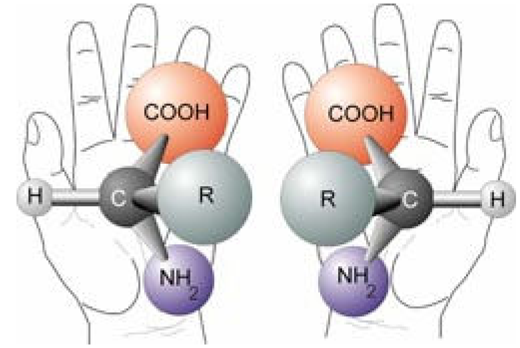
- Made of (usually 3) fatty acids (C_nH_{2n}+1COOH -- e.g. acetic acid with n=1) and a 3-carbon glycerol backbone (C_3H_5)
- Used for energy storage and transport for higher organisms (plants and animals)
  - also role as steroids (hormones) testosterone, cholesterol
- More fundamental role in cell membranes
  - as phospholipids
    - Phosphate group induces polar behaviour
    - Membranes are result of their amphiphilic (one end likes water, other end doesn't) nature

Amino Acids

- Remember: acids *donate* H^+: bases *accept* H^+
  - Acids release H^+ in solution (ionization)
- There are twenty amino acids (Fig. 1.6 G&S) found in life (as monomer units in proteins, see below) on the Earth
- They all share a *carboxyl group*, and *amine group* attached to an alpha carbon atom
- Other than the most simple amino acid (glycine) all show a handedness (chirality -- see Section 1.6.2, G&S)

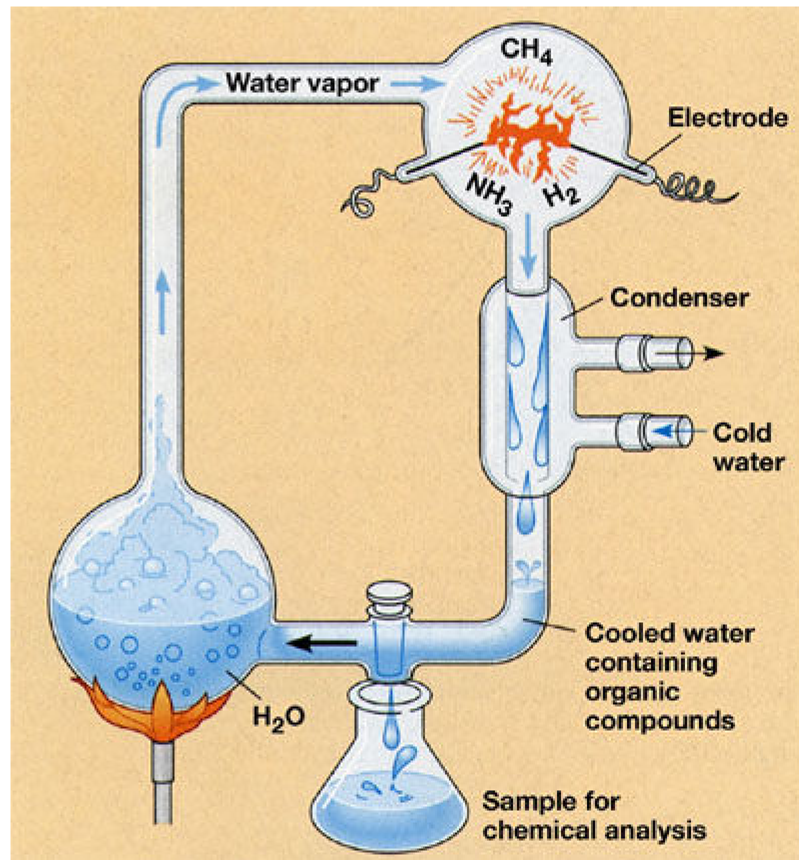


Aside: Chirality



- The amino acids in LAWKI are left-handed
  - Non-biological is symmetrical -- equally left and right-handed
  - This allows us one way of knowing, for example, when studying amino acids found on meteorites to know if they are: potentially terrestrial contamination (ie if left-handed), non-biological (equal), or potentially due to extraterrestrial life (right-handed)
    - This depends in part on assumptions, *i.e.* if life on meteorite not possible...
- Sugars also display chirality, and life has chosen right-handed (D) as in *e.g.* ribose and deoxyribose.
  - L type sugars are frequently (but not always) tasteless
  - Smell different too

- In 1953, Stanley Miller and Harold Urey set up an experiment to test whether a simulation of the primordial Earth ocean+atmosphere could reproduce amino acids
- The "atmosphere" included CH_4, NH_3 and was subject to sparks designed to simulate lightning
- Allowed to run for 1 week
- Produced nearly 20 amino acids + numerous other organic compounds



Miller-Urey & the Murchison Meteorite

- Murchison meteorite: a carbon rich meteorite (carbonaceous chondrite) preserved from the formation of the solar system
- Fell in 1969 in the town of Murchison, just outside Melbourne, Australia
- Analysis of the amino acids on the meteorite showed a remarkable to match to the relative productions of amino acids in the Miller-Urey experiment
- Main problem with Miller-Urey is that there is expected to have been much less NH_3 and CH_4 than assumed
  - Makes synthesis of amino acids harder

Proteins

- Chains of amino acids bond to form polypeptides* -- in the context of life these are proteins
- Proteins are the stuff from which are bodies are primarily made
  - If our bodies were dehydrated, proteins would make 75% of the remaining mass
- In our bodies, proteins make up (*e.g.*):
  - Enzymes (insulin),
  - Collagen (skin, cartilage, blood vessels)
  - Hemoglobin (part of blood which carries oxygen)

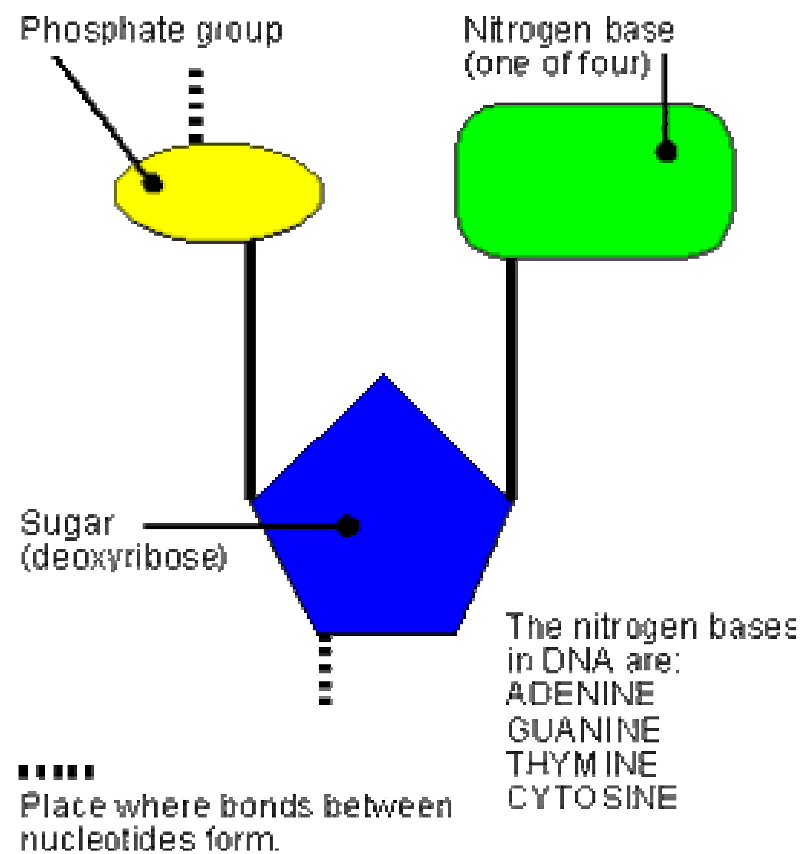
**peptide bond formed when carboxyl group reacts with an amine group to form an amide linkage*

Information carrying potential in a protein

- A protein chain with N amino acid units can be made in 20^N different ways
- Thus protein has a vast potential to store (genetic?) information
  - Given an average protein length of 100 amino acids there are 20^{100} (about equal to 10^{130} -- cf. the visible universe with about 10^{80} particles) possible different proteins
    - Yet most organisms make do with less than 10,000

Bases, Nucleosides, Nucleotides and ATP

- DNA and RNA (slide 26) are built from monomer units (*nucleotides*) which are in turn composed of:
  - A phosphate group (PO_4)
  - A sugar
    - deoxyribose for DNA (deoxyribonucleic acid)
    - ribose for RNA (ribonucleic acid)
  - A nitrogen-containing compound called a nitrogeneous *base*
- In DNA four different nucleotides are used, each with the same sugar and phosphate groups but different bases

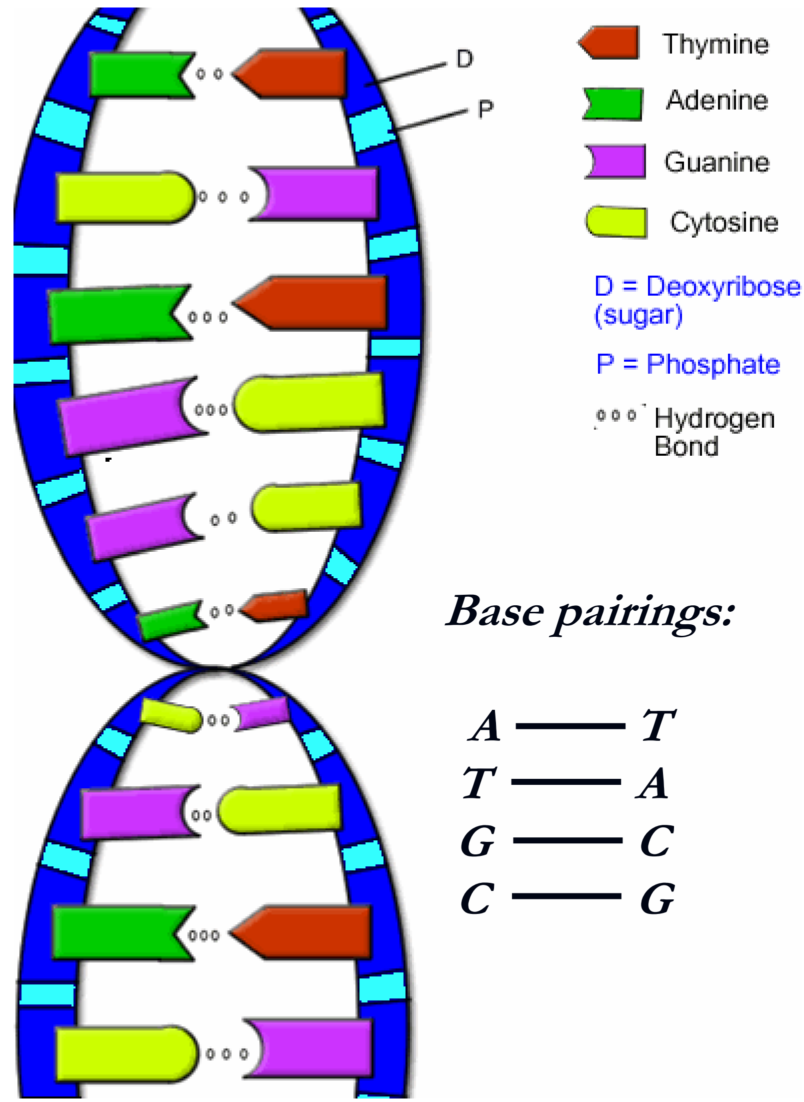


The four bases…

- Nucleotide names:
  - adenosine (A) corresponding base: adenine
  - thymidine (T) corresponding base: thymine
  - cytidine (C) corresponding base: cytosine
  - guanosine (G) corresponding base: guanine
- The nucleotides with additional phosphate groups bonded to them are called, for example: diphosphate, triphosphate etc. *e.g.*:
  - adenosine diphosphate (ADP)
adenosine triphosphate (ATP)
    - ATP is the basic energy currency of life

DNA-RNA

- *Structure of DNA and RNA (Watson and Crick, 1953)*
- The nucleotides form a chain by linking phosphates to sugars producing a sugar-phosphate backbone (polymer) with side bases
  - Somewhat akin to proteins, which are a glycine polymer backbone with various amino side groups.
  - The proteins are actually more capable of carrying info as they can link together 20 independent amino acids.
- Base-pairing (Watson-Crick pairs):
  - C always bonds with G
  - A always bonds with T (DNA), U (RNA)
- The bonded chains spiral together in the famed "double helix" in DNA

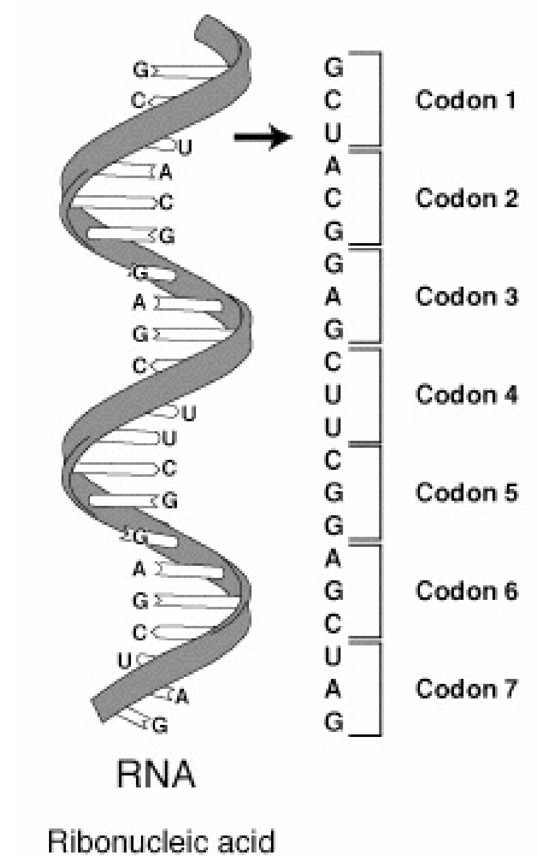


Replication

- One of the necessary roles of the genetic factor is to replicate itself. How does DNA do this?
- The double helix (parent) splits down the middle like a zipper coming undone
  - The base-pairing implies that each strand carries the same information
- Nucleotides floating around pair up with the appropriate bases to form two new (daughter) strands
  - Both of these steps are mediated by enzymes (proteins)
- See later discussion of mitosis and meiosis

The genetic code

- The bases of the DNA form a triplet code whereby each unit of three bases (*codon*) represents an amino acid
- In a triple of four possible choices there are $4^3 = 64$ possibilities
  - This is greater than the 20 amino acids (plus a stop) so there is some redundancy
    - *e.g.* glycine is represented by GGT, GGC, GGA, or GGG
  - If we went to a doublet code only $4^2 = 16$ possibilities, so not enough to code for the aminos needed.



Summary of lecture 19

- Chemistries based on anything other than carbon seem unlikely at best
- Similarly, water seems uniquely positioned as an effective solvent that has numerous other benefits (high heat capacity and so forth)
- Organic monomers can be easily synthesized in conditions similar to the primordial Earth
  - However, strong solar UV means there is probably very little NH_3 and CH_4
    - Much harder to produce amino acids in N_2, CO_2 environment

Next lecture

- Cell evolution & relation to Earth's history
- Guest lecture next Friday (8^{th} March) by Dr Virginia Walker (Biology) on extremeophiles