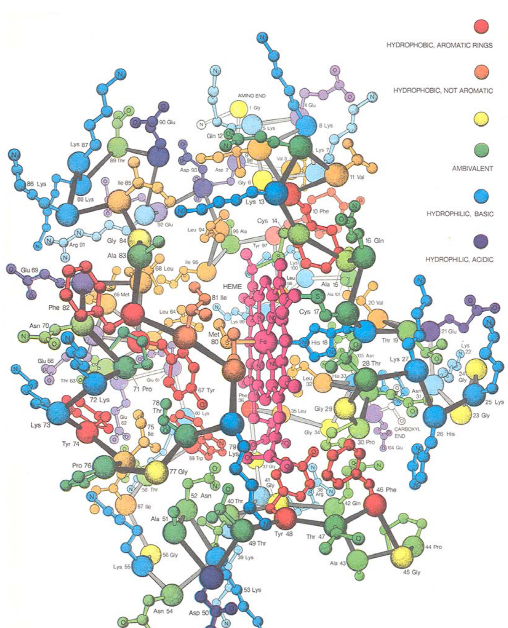
8 October 2019

HABITABILITY, MONOMERS, POLYMERS, & THE LONG MOLECULES OF LIFE

Homework #4 on WeBWorK due 10/21 (after Fall Break)



Habitability, Monomers, Polymers, & The long molecules of life

- The temperature of tidally-locked planets
- Liquid water and the Habitable Zone
- Earthlike planets and the Drake equation's n_e
- Habitability of tidally-heated moons
- Prebiotic molecules: delivered from the protoplanetary nebula or formed from the basics on infant planets?
- Origin of long, organic polymers, the predecessors of biomolecules that encode information
- Wet chemistry of nucelobases
- Nuances of polymerization
- Replication or mass production of nucleic acids
- Transcription
- Codons

Temperatures for fast and slow rotators

Implications for the temperature of a revolving body that is mainly heated by starlight:

- If a body rotates faster than it can cool off, its surface will have a fairly uniform temperature, given by the formula for dust grains. This is the case for the Earth and Mars, for example.
- If not, it will have hot and cold sides.
  - If it is tidally locked in circular orbit around its star, it will have **permanently** hot and cold sides.

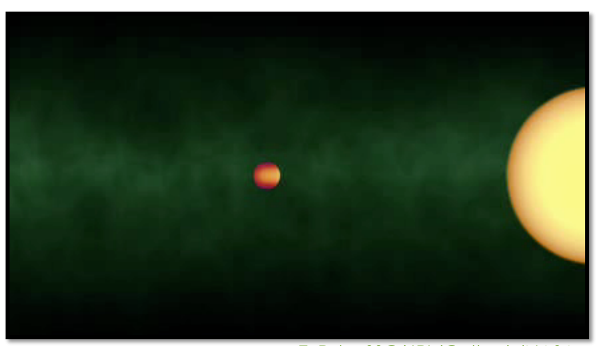
Temperature of slow rotators

For a slow rotator, the maximum temperature, which is generally reached at the substellar ("noon") point, is

$$T = \left(\frac{(1-A)L}{4\pi\sigma r^2}\right)^{\frac{1}{4}} = 394\ \mathrm{K} \times \left(\frac{(1-A)L[L_\odot]}{(r[\mathrm{AU}])^2}\right)^{\frac{1}{4}}$$

You need to understand how to use this formula.

Fortunately, it is the same as the last one, just with 394 K replacing 279 K.



T. Pyle, SSC/JPL/Caltech/NASA

The habitable zone

Since the interstellar medium already provides infant solar systems with the basic, and some processed, ingredients for life, the next basic requirement for habitability is for the ingredients to have the correct temperature.

What is the correct temperature? Clues from Earth:

- Simple organisms are not killed by prolonged exposure to temperatures *slightly* below the freezing point of water, or *slightly* above the boiling point. (These beasts are called **extremophiles**.)
- Complex organisms are most abundantly found in habitats between freezing and boiling.

Earth suggests that **liquid water** promotes habitability by organic chemical/water based life.

Is this geocentrism, to presume that life requires water?

Does life require water?

As we will discuss, **chemistry in liquids is by far the fastest way for life to evolve**.

Usually, this means having a solvent: a liquid for other molecules to dissolve in, that can facilitate their reactions.

Water is by far the most abundant solvent molecule in protoplanetary disks, and it is a great solvent chemically.

The temperature range within which water is liquid overlaps that of many other solvent candidates like methanol and ammonia.

While it is possible that life requires water, we do need to be wary of this Earth-centric bias.

Habitability

The most common definition of habitability in a planetary system is that water exists permanently in liquid form on a suitable planet.

- That is, $T = 273 - 373$ K under normal pressure conditions on Earth, and this range is often used.
- The water need not be exposed on the surface; if it is, the planet better have an atmosphere.

Such planets are found this far from their stars:

$$r[AU] = \left(\frac{T_0}{T}\right)^2 \sqrt{(1-A)L[L_\odot]}$$

where $T_0 = 279$ K for fast rotators and 394 K for slow ones, and T runs from 273 to 373 K if the planets are just "large dust grains."

Question

By this token, the habitable zone for Earthlike planets ($A = 0.37$) in the Solar System lies between 0.44 and 0.82 AU from the Sun. Which planets lie in the Solar System's habitable zone?

(Feel free to use the internet to look up distances!)

The greenhouse effect

Planets are not large dust grains: they have atmospheres.

Recall that the reasoning above gives only $T = 294$ K for the Earth. This is the temperature of the cloud tops; it is (definitely) warmer down below. Why?

Because the atmosphere is transparent at shorter wavelengths (visible, ultraviolet,…) at which stars emit much of their light.

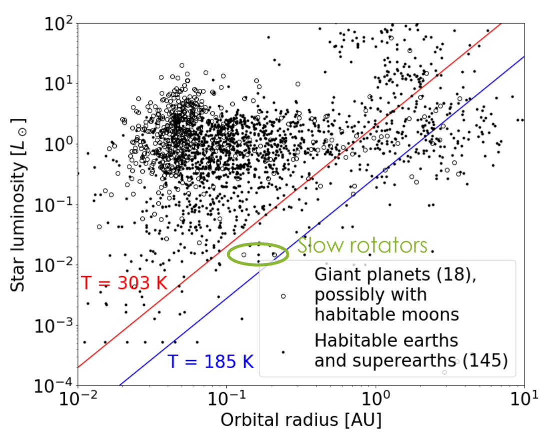
- This light directly heats the planet's surface.
- The extra energy cannot escape quickly. It is trapped: the surface radiates at the same infrared wavelengths at which the atmosphere is opaque.
- Therefore, the surface is warmer than the cloud tops.

This is called the **greenhouse effect**. We will go into more detail about it at the end of the semester.

The habitable zone (w/ greenhouse)

A simple estimate of the magnitude of the greenhouse effect, popularized by the *Kepler* team, is to use $A = 0.3$ and to take the temperature bounds to be $\boldsymbol{T =}$ **185 K and 303 K**, which in typical atmosphere models would correspond to surface temperatures of 273 K and 373 K.

- By this token, at least 145 of our current known Earth-sized planets (less than twice the size of Earth) lie in the habitable zone.
- There are some giant planets which also exist in the habitable zone. Any moons with atmospheres around these giant planets would be habitable.



Data: exoplanet.eu

The Drake equation: n_e

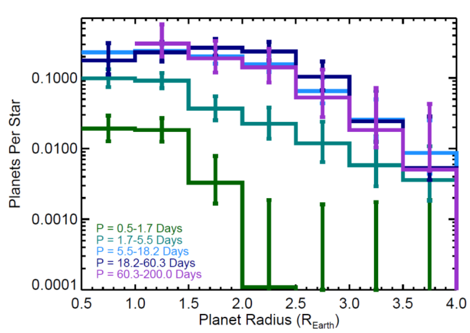
This is what the NASA *Kepler* mission was designed, and succeeded, to measure.

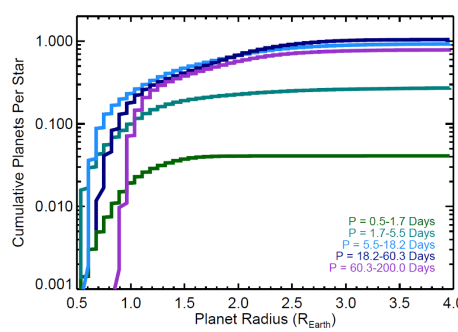
Originally, the n_e factor was supposed to count Earth-like planets, meaning habitable ones. Now, with such unexpected things as super-Earths, abundant tidally-locked planets, and the trickiness of the greenhouse effect, there is more context required around the numbers.

- Around Sun-like stars, there appear to be more planets of radius $2-2.8R_\oplus$ – super-Earth size – than planets larger or smaller (Silburt et al. 2015).
- Earths and super-Earths are more abundant around low-mass, cool stars ("M") than around Sun-like stars (G-K):
  - G-K: 46% ±3% of stars have E or SE (Silburt et al. 2015)
  - M: 56% ±6% of stars have E, 46% ±7% have SE (Dressing & Charbonneau 2015)
- Within the habitable zone as modeled by Kopparapu et al. (2013), the fraction of stars possessing planets is
  - G-K stars: 6% Earths, 17% SE (Silbert et al. 2015)
  - M stars: 16% E, 12% SE (Dressing & Charbonneau 2015)

The Drake equation: n_e

Splitting the difference in percents and ignoring the difference in E/SE, we will adopt $\boxed{n_e = 0.25}$ (25%)





Dressing & Charbonneau (2015)

Question

Ignoring habitable moons of giant planets, about how many stars would we have to visit to find one habitable planet (on average)?

Habitability outside the habitable zone

We chose starlight as the energy source above because it is generally provided at a steady rate for billions of years while other heat sources are not. All but one, anyway:

- Tidal heating of suitably-placed moons and planets can be significant sources of energy for as long as they rotate rapidly and/or do not have circular orbits.
- Typically, as the moon or planet radiates the energy away, the rotation slows and the orbit circularizes over time, reducing the tidal heating to zero.
- But sometimes, if something can force a suitably-placed planet or moon to rotate or follow an elliptical orbit permanently, the tidal heating would be permanent.
- And something can: perturbations of moons and planets on each other's orbit can result in orbits being locked into orbital resonance.
- Since there is an attractive impulse at closest approach, and since for resonant orbits this happens in the same spot in the orbit every time, these **resonantly-locked** orbits cannot be precisely circular.
- Thus, tidal heating can be permanent and substantial.

Habitability on tidally-locked bodies

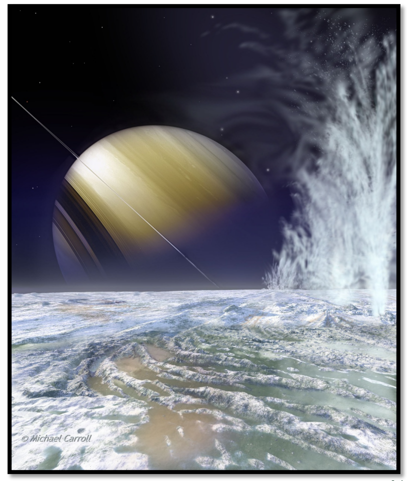
This is the case for the large moons of Jupiter and Saturn, particularly **Io, Europa, and Ganymede** (orbital periods in ratio 1:2:4).

- Permanent liquid water further away from the star than the habitable zone!

We will discuss this further when our talk turns to the search for life elsewhere within the Solar System.

Questions to ponder:

- In what important ways would life be different on such a habitable world outside the habitable zone?
- Do you think that microbial life could develop in such a place? Complex organisms?
- Do you think life could survive in such a place if implanted from elsewhere?



Michael Carroll (spacedinoart.com)

We are about to move on to topics in which we will include much more scientific speculation than we have so far. Which of the following statements is speculation? Select **all** that apply.

Question!

A. The Solar System is 4.567 billion years old.
B. The chemical composition of the universe evolved over the Universe's life.
C. About 16 new stars form in the Milky Way galaxy each year.
D. Practically every star has one or more planets.
E. One out of four Earth-like or super-Earth planets is habitable.
F. All of the above.
G. None of the above.

Which of the following statements is theoretical? Select **all** that apply.

Question

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F. All of the above.
G. None of the above.

Which of the following statements is experimental fact? Select **all** that apply.

Question

A. The Solar System is 4.567 billion years old.
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F. All of the above.
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The origin of biology on habitable planets

A rocky planet survives migration and settles down in an orbit in which the temperature will stabilize in the liquid-water range. The temperature will stay there for billions of years, either because it is in the habitable zone, or because it is tidally heated in a resonant orbit.

The temperature will not equilibrate to that happy value for a long time, though, since the planet is born molten and will take millions of years to cool off to a solid, silicate-rock surface.

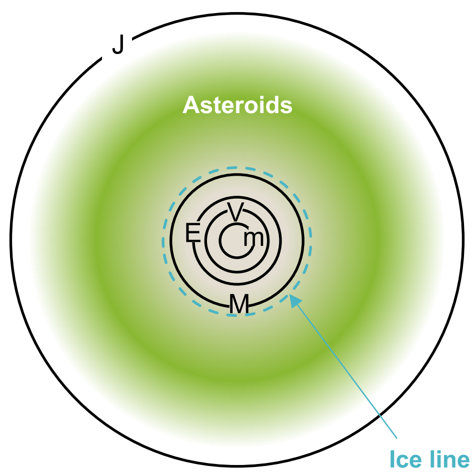
While the planet is molten, it retains very few of the **prebiotic** or **volatile** molecules that went into its creation, except for the heavier gases in the atmosphere (e.g. N_2, CO_2).

These volatile molecules are extremely important for life, so it is a good thing that there are still smaller bodies around which had never completely melted and therefore still retain some volatiles.

The Solar System's smaller bodies

The best-known nearby collection of small bodies is the **Asteroid Belt** between the orbits of Mars and Jupiter.

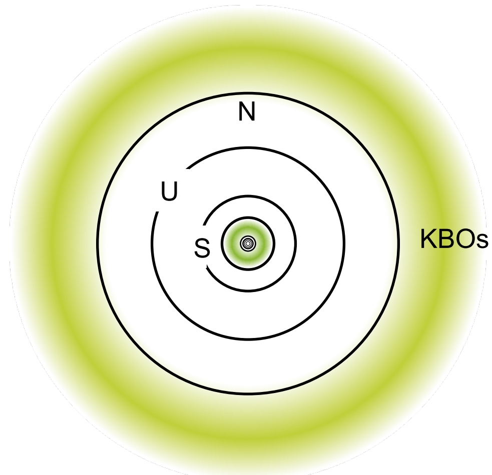
The total mass in the main belt is thought to be about 0.04% of Earth's mass. There are about 200,000 asteroids larger than 1 km in diameter. They typically lie about 0.07 AU (about 3.5 million miles) apart – not close together as is normally depicted in the movies.



Asteroids in the Kuiper Belt

Outside Neptune's orbit is the **Kuiper Belt**, best known as the source of short-period comets, and as the family to which Pluto belongs.

Kuiper-belt objects (**KBOs**) are small and cold, and therefore faint; it will take another 10-20 years to complete their census. But there used to be many more.



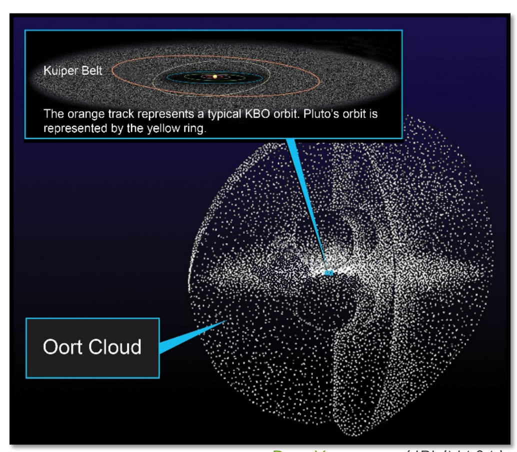
The Oort Cloud

Even further out, at about 10,000 AU, we find the **Oort Cloud**, best known as the reservoir of long-period comets.

- There is only one non-cometary candidate known to be an Oort Cloud object – Sedna.

When Uranus and Neptune switched orbits due to perturbations by Jupiter and Saturn around 600-800 Myr after the Sun formed, something like 99% of the small bodies of the Solar System were violently displaced.

- Many were ejected and formed the Oort Cloud.
- Many others were driven into the inner Solar System, where the episode known as the Late Heavy Bombardment is evident in the cratering records of the Moon, Mars, and Mercury.



Don Yeomans (JPL/NASA)

Sweeping up the small bodies

Like all the planets, Earth constantly sweeps up smaller bodies. The rate is always much larger than the rate at which Earth loses mass (hydrogen, helium, satellites,…)

The accumulation rate seems to vary quite a bit: 10^7–10^9 kg per year.

Much of the mass is in rather large bodies, most of which come from the asteroid belt. Since these are relatively infrequent, they are responsible for this variation.

There is substantial mass, though, in the small bodies and interplanetary dust particles (**IDPs**), nearly all of which come from comets (comet tails, specifically).

All of these bodies come from beyond the snow line (1.5–1.9 AU).

About 4 Gyr ago, the rate was about 1000 times the present rate.

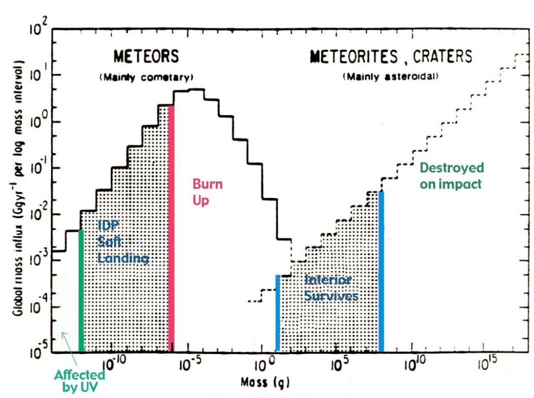
Sweeping up the small bodies

These small bodies have been decorating the surface of the Earth with ices and organics.

Much of it burns up, which of course does not necessarily destroy small molecules like water.

90% of Earth's oceans were probably delivered by asteroids, the rest by comets.

However, not all of them burn up: IDPs make a soft landing with their molecules intact, and moderate-size meteorites land with their interiors intact. Molecules that have been preserved since the object's beginning are then released.



Anders (1989)

Sweeping up the small bodies

Of particular interest are hydrocarbon molecules, since Earth's surface is so poor in carbon.

IDPs are rich in organic molecules (10% by mass). They account for most of the 3.2×10^5 kg per year of carbon the Earth currently sweeps up (Chyba & Sagan 1992).

But large parcels arrive as well, like the Murchison meteorite (1969, Australia), which contained a treasure trove of biomolecules (table from Machalek 2007).

Prebiotic molecule	Concentration by mass
Water	12%
Amino acids	17-60 ppm
Ordinary hydrocarbons	> 35 ppm
Aromatic hydrocarbons (PAHs)	3319 ppm
Fullerenes	> 100 ppm
Organic acids	> 315 ppm
Purines and Pyrimidines	1.3 ppm
Alcohols	11 ppm
Sulphonic acids	68 ppm
Phosphonic acids	2 ppm

Question

Of the five most abundant classes of molecules present in the Murchison meteorite, how many are found in the interstellar medium?

A. Only water
B. Water, PAHs, and fullerenes
C. Water, organic acids, and alcohols
D. All but amino acids
E. All five

Is delivery necessary? Formation of prebiotic molecules *in situ*

It was long assumed that any prebiotic molecule would need to be formed *in situ* (in place, so on Earth) from simpler, inorganic molecules.

In the 1920s and 1930s, Oparin (USSR) and Haldane (UK) proposed that the early Earth would have had no prebiotic molecules and that a **reducing** atmosphere similar to the giant planets would give rise to them.

- Reducing = components of gas easily give up electrons. Examples include hydrogen, ammonia, methane.
- Opposite of **oxidizing**.

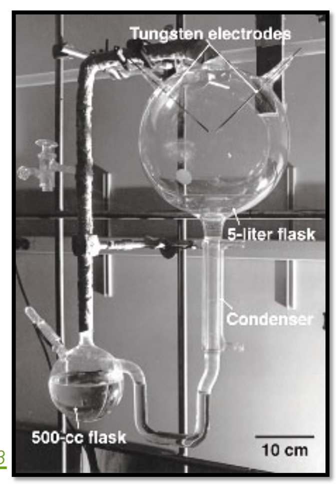
Miller and Urey (USA) reasoned that lightning and solar UV would provide the energy necessary for the neutral-neutral reactions and simulated these conditions in the lab.

The original Miller-Urey experiment

A classic molecular biology experiment

- Ingredients: H_2, ammonia (NH_3), methane (CH_4) gas in 5-liter flask, connected by condenser to the "ocean," consisting of water in the 500 cc flask.
- A high-voltage discharge (a continuous spark) simulated lightning and provided ultraviolet light as well.
- Ran like this for one week. The experiment was repeated several times with new glassware and electrodes.

Result: After one week, 10-15% of the carbon had become incorporated into a wide variety of **prebiotic molecules** including several amino acids, sugars, lipids, and other organic acids.



Miller 1953

Compound	Yield	Compound	Yield
Glycine	270	Iminoacetic-propionic acid	6
Sarcosine	21	Lactic acid	133
Alanine	145	Formic acid	1000
N-methylalanine	4	Acetic acid	64
Beta-alanine	64	Propionic acid	56
Alpha-amino-n-butyric acid	21	Alpha-hydroxybutyric acid	21
Alpha-aminoisobutyric acid	0.4	Succinic acid	17
Aspartic acid	2	Urea	8
Glutamic acid	2	N-methyl urea	6
Iminodiacetic acid	66		

Miller 1953, Miller & Urey 1959

Results of the original Miller-Urey experiment

Lots of formaldehyde (H_2CO), hydrogen cyanide (HCN), cyanopolyyne (HC_3N), and urea (NH_2CONH_2) formed in the gas and condensed into the "ocean."

Note that these are also seen in the ISM and/or meteorites.

The other molecules formed in the water with "wet chemical" reactions, among the formaldehyde, hydrogen cyanide, cyanopolyyne, and urea. A good example is the "Strecker synthesis" of the amino acids.

Modern "Miller-Urey" results

Alas, it is not so simple: it seems impossible that Earth's early atmosphere was *this* reducing.

- Gravity is insufficient to retain much hydrogen.
- Volcanism, heat, and solar UV light seem sure to have made the atmosphere oxidizing (opposite of reducing), producing lots of CO_2 and N_2, and vaporizing water. The atmosphere would have been more like that of Saturn's moon Titan.
- Formaldehyde, hydrogen cyanide, cyanopolyyne, and urea are not produced by reactions in a $CO_2/N_2/H_2O$ atmosphere.
- This has moved attention to volcanic vents, which can produce locally high concentrations of reducing gases like methane (CH_4) and ammonia (NH_3), and where lightning naturally occurs.

As long as the precursors formaldehyde, hydrogen cyanide, cyanopolyyne, and urea are supplied, interesting molecules get formed in the "ocean."

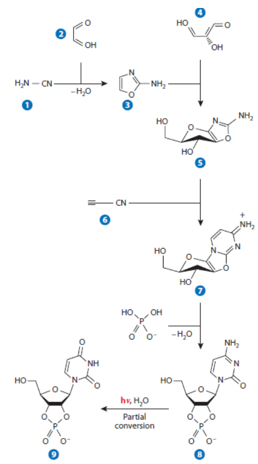
Modern Miller-Urey results

Hydrogen cyanide and ammonia have been shown to react with water to produce adenine, one of the **nucleobase** components of DNA and RNA (Oro 1961).

Two more nucleobases, cytosine and uracil, are made in water by reacting cyanopolyyne and urea (Robertson & Miller 1995).

The sugar ribose can be formed in high concentrations of formaldehyde: five formaldehyde molecules make one ribose (Reid & Orgel 1967). This works better in soil or clay than in water, though.

From these, entire **nucleotides** – combinations of nucleobases, ribose and phosphate from which RNA is built – form, all in the same "ocean" (Powner et al. 2009).



M-U formation of nucleotides (McCollum 2013)

Summary: synthesis of prebiotic molecules

Either by the slight reducing properties of the early atmosphere ***or*** by the reducing atmosphere near volcanic vents ***or*** by delivery *via* IDPs and meteorites of molecules formed in the reducing atmosphere of the ISM, it seems that the early Earth had supplies of formaldehyde, hydrogen cyanide, cyanopolyyne, and urea.

With the liquid water supplied by meteorites serving as the solvent, the primary prebiotic molecules – the amino acids and the nucleoside bases – can be made without much trouble or imagination.

The next step is the polymerization of these monomers: the generation of long, much more complex molecules that can encode information.

Wet chemistry of amino acids

In water, important modifications are made to amino acids and nucleoside bases, owing to the **propensity of water to grab positive charges**.

When any acid dissolves in water, loosely-bound hydrogen nuclei attach themselves to water and leave their electrons behind. Example of hydrochloric acid:

$$HCl + H_2O \rightarrow Cl^- + H_3O^+ \qquad \text{(in liquid water)}$$

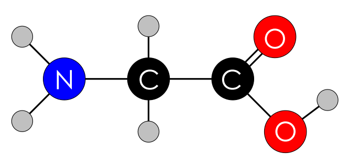
This would happen just as well in liquid ammonia, which shares this propensity with water:

$$HCl + NH_3 \rightarrow Cl^- + NH_4^+ \qquad \text{(in liquid ammonia)}$$

Wet chemistry of amino acids

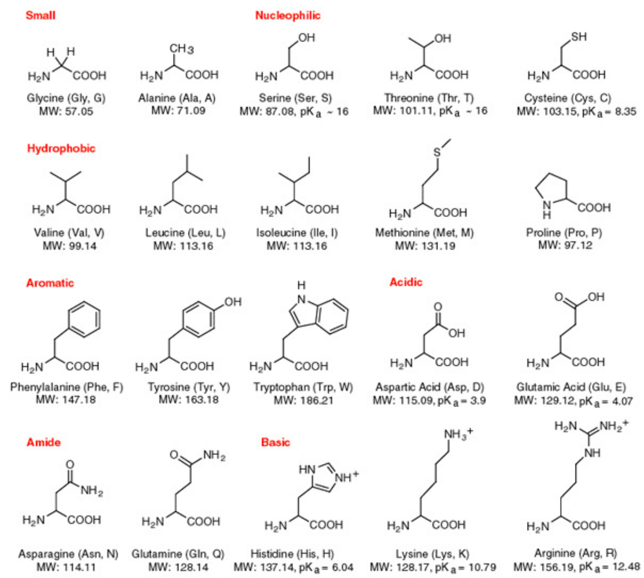
Amino acids express these tendencies on both of their ends: "amino" refers to the NH_2 group they all have at one end, and the H in the COOH organic-acid group they have at the other end is the one that comes off in the solution.

- Example: the simplest amino acid, glycine – NH_2CH_2COOH



Note the color code, which we will use from here on.

The cool thing about them is that **the NH_2 group on the end has the same propensity to grab positive ions as ammonia does in liquid**.

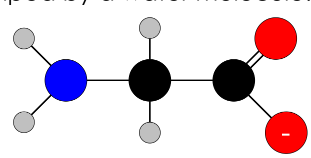


Amino acids

Wet chemistry of amino acids

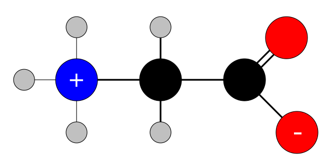
In an aqueous solution, the H in the COOH group is swiped by a water molecule…

$NH_2CH_2COOH + H_2O \rightarrow NH_2CH_2COO^- + H_3O^+$



And the amino group acquires an H^+ from a H_3O^+ (hydronium) ion:

$NH_2CH_2COO^- + H_3O^+ \rightarrow (NH_3)^+CH_2COO^- + H_2O$

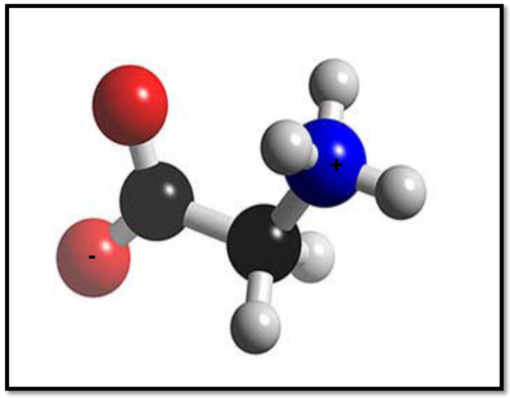


Wet chemistry of amino acids

This is a general and key property of amino acids in solution: there is a positive electrical charge localized on one end (the amino group) and a negative charge on the other end, with the molecule being electrically neutral.

These molecules are called **zwitterions** by biochemists. All amino acids are zwitterions when dissolved in water.

Zwitterions can thus undergo **ion-molecule** chemical reactions with each other, plus-end to minus-end. This is the same class of reactions as in molecular synthesis at low T in the interstellar medium.



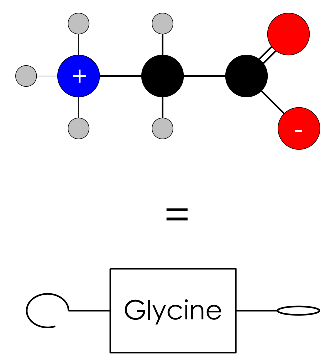
Question

What is special about ion-molecule chemical reactions as compared to neutral-neutral (n-n) reactions?

A. They have no energy barrier, and the n-n reactions do.
B. They are much rarer under most conditions because high degrees of ionization are rare.
C. They heat their surroundings much less than n-n reactions do.
D. They only work in the interstellar medium, and n-n reactions only work elsewhere.

Wet chemistry of amino acids

That the electrical charges are localized on these groups rather than shared among the atoms of the molecule as, for example, the electrons are among a benzene ring, means that the amino ends of amino acids will be electrically attracted to the acid ends of other molecules.

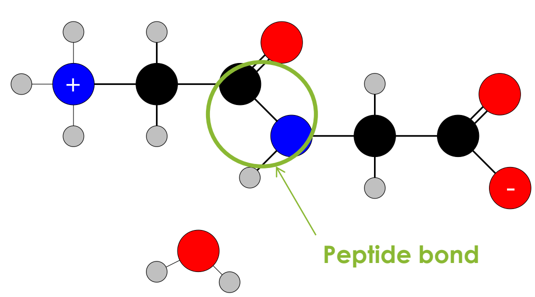


It is as if each amino acid has hook and eye connectors on opposite ends.

Wet chemistry of amino acids

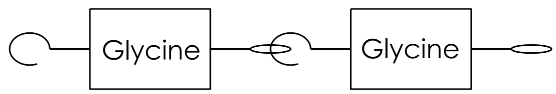
The electrostatic attraction between hook and eye can lead to chemical bonds, creating a longer zwitterion and a spare water molecule. Example of two glycines:

$$2[(NH_3)^+CH_2COO^-] \rightarrow (NH_3)^+CH_2CONHCH_2COO^- + H_2O$$

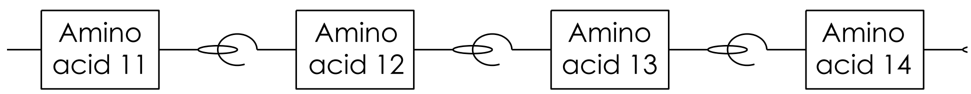


Wet chemistry of amino acids

Or, using our hook and eye shorthand, and noting that a spare water molecule is generated every time a hook and eye connect:



Obviously, this can be repeated *ad nauseam*, and it does not need to be the same amino acid every time. A long-chain **polymer** has been created from amino-acid **monomers**.

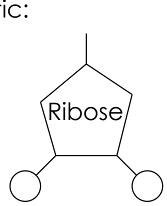


A polymer of amino acids is generally called a **protein** (or a polypeptide).

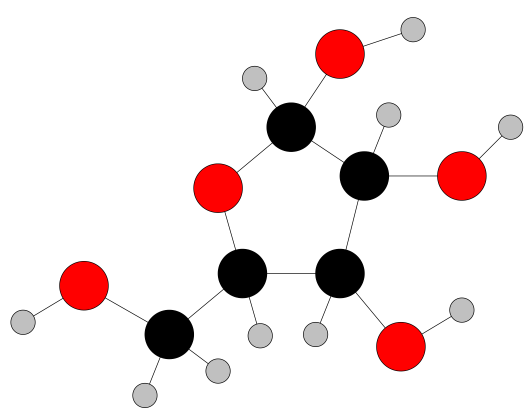
Other monomers: wet chemistry of ribose

Ribose ($C_5H_{10}O_5$) is a sugar that is made in the "ocean," or even better on dry land, by formaldehyde either delivered or made by Miller-Urey means.

Some of the dangling OH groups are good at making bonds in much the same way as the dangling OH in glycine. A shorthand schematic:



Glycine-like "eyes" ⟶

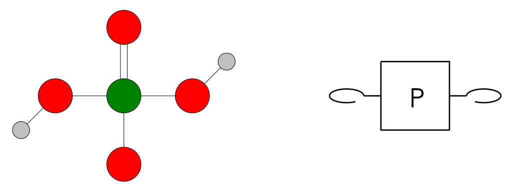


Other monomers: phosphoric acid

Phosphoric acid (H_3PO_4) can also be made in electrical discharges in a reducing atmosphere if there is any phosphorous around. (There is never much.)

In solution, $H_2O + H_3PO_4 \rightarrow H_3O^+ + H_2PO_4^-$

The two dangling OH groups of $H_2PO_4^-$ (phosphate ion) are good at making bonds with the "eyelet" groups on sugars in much the same way that the "hook" groups do in amino acids. The phosphate ion hook plus sugar eye lead to a bond that, like a peptide bond, releases a water molecule.



Question

What is a zwitterion?

A. A molecule with positive charges on each end.
B. A molecule with negative charges on each end.
C. A molecule with positive and negative charges on opposite ends.
D. A molecule with a net positive or negative charge.

Which is an example of a zwitterion?

Question

A. Any amino acid in water
B. Any amino acid in crystalline form
C. Any acid in water
D. Any acid in crystalline form
E. Any organic acid or alcohol in water

What do zwitterions have to do with the polymerization of amino acids (AAs)? **Select all that apply.**

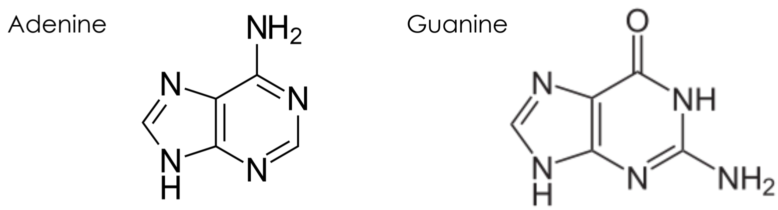
Question

A. AAs are zwitterions in the interstellar medium.
B. AAs are zwitterions in solution.
C. Electrostatic attraction guarantees that NH_3 groups of two AAs will match up.
D. Electrostatic attraction guarantees that NH_3 groups will match up with OH groups.
E. Peptide bonds form between two AAs when an NH_3 group encounters an OH group.
F. Peptide bonds form between two AAs when their NH_3 groups encounter each other.

Other monomers: wet chemistry of nucleobases

A particularly interesting family of molecules made in the Miller-Urey ocean are the **nucleobases**, which divide into two categories: **purines** and **pyrimidines**. Five of these are of particular importance.

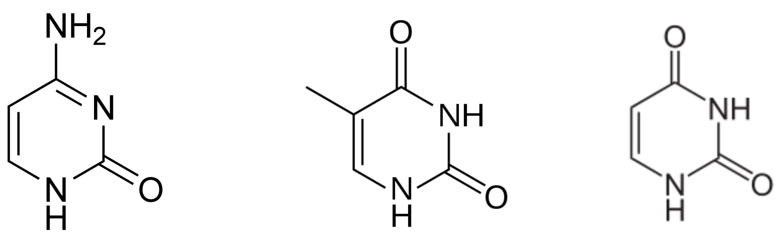
- Purines: **adenine** ($C_5H_5N_5$) and **guanine** ($C_5H_5N_5O$), planar molecules each containing two CN rings



- These two purines are essential in all Earth life forms. Another purine, caffeine, is essential to most of the life forms in this room. ☺

Wet chemistry of nucleobases: pyrimidines

- Pyrimidines: **cytosine** ($C_4H_5N_3O$), **thymine** ($C_5H_6N_2O_2$), and **uracil** ($C_4H_4N_2O_2$), also planar molecules. Their structure, in order (C-T-U):

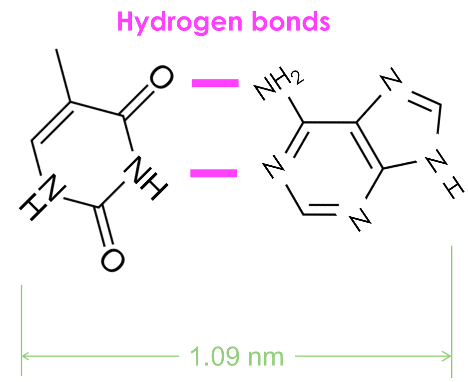


- These are also essential to Earthly life forms: thymine in DNA, uracil in RNA, cytosine in both.
- The sizes of these five molecules match each other in a special way that promote **hydrogen bonding**.

Wet chemistry of nucleobases: hydrogen bonds

Hydrogen bonds are weaker than the usual (covalent) chemical bonds: they are the manifestation of the attraction of an atom (like O and N) that is good at stealing hydrogen, for the hydrogen atoms are covalently bound to other atoms.

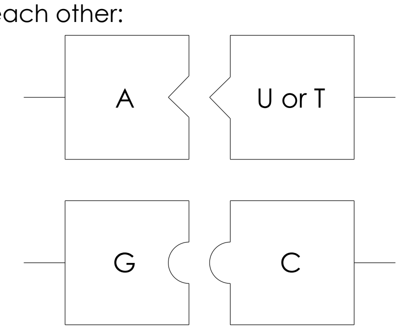
The essential purines and pyrimidines match up in pairs with particularly strong hydrogen bonds: adenine with thymine or uracil…

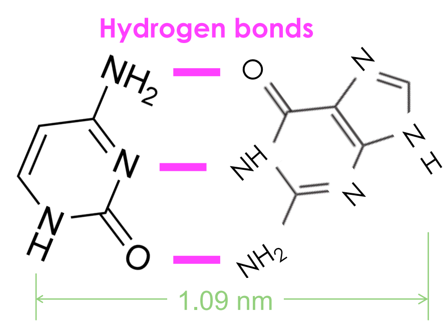


Wet chemistry of nucleobases: H bonds

…and guanine with cytosine

It will be useful to have a schematic shorthand for these monomers, too, to reflect their key-like ability to bond with each other:



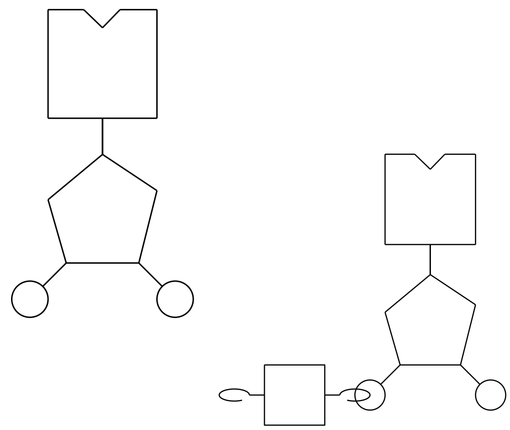


Note that A-T/U and G-C pairs are precisely the same length, 1.09 nm between the NH groups. All other abundant purine-pyrimidine pairs have quite different lengths.

Wet chemistry of nucleobases

Each nucleobase has an NH group that is good at combining with a dangling OH group on ribose, making a bond rather like a peptide bond and releasing yet another water molecule. The combination is called a **nucleoside**.

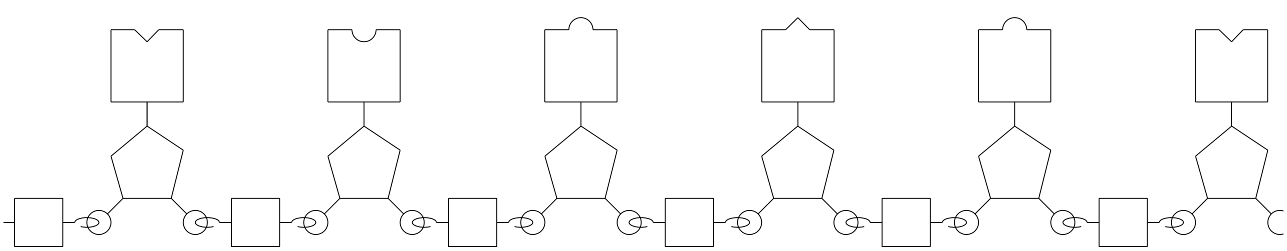
Hanging a phosphate group on the sugar (releasing a water molecule, of course) produces an interesting monomer called a **nucleotide**. Note that they can be chained together, hook to eye, making a sugar-phosphate backbone with nucleobases sticking out.



Nucleotide polymers

Nucleotides can polymerize into long chains, like amino acids can polymerize into proteins.

Owing to the use of ribose and nucleobases, and the hook-and-eye ends, this particular kind of polymer is called a **ribonucleic acid (RNA)**.

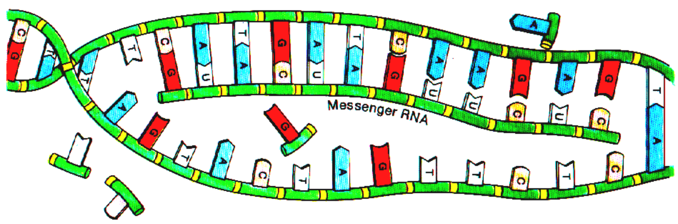


Nature “makes” choices

There are several chemically equivalent ways to polymerize amino acids and nucleotides, but only one each prevailed in Earthly life.

Why? The leading explanation is that those were the ones easiest to replicate, and **natural selection** therefore favored them: they were made consistently, and thus outnumbered the ones that were randomly made.

How? That is debated, but several experiments and theories provide explanations, as we will see.

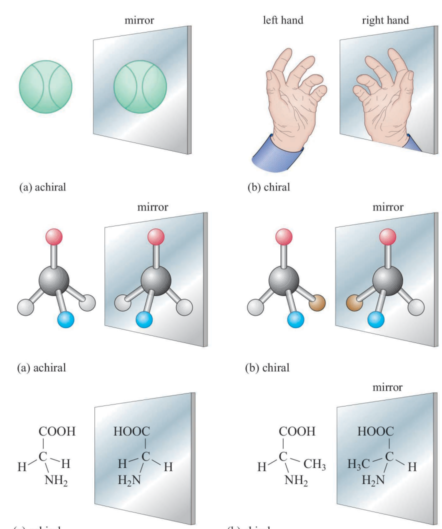


Isomers & chirality

Isomers: Molecules with identical chemical contents but different atomic arrangements

Isomers can be classified as either left-handed (levo, **L**) or right-handed (dextro, **D**), depending on the specific arrangement of the atoms; this is known as **chirality**.

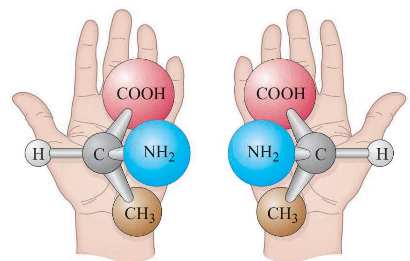
Discovered by Biot, who also discovered that meteorites fall from the sky.



Isomers & chirality

All amino acids in Earthly life are L-type. (Except glycine, which is achiral.) We are not sure why.

- Chemical reactions (like the Miller-Urey experiment) produce an equal amount of L and D (called a **racemic** mixture).
  - The ISM probably does as well.
- There is an excess of L-type amino acids found in meteorites.
  - Certain minerals in meteorites have a helical form.
  - UV circularly polarized light preferentially destroys either L- or D-type molecules, depending on its polarization.



Alanine is a chiral amino acid.

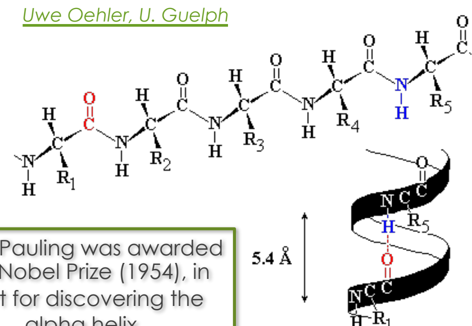
Chirality & the alpha helix

A protein of all L or all D amino acids forms a spiral structure called an **alpha helix**, with the alpha Cs (the ones between the NH_2 and COOH groups) and Ns on the inside, the side groups on the outside, and hydrogen bonds between the C=Os and the NH groups four amino acids down the chain.

Ls make a right-hand spiral; Ds would make a left-hand spiral.

A racemic mix of amino acids could not make such a spiral.

Uwe Oehler, U. Guelph



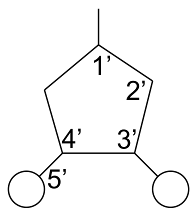
Linus Pauling was awarded the Nobel Prize (1954), in part for discovering the alpha helix.

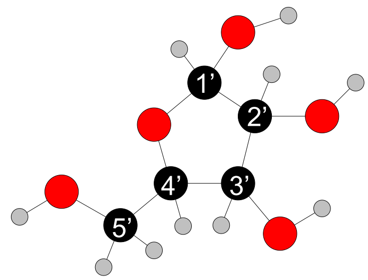
Right-hand spiral

Nucleotides – binding to ribose

Binding to ribose: Carbons 1', 2', 3', and 5' look identical, but a long straight polymer chain is only possible if a nucleobase bonds to 1' and phosphates to 3' and 5'.

Not sure how it originally effected, but it was found by Leslie Orgel that, when in a solution, double-oxidation-state ions like Zn^{++} catalyze polymerization of long chains (as long as 50) in the correct alignment.



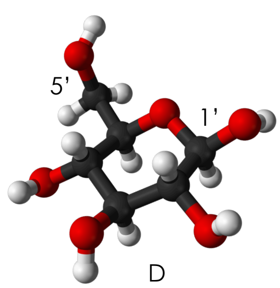


Sugars are also isomers

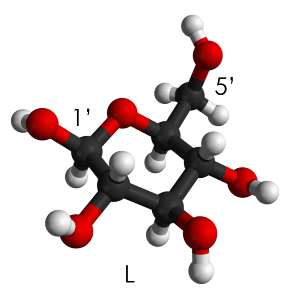
The five important nucleobases and phosphoric acid do not exhibit isomerization, but sugars do.

Sugars used in Earthly life are all D-type: not just the ribose that forms the backbone of RNA, but also the other sugars like glucose that play roles in energy and metabolism of organisms.

Ribose

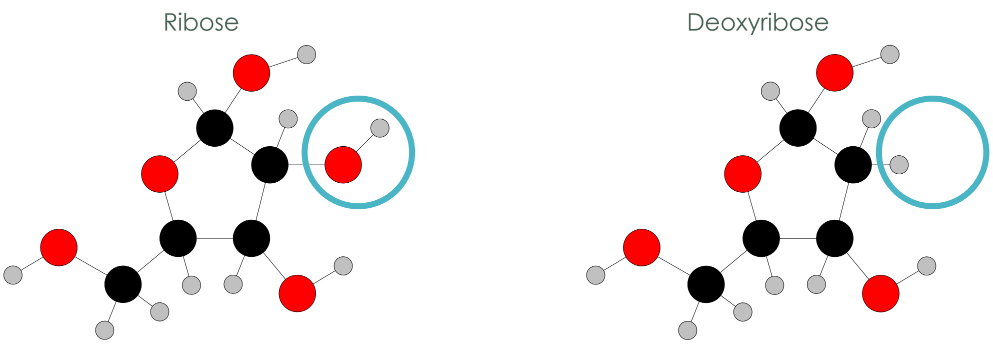


D

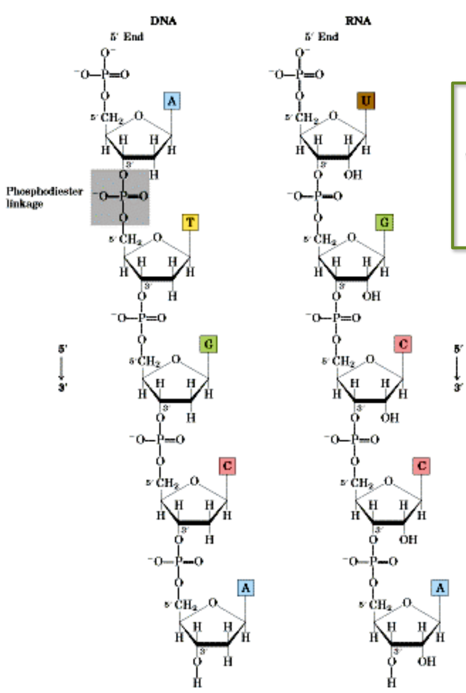


L

Nucleotide polymerization



Nucleotide polymerization is just as easy with **deoxyribose** instead of ribose: this lacks an OH on the 2' carbon and has a hydrogen in its place.



Crick, Watson, and Wilkins were awarded the Nobel Prize (1962) for discovering DNA's double helix.

DNA

When deoxyribose is the sugar, thymine is substituted for uracil; otherwise, the same bases are used.

The polymer that uses deoxyribose is called a **deoxyribonucleic acid (DNA).**

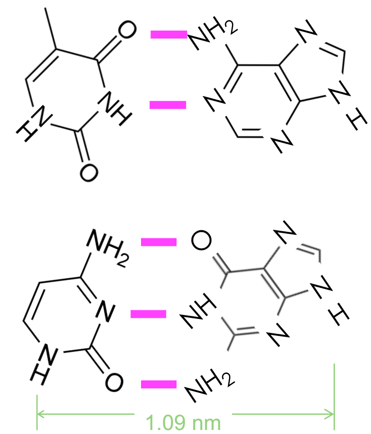
Both DNA and RNA have helical structures, dictated by the twists in their D-sugar backbones.

Geometry of nucleobase pairs

Bonds to the sugars are made by NH groups on opposite sides of the hydrogen-bonding sites.

In adenine-thymine or guanine-cytosine pairs, these sugar-bonding groups are precisely 1.09 nm apart.

The five essential nucleobases are the only ones this size. We cannot substitute others, or else DNA and RNA would not **replicate**…



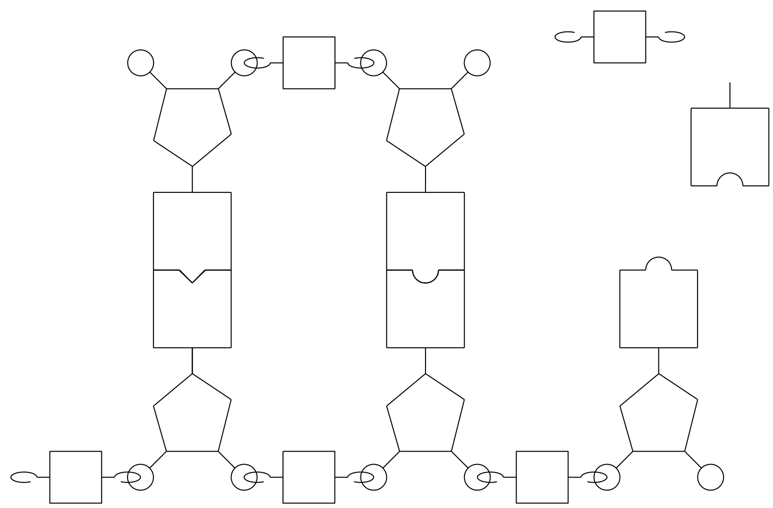
Replication of nucleic acid

Requirement (#3) of life is replication. Can proteins and nucleic acids replicate, or at least mass-produce?

- If they can, this could explain the emergence of classes of proteins and nucleic acids as components, the assembly of which could serve more complex, life-like roles.

Perhaps the easiest to envision is for short strands of RNA. Suppose a short RNA lies in a solution containing nucleobases, ribose, and phosphoric acid.

- A **complementary polymer** can form by hydrogen-bonding nucleotides onto the RNA's nucleobases, hooking up the phosphates and sugars, and then severing the hydrogen bonds.
- The complementary polymer can do the same, thus replicating the original.
- Hydrogen bonds are much weaker than covalent bonds. The "copies" can be stripped off without harming the original chain.
- Other polymers are capable of "unzipping" the H bonds in DNA. Once unzipped, both sides can bond to nucleotides in the solution just like RNA, and thus the DNA replicates: bases in same order as original.



Replication of RNA

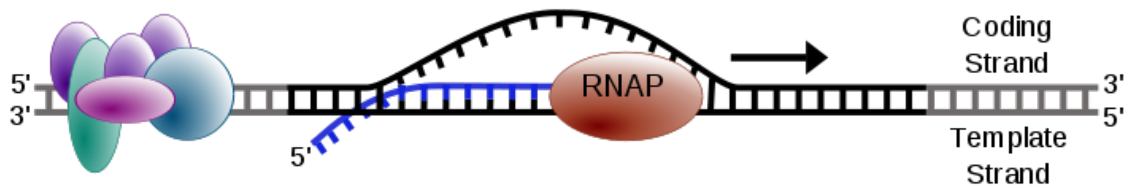
Transcription

Long chains of DNA can be partially unzipped, capture a complementary chain of nucleotides, have this new chain of RNA zip off, and have the DNA zip back up. This form of partial replication is called **transcription**.

Unzipping does not frequently happen spontaneously, except when the solution temperature experiences small increases.

- Certain polymers with the right molecules in the right spacing can do it, though.
- Among Earth life forms, the unzipping and rezipping of DNA is done with a protein we call **RNA polymerase**.
- This is an example of an **enzyme**: proteins that catalyze chemical reactions which means that they do not get chemically changed in the process, like the dust grains that catalyze the formation of molecular hydrogen.
- Replications of DNA and RNA, and transcriptions, require – in the current age – a special class of proteins.

Animation of transcription



Codons

Three-nucleotide sequences have a special significance, and thus their own name: **codon**.

Because there are four different nucleobases used in either nucleic acid, there are

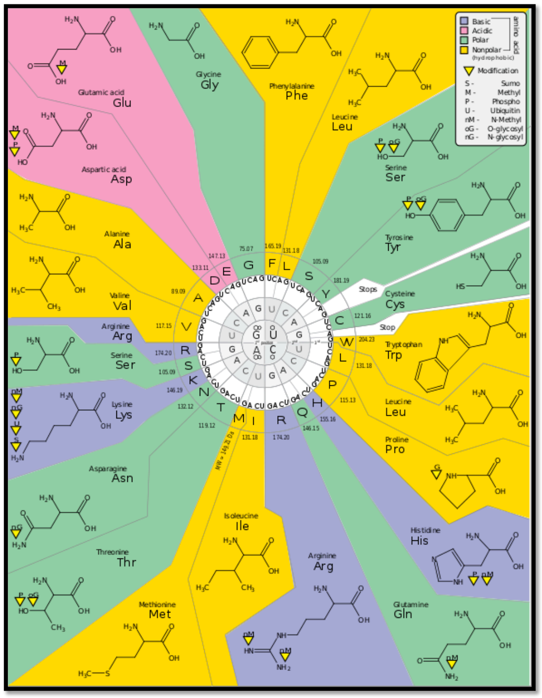
$$4 \times 4 \times 4 = 64$$

different codons.

As we will see, this has significance for the encoding of information used by modern organisms to build proteins.

- For example, there are 20 amino acids* used in human proteins, and the base sequences that indicate the beginnings and ends of codon sequences. 20 + 2 = 22 < 64, so three-base codons work.
- *Note: There are really 21 amino acids used in human proteins, but the 21st (selenocysteine) is relatively rare in proteins and uses a special signal in addition to the Stop codon.

Codons – the genetic code



Question

Instead of 20, suppose Earthly organisms used only 10 different amino acids. How many nucleotides could be used in a codon?

A. 1
B. 2
C. 3
D. 4
E. Any number greater than 1