THE DANCE OF THE BIOMOLECULES—BIOCHEMISTRY

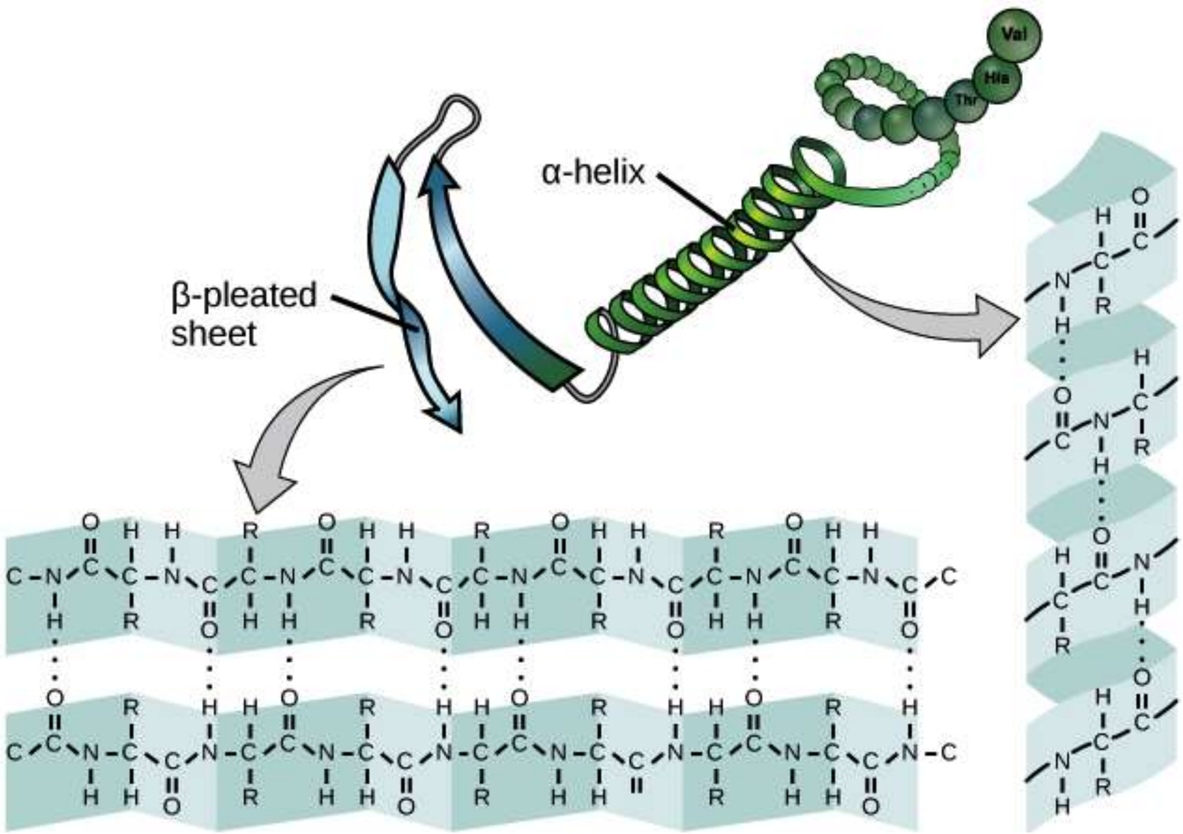
> "We are many parts, We are all one body,
> and the gifts we have, we are given to share.
> May the Spirit of Love make us one indeed;
> One, the love that we share,
> one, our hope in despair,
> one, the cross that we bear."
>
> --refrain, "We are Many Parts", Marty Haugen, GIA Publications
> https://www.youtube.com/watch?v=u8oWIiE75mI

QUESTIONS TO PONDER

- What functions are most important to you?
- We most often interact with those who are nearest to us, just like the neighboring atoms. However, there are interactions at a distance that are often transformative for us. After listening and watching this video, consider the following questions: https://www.youtube.com/watch?v=IjMGpE3TQWo The Molecular Music Project
    - Name those more distant connections in your own life.
    - What is the attraction?
    - How does that attraction allow you to function in a way you could not do by simply associating with your nearest neighbors?
- What does my own dancing with others teach me about myself? You may wish to consider pondering this question both
    - from your actual experience of dancing as well as
    - from the metaphorical experience of moving around with other people.
- In our lives are basic building blocks we use to create spaces for ourselves, allowing us to complete the functions we desire, individually and as a community.
    - What are the basic building blocks in your life that you use to create those spaces?
    - How do you construct your spaces?
    - For what do you use these spaces?
    - Do these spaces benefit
        - only yourself?
        - yourself and your nearest neighbors?
        - yourself and more distant others?
        - everyone?
- Life is not the same day-to-day and how we function needs to be flexible. How could you increase the flexibility of your spaces by changing
    - its building blocks? That is, how can we make the blocks so they can potentially come together better to achieve the function you intend?
    - the ways we connect the blocks together to create space, and therefore, function?

REFLECTION #1—Proteins, Carbohydrates, Nucleic Acids, Fats—Many Parts, One Body!!!
What would it look like if molecules could dance? Well, just like we move our bodies in expressive movement and to accomplish intended tasks, so biomolecules can move their structures to orient themselves for a specific function. This overall molecular geometry is driven by dozens of small interactions between the parts of each biomolecule. In each case the communal shape of the biomolecule determines its function.

PROTEINS
Look at this video clip of a *protein*, a series of amino acids in sequence, showing the choreography of protein folding: https://www.youtube.com/watch?v=yZ2aY5lxEGE

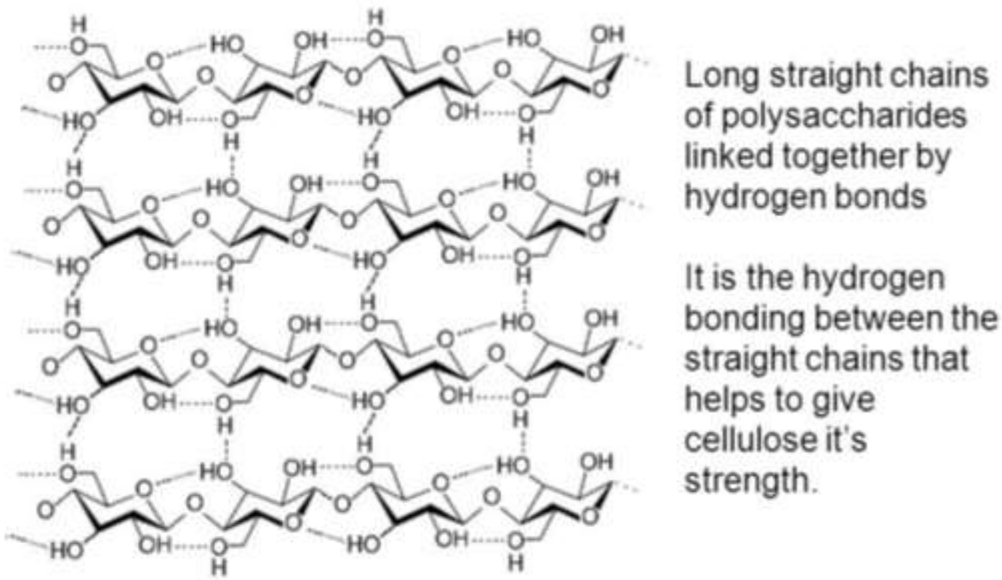


https://cdn.kastatic.org/ka-perseus-images/cd59edaf690af9b30fad410a48d4a8003f3cda53.png
Protein folding first occurs mostly by *hydrogen bonding* (shown with dotted lines in the above pictures) into two types of structures.

- In the *alpha helices* (on the right in the above figure), several pairs of H atoms of amino groups (-NH) in a peptide bond are hydrogen bonded to O atoms of the acid group (-CO) of another peptide bond 3½ residues earlier.
- Between these same groups but separated farther apart are hydrogen bonds forming *beta-pleated sheets* (on the left in the above figure).

CARBOHYDRATES

In the first video, only alpha helices were formed to simplify the animation.



https://images.slideplayer.com/26/8450011/slides/slide_21.jpg

Similarly, the overall shape of *carbohydrates* is driven by which -OH groups are connected to one another along neighboring parallel chains. Some lead to efficient storage of energy in the organism. Others, like cellulose illustrated in the above picture, are structural structures forming hair or skin.

NUCLEIC ACIDS

DNA also folds into larger structures providing the way for 2 meters of DNA to fit into cell!

How DNA is Packaged (Advanced) https://www.youtube.com/watch?v=gbSIBhFwQ4s

Nucleic acids have the familiar double-helix shape, attributed again to hydrogen bonding, but now between the nucleotides A—T & C—G in DNA; A—U & C—G in RNA, which hold the 2 opposite strands of DNA or RNA together. Bonding also occurs alternately between sugar and phosphate groups creating the backbone of the DNA or RNA. The DNA folds into coils and then coils of coils, next to chromatids, and finally to chromosomes, which are visible at cell division.

https://www.youtube.com/watch?v=brs2nMubr84

Unsaturated vs Saturated vs Trans Fats (Animation)

FATS

Finally, *fats* because of their extended non-polar side chains have numerous small, but as a total significant intermolecular forces which hold the chains together at room temperature either as solids (saturated fats) or liquids (unsaturated fats).

REFLECTION #2

Biomolecules are biopolymers which are simple collections (a.k.a. communities) of monomers repeated many times. It may at first be difficult to appreciate how this can be a creative exercise so I'd like to suggest some images that will help us to appreciate the power of this idea.

FIRST MODEL—Knitting a Sweater

I don't knit or crochet myself, but I've watched enough friends, family and even strangers to know that a very simple repetitive action, the stitch, can lead to a wide variety of objects: potholders, scarves, sweaters and afghans, to name a few. Step-by-step the pattern is repeated in a line and then that line is either repeated in its entirety or closely in some way to shape the final object. So many different things can be created from one thread of yarn! It is the interactions among the rows that holds the object together and gives it shape. All these small stitches contribute to shape of the crafted object so it can serve its purpose.

SECOND MODEL—Building a Brick Wall

Bricks are simple units that can be used to build all sorts of structures. It just takes an enormous number of them to do it. It is estimated that the Empire State Building in New York City contains over 10 million bricks as well as other associated building materials like steel, limestone and granite. One brick is a rather small unit, but lots of bricks can form impressive spaces, spaces whose specific functions are supported by its structure.

Biomolecules build at a molecular level just as architects do at a human level. There are lots of monomer units that together form the spaces needed by the cell to perform specific functions. (See the next section.)

- The average number of amino acids in a typical *protein* is 300 to 400.
- There are 6 billion base pairs in the *DNA* of just *one* cell, with an average length of about 2 to 3 meters. That's an average of 130 million base pairs in the total of our 46 chromosomes in the human body!
- There are around 30,000 glucose *carbohydrate* units in a typical glycogen molecule and a few thousand units of monosaccharides in a starch molecule.

The following contains typical examples of what functions are facilitated by the distinctive structures of each biomolecule type.

NUCLEIC ACIDS

Transferring genetic information from one generation to the next is the primary function of the *nucleic acid* DNA. Working together DNA and RNA produce all the proteins needed to make all the other biomolecules in the cell.

an animation showing 1. (at the beginning) DNA Wrapping and 2. (at 1:45) DNA Replication in "Molecular Visualization of DNA—Original High Quality Version": https://www.youtube.com/watch?v=OjPcT1uUZiE

The DNA in the nucleus of a cell contains all the genetic information of the individual organism. DNA is replicated in the nucleus with the assistance of the corresponding enzymatic proteins, just prior to cell division.

> another animation showing the pathway from DNA to a protein molecule
> https://www.youtube.com/watch?v=D3fOXt4MrOM

Parts of the DNA in a cell are used to manufacture various other substances outside the nucleus. *Messenger RNA* (mRNA) is literally the "runner" containing the complimentary-coded message from DNA, transporting it from the nucleus to the *smaller* subunit of a structure called the *ribosome* in the cytoplasm.

After the arrival of the mRNA to the ribosome, another type of RNA, called *transfer RNA* (tRNA) delivers the complimentary amino acid monomer for a protein to the ribosome. As the amino acids line up on the ribosome, its *larger* subunit makes the peptide bonds connecting the amino acids and thus forming the protein itself.

PROTEINS

Proteins have a wide variety of functions in the cell:

- As enzymes, they control the rate at which chemical reactions occur. Thus, they regulate the processes of a cell:
    - making hormones in the endocrine system and antibodies for the immune system.
        - transporting nutrients, from the very small, like ions and O_2 we breathe, to relatively larger molecules such as cholesterol.
        - regulating pH via buffer systems.
- They are used to form muscles and bones for movement.
- Proteins can also provide energy when it is in short supply from carbohydrates.

CARBOHYDRATES

Simple *carbohydrates* provide energy via cellular respiration by the breakdown of larger 6-carbon molecules into smaller ones; complex carbohydrates store energy effectively and are typically used for structural purposes in the cell walls of plants and in the hair and nails of animals.

FATS

Derivatives of *fats* with phosphoric acid are found in *every* cell membrane, both plant and animal. (See the cell membrane description in the next section for details.) Fat-based hormones are essential to the body as chemical messengers, especially in times of crisis. Fats cells store even more energy for anticipated times of food scarcity, much to the disappointment of those who are overweight!

Bless the Lord, all you biomolecules,
Proteins with your many-layered structures, bless the Lord,
Carbohydrates that supply and store energy, bless the Lord,
Nucleic acids that replicate and produce proteins, bless the Lord,
Fats with long chains of carbon, bless the Lord,
Praise and exult God forever!

MORE SCIENCE BEHIND THE REFLECTION

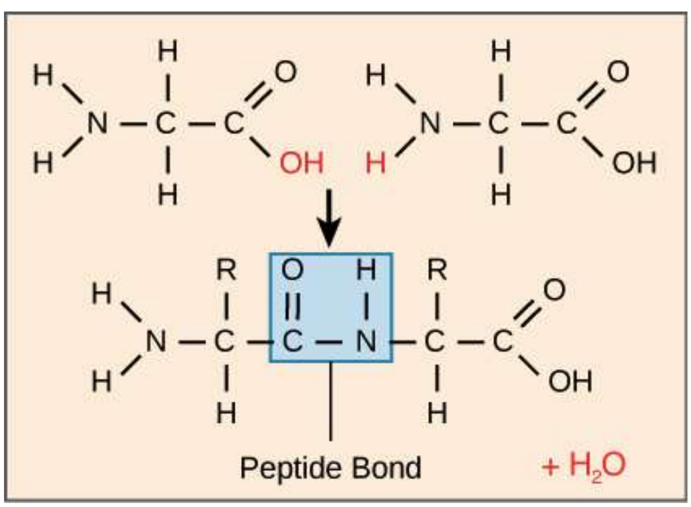
This next level of interaction is based on the chemistry of carbon compounds. Carbon has a distinctive property among the nonmetals since it can bond to itself, and sometimes to other elements, like oxygen and nitrogen in a chain. The very length of a molecule can lead to a variety of interactions beyond the bonding between two adjacent atoms, because as that chain folds onto itself the originally distant atoms in a molecular chain can begin to interact with one another. The resulting overall *shape* of each of the biomolecules has the extraordinary ability to control its *function*.

There are several classes of compounds that play important roles in supporting life. These include the biopolymers called

- *proteins* made of amino acids,
- *carbohydrates* made of sugars and
- *nucleic acids* made of nucleotides.

as well as the extended molecules called *fats,* which are simpler derivatives of glycerol.

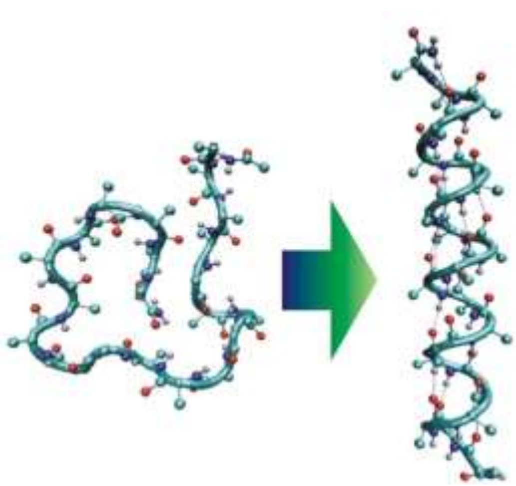
PROTEINS

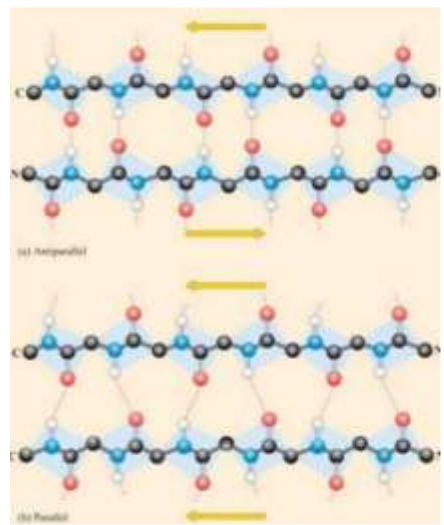


https://ka-perseus-images.s3.amazonaws.com/53664237b113b7de95110677b7c6fdca99a26baa.png

Proteins are polymers of amino acids, so called because they contain both the *amine* ($-NH_2$) functional group *and* the *carboxylic acid* (-COOH) functional group. The bonding of one amino acid to another in a straight chain is called its *primary structure*. It consists of covalent bonds as previously discussed, since the elements making up organic molecules are all nonmetals, mostly carbon, hydrogen, oxygen and nitrogen.

Just as individuals can form a long line by holding hands, so the amine and the carboxylic groups of the amino acid units join in *peptide bonds* (-CONH) to form the primary sequence of a protein molecule. (see picture above)

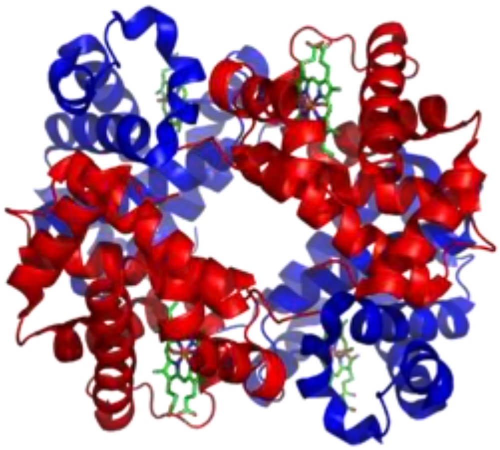




left (primary structure to alpha helix):
http://oasys2.confex.com/acs/228nm/techprogram/images/773650-0.jpg
right (beta sheet):
http://www.open.edu/openlearn/ocw/pluginfile.php/67274/mod_oucontent/oucontent/482/5de533b5/a2b23f94/s377book1chapter3_f010hi.jpg

There are 20 or so different amino acid building blocks, each with distinctive side chains, R, in the picture at the beginning of the section. The *secondary structure* of a protein consists of hydrogen bonds between sometimes distant side chains on the protein chain in structures with exotic names like *alpha helices*, *beta sheets* and *beta turns*. These interactions allow the protein to fold and to take on a 3-dimensional structure which drives its function. For instance, the folding into beta sheets often crafts an entirely new hydrophobic (water adverse) or hydrophilic (water attractive) region on one side or the other of the sheet!

Numerous other interactions of various types occur between distant parts of the protein polymer which are not specifically related to one of the three types of structures listed as secondary structures. These are referred to as *tertiary structures*, which play a parallel role in protein folding and function.



https://upload.wikimedia.org/wikipedia/commons/thumb/3/3d/1GZX_Haemoglobin.png/274px-1GZX_Haemoglobin.png

Finally, when complete protein chains interact with other complete protein chains, we call that overarching interaction a *quaternary structure*. Such interactions occur within superstructures such as hemoglobin, consisting of two pairs of identical chains (pictured as red and blue here), referred to as $\alpha_2\beta_2$. This last level of architecture creates a cradle for the delivery of the oxygen molecule to tissues throughout our bodies!

To summarize, protein folding occurs by several types of intermolecular forces between the side chains on different amino acids:

- These are hydrogen bonds, polar interactions, or induced dipole forces collectively called van der Waals forces after the Dutch scientist who first studied them.

In addition, the side chains may also form ionic bonds. They can form disulfide (S-S) bridges in the case of two of the twenty or so amino acids.

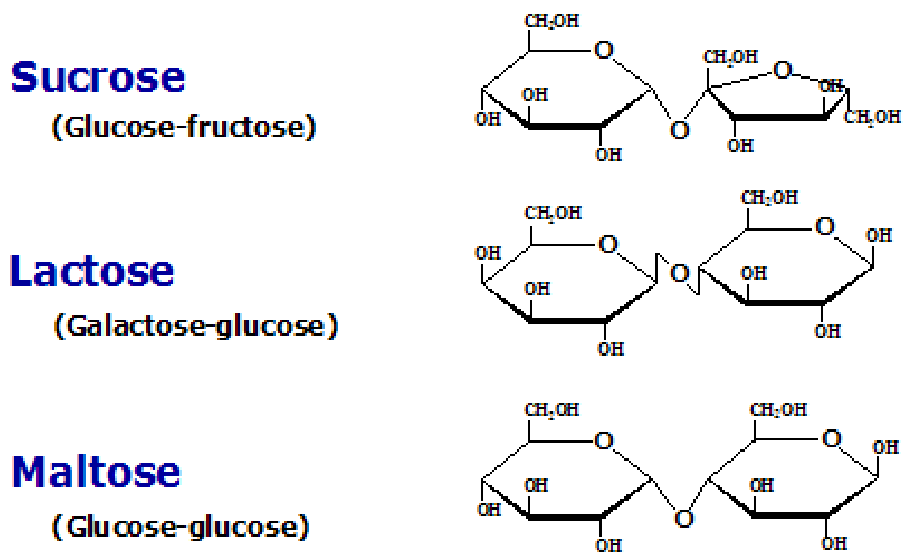
The overall shape of any strand is also influenced by whether the side chain is attracted to water (hydrophilic) or not attracted to it (hydrophobic). As you might expect, the hydrophilic side chains remain on the outside of the protein next to the water molecules, and the hydrophobic ones tend to be buried on the inside of the protein. In the video each of the spirals ended up looking like a pile of logs in a fireplace. This overall shape gives the protein its function.

Thousands of other proteins act as biological catalysts (a.k.a. enzymes) promoting specific chemical reactions within organisms. Each one has a shape distinct to its function. Structural proteins are found in hair, skin and muscle. Each molecular shape has an impact on the function and/or appearance of the larger structure. If just one amino acid is changed by mutation, the shape, and therefore, the function of the protein is lost.

CARBOHYRATES

https://www.ontrack-media.net/biology/bm1l1rimage11.jpg

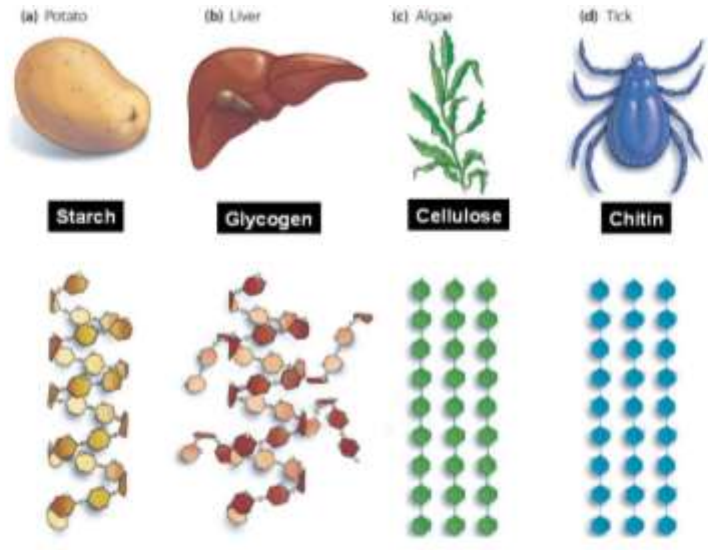
Carbohydrates, $(CH_2O)_n$, carbon + water [hydrated], are sugar polymers. All three of these 6-carbon *monosaccharides* can be funneled into cellular respiration as glucose releasing energy.



https://cdn1.byjus.com/chemistry/wp-content/uploads/2016/02/CarbCh4.png

Disaccharides are pairs of monosaccharides, bonded together with the release of water. For two $C_6H_{12}O_6$ monosaccharides they become $2(C_6H_{12}O_6) - H_2O = C_{12}H_{22}O_{11}$. The most familiar of these $C_{12}H_{22}O_{11}$ *disaccharides* include:

- sucrose [table sugar], consists of 1 unit of glucose and 1 unit of fructose
- lactose [milk sugar, from the word for lactation], 1 unit glucose + 1 unit galactose.
- maltose [sugar in malted drinks], 2 units of glucose

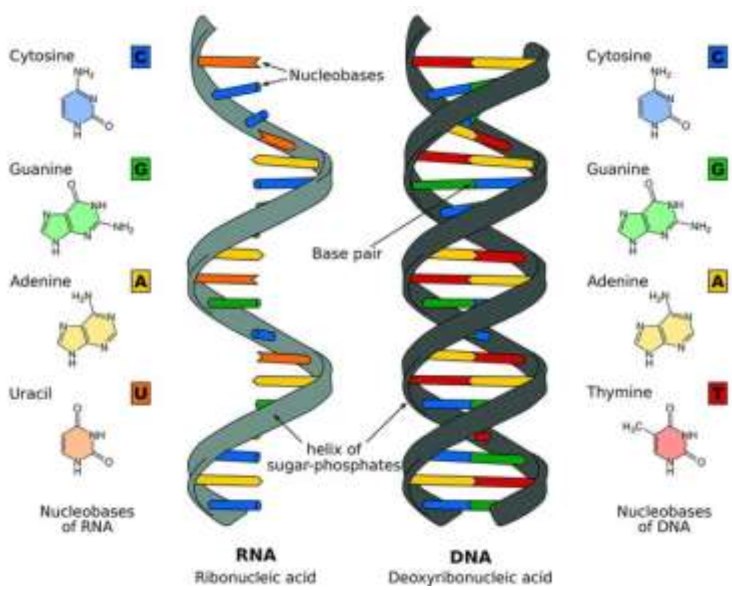


https://images.slideplayer.com/33/8239443/slides/slide_12.jpg

Longer chains of saccharides include the *polysaccharides* that may be used for the storage of energy, such as in *starch* or *glycogen*, or for structural purposes, such as in *cellulose* or *starch* from plants or *chitin* in the exoskeletons (shells) of insects. Again, the joining together of these smaller biomolecule units serves a macroscopic purpose!

NUCLEIC ACIDS

The most famous nucleic acids are DNA, deoxyribonucleic acid, and RNA, ribonucleic acid, which we know encode and store information in every cell or help in its replication, respectively!



https://www.thoughtco.com/thmb/8NJbTcgkHWzcpZX0EQysOr4mPjE=/768x0/filters:no_upscale():max_bytes(150000):strip_icc()/DNA-RNA-58dacf2e5f9b584683a1c375.jpg

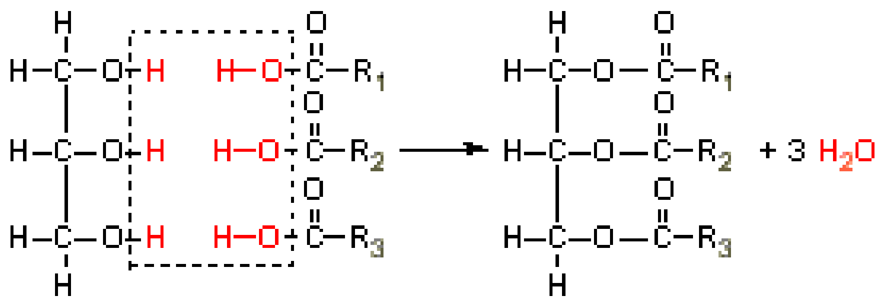
The primary structure of each consists of a sugar-phosphate backbone to which a nitrogenous (nitrogen-containing) base, or *nucleobase*, is attached. DNA consists of a *deoxygenated* ribose sugar molecule; RNA, a regular *ribose* molecule. DNA is found in the nucleus of every cell—in eukaryotes, it is confined to the nucleus of the cell; in bacteria and prokaryotes, it is not confined to a single location.

The secondary structure consists of two oppositely oriented strands, the second of which contains the complementary base pair hydrogen-bonded (no surprise!) to the first:

- In DNA and RNA, cytosine (C) matches with guanine (G).
- In DNA, adenine (A) matches with thymine (T) and in RNA adenine (A) matches with uracil (U).

This pairing in both DNA and RNA allows for the replication of the genetic code in every living creature! The DNA and RNA molecules for most species are remarkably the same, 99%. The kicker is that the 1% difference in the DNA and RNA molecules within a species accounts for all the visual differences in individuals we see among them.

FATS



http://www.dietobio.com/dossiers/en/fatty_acids/images/tgl.gif

Fats are not polymers per se. They are formed by the three-time combination of long-chain (14 to 18 carbon atoms) organic acids (-COOH) to glycerol $(CH_2OH)_3$ to form *lipid* molecules. One of their primary functions is to store energy for long-term use in an organism. In fact, there are cells dedicated to the storage of this biomolecule, called appropriately *fat cells.* They are the bane of anyone trying to lose weight. They evolved because they are part of the saving mechanism for those who temporarily are not able to eat sufficiently for the day to provide enough energy for what must be done!

Solid saturated fats are those containing only single bonds in the organic acid side chains. By contrast, liquid unsaturated fats are those with at least some double bonds in the side chains. The lower melting points for the unsaturated fats are due to the rigidity of their shape, which is typically bent resulting in less effective intermolecular forces and therefore, lower melting points.

CATCHING OUR BREATH

The biomolecules discussed in this section contain all the building blocks for cells as we will see in the next section. So far, we have come through the first six levels of complexity since the Big Bang, from energy

- quarks and other elementary particles
- to protons and neutrons,
- to atoms,
- to crystals, molecules and metals,
- to liquids and solids,
- to biomolecules.

In the next and seventh step of our journey, we will find organelles and cells, the first of what we consider to be living organisms.

FOR MORE INFORMATION ON BIOMOLECULES

General Videos:

- https://www.youtube.com/watch?v=f8FAJXPBdOg&t=181s
  The Molecular Shape of You (Ed Sheeran Parody) | A Capella Science (start at 2:50)
- https://www.youtube.com/watch?v=YO244P1e9QM
  Biomolecules (updated)—Amoeba Sisters
- https://www.youtube.com/watch?v=H8WJ2KENlK0
  Biological Molecules - You Are What You Eat: Crash Course Biology #3—Hank Green
- https://www.youtube.com/watch?v=QWf2jcznLsY
  The Molecules of Life—Bozeman Science
- https://www.youtube.com/watch?v=4DK6aS5ual4
  "Royals" Parody - "Macromolecules"

Proteins:

- about the basic of protein structure and folding watch this fun cartoon-like presentation by the Amoeba Sisters: https://www.youtube.com/watch?v=hok2hyED9go&t=45s
- about how we can now predict how a particular amino acid sequence will most likely fold, watch "The Protein Folding Revolution"—from Science AAAS, American Association for the Advancement of Science: https://www.youtube.com/watch?v=cAJQbSLlonI
- about the 3-D Shape and Function of Macromolecules, check out "What is a Protein?": https://www.youtube.com/watch?v=qBRFIMcxZNM

DNA (Nucleic Acids):

- to see how the 2 meters of DNA in each living cell fits, watch "DNA Origami: How to Fold a Genome" https://www.youtube.com/watch?v=KWcUs-d1mCg
- to make your own example of DNA Origami: https://www.youtube.com/watch?v=pB0FMshudqE

Carbohydrates (Sugars):

- to learn "All about Carbohydrates in 6 Min! From a High School Student," watch https://www.youtube.com/watch?v=X5sWXBJ9Yj8
- to understand why we can eat starch and metabolize glycogen, but not cellulose, watch this video on polysaccharides: https://www.youtube.com/watch?v=e0ijBDroE48

Lipid (Fats):

- to understand the structure of lipids and some of its derivatives such as phospholipids and prostaglandins, watch https://www.youtube.com/watch?v=_ExVXeovB6s
- to get an overview of lipids themselves and how to recognize which ones are "good fats" or "bad fats": https://www.youtube.com/watch?v=ulIjtl4FPDQ

Just for fun, listen to these songs. Thanks, Avi Silber:
Carbohydrates—Macromolecule Song 1 of 4: https://www.youtube.com/watch?v=bwup7OIAJu4
Lipids—Macromolecule Song 2 of 4: https://www.youtube.com/watch?v=eB793h16R8A
Proteins—Macromolecule Song 3 of 4: https://www.youtube.com/watch?v=9hyiKNaLqTo
Nucleic Acids—Macromolecule Song 4 of 4: https://www.youtube.com/watch?v=bwup7OIAJu4