syllabus

syllabus

summary of links

shared doc: https://docs.google.com/document/d/1aNVEKZYDac3acFXKLxAs_SMPpM_5sAhywgUh4t3gU-8/edit

- includes lecture outlines, slides, and FAQ

worksheet submissions: S16427-teachers@esp.mit.edu
topic suggestions: https://forms.gle/vs54xjdSPzGry5Pt8
questions, comments, feedback: https://forms.gle/8w3NXYKqTKGTzmXE7 or S16427-teachers@esp.mit.edu

motivation/goal

welcome to food (bio)chemistry!! (the first exclamation mark is part of the course title; the second one is for the sentence.) when we took 7.05 (mit's biochemistry course), we found it really cool to consider ways in which the content applied to our everyday experiences. many of these everyday experiences involved food — perhaps unsurprisingly, since food naturally involves a lot of rich chemistry and biology.

our goal for the class is to connect [the tangible, everyday experiences/knowledge that you have with/about food] to [the abstract chemistry responsible for these phenomena you experience/know about]. in other words, we aim to inspire you to *think deeply about simple things*. for example, after lecture 1, the next time you come across butter or oil, we want you to remember/think about why butter is solid while oil is liquid (at room temperature).

class overview

we will connect various food groups to corresponding biological (macro)molecules, including but not limited to the following:

food group	**biological molecule**
grains	carbohydrates
proteins	proteins/amino acids
fats	lipids
fruits/vegetables	fiber, vitamins, minerals, antioxidants
(dairy will be mostly skipped)	(nucleic acids will be mostly skipped)

(as noted in the course description) for each of these molecules, we will discuss:

- their chemical structure
- their reactivity in the kitchen
- their function and metabolism in the body
- what these mean for your everyday interactions/experiences with food

for you to do

each lecture will have a worksheet accompanying it, to help reinforce concepts. obviously you're not Required to do them, and we know you're busy with your own classes (so are we!), but (also obviously) you'll understand/retain the information better if you do, and **lectures are cumulative** (i.e. lectures will often use/build on information from previous lectures), so it's encouraged! **you can submit your work for feedback by emailing S16427-teachers@esp.mit.edu.**

given that the motivation/goal for this class is to explain more deeply the tangible, everyday experiences/ knowledge that *you* have with/about food, **we are taking suggestions for topics to cover!** if there are some food-related phenomena or food facts that you want to know the (bio)chemical details of, submit them to this form: https://forms.gle/vs54xjdSPzGry5Pt8.

in addition, if you have any **questions, comments, or feedback** about any of the lectures, you can submit them to this form: https://forms.gle/8w3NXYKqTKGTzmXE7. we will respond to common questions/comments in class, and to other questions/comments this shared doc (student names will not be included, of course): https://docs.google.com/document/d/1aNVEKZYDac3acFXKLxAs_SMPpM_5sAhywgUh4t3gU-8/edit.

qr codes

thanks for attending!

slides

lecture notes

feedback form

(note that this feedback form is our own google form, not the esp one (which is more important)!)

main

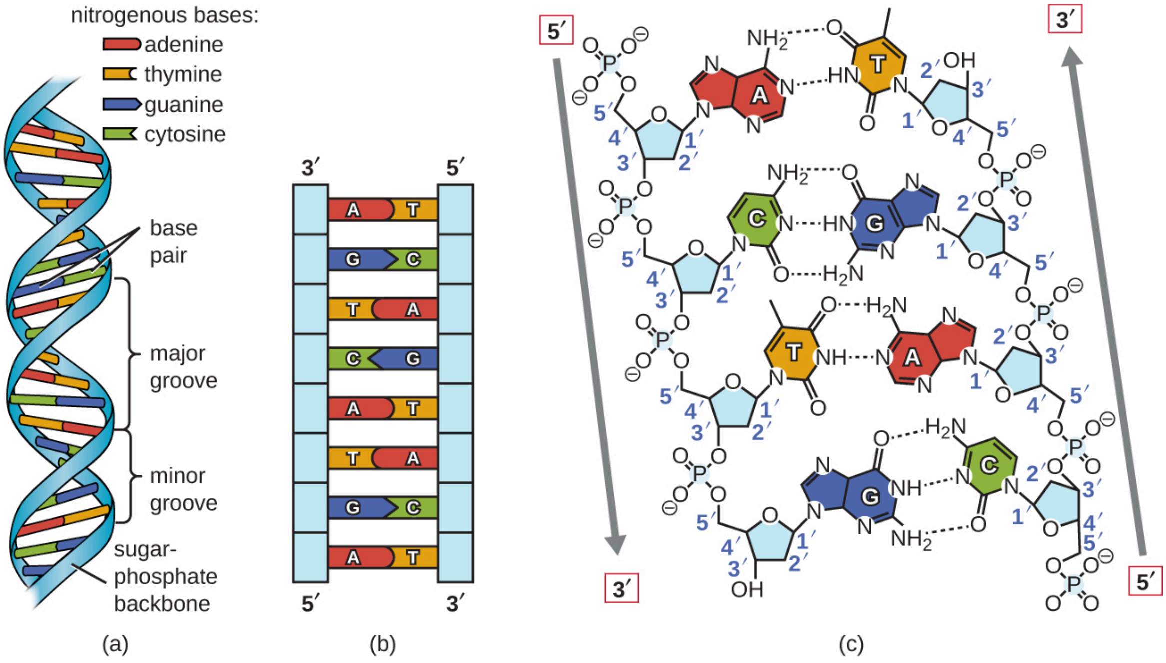
extra info

this is stuff we didn't get to in class, either because we thought of it Later, because we forgot to mention it, or because we didn't have time.

lecture 1

- trans fats are much, much unhealthier than 'conventional' (cis) saturated fats found in nature. saturated fats are already linked to heart disease, but trans fats even more so — for each increase of 2% in the amount of calories from trans fat you consume, your risk for coronary artery disease doubles (yes, doubles!). in the united states, the food and drug administration (fda) banned trans fats in 2018.
- the reason that you can still buy crisco (and other hydrogenated vegetable fats) despite the ban is that they switched to a different and more complicated method for hydrogenating fats that reduces the amount of trans fat byproducts. nowadays, a lot of manufacturers start off with a small amount of already solid vegetable fat (like palm oil) and use that as a 'starting crystal' that helps make the rest of the liquid vegetable oil crystallize and become saturated.
- another way of making a solid vegetable fat product is by *emulsifying* the oil with water to create margarine. we covered how that's done in lecture 2 :)

- by the way, **"hydrogen bonds" don't have to involve hydrogen!** they just occur between partial positive and partial negative charges (which arise from polar bonds), which includes C=O (C is δ+ and O is δ-; see the cytosine-guanine base pairs in the image below), on top of OH and NH_2 groups. it's just that H is pretty commonly the δ+, since its electronegativity is only 2.20.
- hydrogen bonds are responsible for the base pairing in DNA! see (c)[1]:



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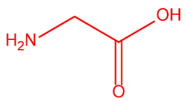
[1] https://bio.libretexts.org/Courses/Clinton_College/BIO_300%3A_Introduction_to_Genetics_%28Neely%29/01%3A_Chemistry_to_Chromosomes/1.01%3A__The_Structure_of_DNA

lecture 2

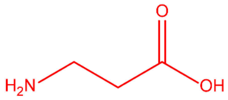
- cholesterol molecules (in addition to phospholipids) also make up membranes.
- bile acids/bile salts (derived from cholesterol; look up their structure!) emulsify dietary fats.

lecture 3

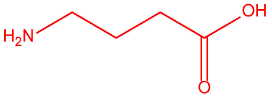
- the (vast majority of) amino acids found in proteins are *alpha*-amino acids (discussed in class), but non-alpha amino acids exist! amino acids are called *alpha*, *beta*, *gamma*, etc. based on how many carbons away the amino group is from the carboxyl group:[2]



glycine
(Gly)

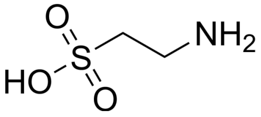


beta-alanine
(β**-Ala)**



gamma-aminobutyric acid
(γ-Aba)

- you may have heard of *taurine* (structure to the right[3]) as an amino acid. indeed, it has an amino group (NH_2) and an acid group, but its acid group is a *sulfonic* acid ($S(=O)_2OH$) instead of a carboxylic acid ($C(=O)OH$) (both of these are acids because they can donate ("give up") a proton (H^+)). the amino acids found in proteins have *carboxylic* acid groups.



lecture 6

- i can't BELIEVE i forgot to mention this. we talked about how, in order to make the tight helices in collagen (a structural protein found everywhere: skin, bones, cartilage, tendons, ligaments), we need *hydroxy*proline and *hydroxy*lysine—and how, in turn, the enzymes responsible for making them (prolyl hydroxylase and lysyl hydroxylase, respectively) require vitamin C to function. therefore, if you don't get enough vitamin C, your skin, bones, and connective tissue will be affected; you'll be weak, for example. well, there's a name for the disease caused by vitamin C deficiency (often mentioned in the context of pirates not having enough fruit to eat): ***scurvy!*** in fact, the other name for vitamin C, ascorbic acid, literally means "anti-scurvy acid" (*a-* means "against", and *-scorb-* refers to scurvy)!

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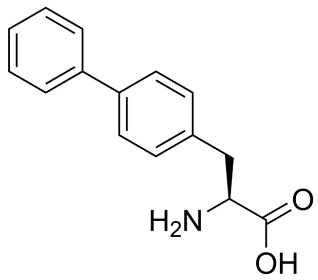
[2] https://www.pnas.org/doi/10.1073/pnas.2500503122
[3] https://www.medchemexpress.com/taurine.html

“faq”—responses to questions, comments, feedback

submit questions, comments, and/or feedback here (https://forms.gle/8w3NXYKqTKGTzmXE7), or on index cards in class!

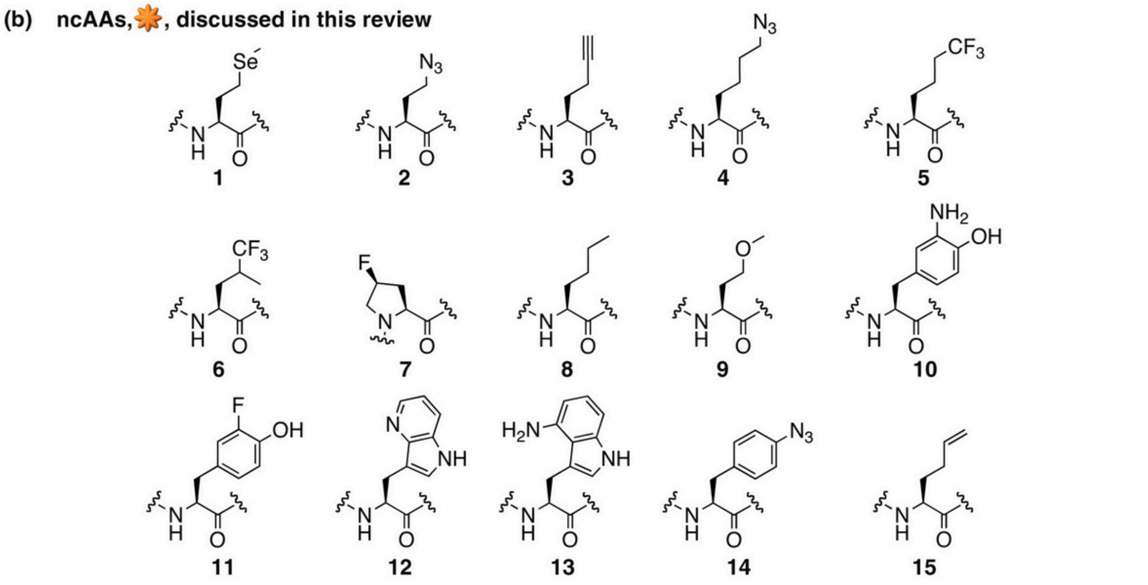
lecture 3

Q: Can new synthetic amino acids be produced by artificially adding a new R group that wouldn’t be found in nature, and would these have any uses?



A: yes! Mandell et al.[4] made a GMO that requires the synthetic amino acid biphenylalanine for its metabolism (i.e. it needs biphenylalanine to stay alive), which prevents the GMO from “escaping” controlled laboratory environments, since natural environments don’t contain biphenylalanine. news sources like NPR[5] and Yale News[6] reported on this work. the structure of biphenylalanine is to the right (note the amino and carboxyl groups); its side chain is like alanine’s side chain, but with a hydrophobic (nonpolar) biphenyl group attached. this website[7] includes “synthetic route[s]” for making biphenylalanine in the lab.

Johnson et al.[8] wrote a review paper discussing the following synthetic amino acids (they call them non-canonical amino acids (ncAAs) in their paper) (again, note the amino, carboxyl, and R groups):



Current Opinion in Chemical Biology

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[4] Mandell, D., Lajoie, M., Mee, M. *et al.* Biocontainment of genetically modified organisms by synthetic protein design. *Nature* **518**, 55–60 (2015). https://doi.org/10.1038/nature14121.

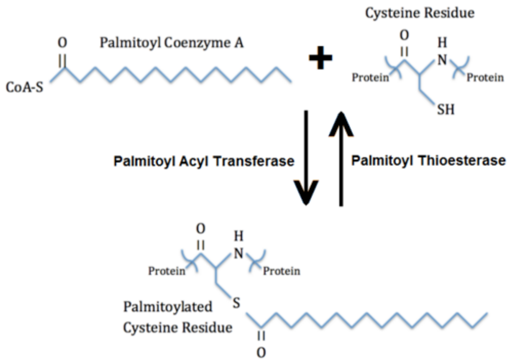
[5] https://www.npr.org/sections/health-shots/2015/01/21/378820888/scientists-give-genetically-modified-organisms-a-safety-switch

[6] https://news.yale.edu/2015/01/21/synthetic-amino-acid-enables-safe-new-biotechnology-solutions-global-problems

[7] https://www.chemsrc.com/en/cas/155760-02-4_765799.html

[8] Jeremiah A Johnson, Ying Y Lu, James A Van Deventer, David A Tirrell. Residue-specific incorporation of non-canonical amino acids into proteins: recent developments and applications. *Current Opinion in Chemical Biology*, Volume 14, Issue 6, 2010, Pages 774-780, ISSN 1367-5931, https://doi.org/10.1016/j.cbpa.2010.09.013.

the applications they mention include:

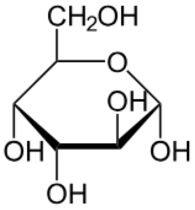


- labeling proteins, for visualization (section 'Applications of time-resolved residue-specific protein labeling'; "S-acylation" or "S-palmitoylation" means attaching a fatty acid like palmitic acid to the sulfur (S) atom on cysteine side chains—see right[9]), similar to labeling with isotopes[10] or with GFP[11]
- making proteins more fluorescent or more resistant to melting (section 'Altering global protein properties')
- making new materials (section 'New materials'. the synthetic amino acids mentioned are N_3Phe, Aha, Hpg, and Se-Met (these abbreviations are defined elsewhere in the paper)

for what it's worth, here are other papers i found when researching this answer:

- Fan, Y., Evans, C. R., & Ling, J. (2017). Rewiring protein synthesis: From natural to synthetic amino acids. *Biochimica et biophysica acta. General subjects*, *1861*(11 Pt B), 3024–3029. https://doi.org/10.1016/j.bbagen.2017.01.014.
- Rovner, A., Haimovich, A., Katz, S. *et al*. Recoded organisms engineered to depend on synthetic amino acids. *Nature* **518**, 89–93 (2015). https://doi.org/10.1038/nature14095.

Q: Why are only some of the bonds spacefilling?



A: we're not sure what you mean by spacefilling (feel free to elaborate by leaving a comment here, or, if you want to stay anonymous, by submitting another index card next class). if you're asking why only some of the bonds are drawn with lines (for example, above, C–C bonds and C–O bonds are drawn with lines, whereas O–H bonds are not): **it's just a shorthand.** physically, the O–H bonds (and the C–H and C–O bonds in CH_2OH) are still there (although bonds involving a hydrogen atom (not to be confused with hydrogen bonds, which occur between polar moieties) do tend to have shorter bond lengths because hydrogen is smaller than other atoms).

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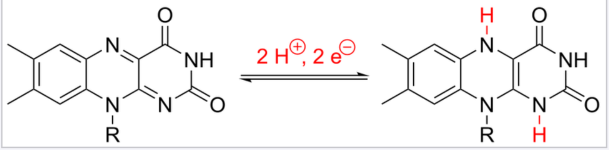
[9] https://en.wikipedia.org/wiki/Palmitoylation
[10] https://en.wikipedia.org/wiki/Isotopic_labeling
[11] https://en.wikipedia.org/wiki/Green_fluorescent_protein#Fluorescence_microscopy

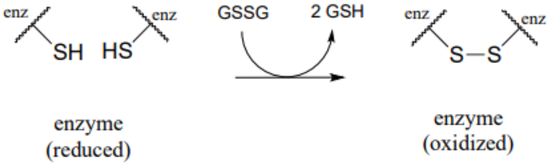
Q (in class): When two cysteines form a disulfide bond (cys-SH + cys-SH → cys-S–S-cys; see bottom right of lecture 3 board), where do the two hydrogens go?

A: we wrote FAD → $FADH_2$ on the board, which is indeed one option (see right[12]).

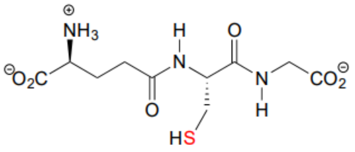


Reaction of FAD to form $FADH_2$

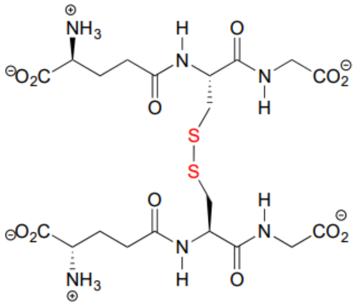
more commonly, the hydrogens go to *glutathione*, which is responsible for balancing *many* redox reactions in cells; instead of FAD → $FADH_2$, we would have GSSG → 2 GSH:



where GSH and GSSG are abbreviations for the following:



glutathione (GSH)
reduced state



glutathione dimer (GSSG)
oxidized state

you can find a more comprehensive description here[13] (which is also where i got the images).

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[12] https://en.wikipedia.org/wiki/Flavin_adenine_dinucleotide

[13] https://chem.libretexts.org/Bookshelves/Organic_Chemistry/Book%3A_Organic_Chemistry_with_a_Biological_Emphasis_v2.0_(Soderberg)/15%3A_Oxidation_and_Reduction_Reactions/15.07%3A_Redox_Reactions_of_Thiols_and_Disulfides

lecture outlines & slides

these are rough bullet points designed for our own teaching, not written-up paragraphs designed for student reading (we're too busy to do the latter :((though we *did* do the first half of lecture 1)). so a lot of the ideas/information here aren't explained or spelled out (though they were in class), but hopefully these are useful for review/remembering what we covered.

in addition, here are the slides for the class:
https://docs.google.com/presentation/d/1eT1ju26lguTpl03rpBAIL1wGbBh1A4sdS4cE9Qtdmfc/edit.

lecture 1: line structure, fats, polarity

line structure

BLIND SURVEY: do you know how to find the molecular formula of 3-buten-2-ol? (C_4H_8O)

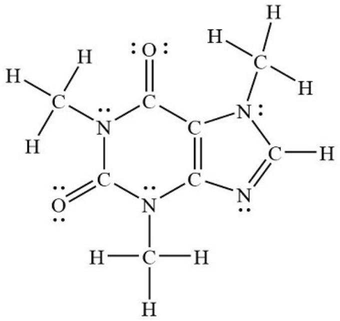
we begin by introducing a notational convention/shorthand in organic chemistry ("**organic**" chemistry is *carbon*-based chemistry). in Lewis structures, we represent atoms with their elemental symbols/abbreviations and represent covalent bonds by drawing lines between them. in ***line structures*** (also known as ***skeletal structures***), we omit the symbols for carbon (i.e. the C's), and we also omit the C-H bonds (and, by extension, the H's bonded to C's)—they are implied. this makes a convenient shorthand because carbon atoms and C-H bonds are so common, and because carbon almost always forms four bonds (meaning you can deduce how many C-H bonds each carbon atom has).

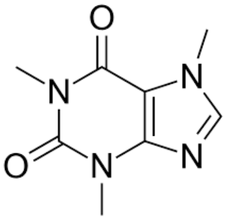
to generate a Lewis structure from a line structure:

1. write in the implied C's: there is a C atom at every endpoint ("ends") and every vertex ("bends").
2. write in the implied C-H bonds: all C atoms have four bonds, so if a C atom has *n* bonds shown, then there are 4 – *n* implied H atoms bonded to it.

you should be able to do this in your head—when we draw a line structure, you should be able to "see" where all the implied C atoms and C-H bonds are.

for example, compare the Lewis structure and line structure of caffeine (oh yeah, i forgot to mention lone pairs are also implied)[14,15]:





structure of a fatty acid

a ***functional group*** is a group of bonded atoms that often appears across many molecules. here are a few common examples, and their names[16]. "R" is a notation that stands for anything starting with a carbon. we use "**R-groups**" as variables: when we write "R", we imply that any statements we make about reactivity or whatever are true for *any* R, just as a statement like "$2x + 3x = 5x$" is true for any x.

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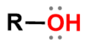
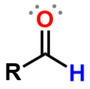
[14] https://homework.study.com/explanation/the-structure-of-caffeine-present-in-coffee-and-many-soft-drinks-is-shown-below-1-how-many-pi-bonds-are-present-in-caffeine-2-how-many-sigma-bonds-3-insert-the-lone-pairs-in-the-molecule-4-what-kinds-of-orbitals-do-the-lone-pairs-occupy.html

[15] https://en.wikipedia.org/wiki/Caffeine

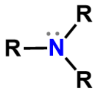
[16] https://www.chemistrysteps.com/functional-groups/



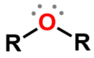
Alcohol



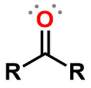
Aldehyde



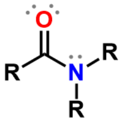
Amine



Ether

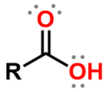


Ketone

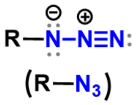


Amide

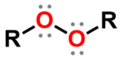
Epoxide



Carboxylic Acid



Azide



Peroxide

the "acid" part of a fatty acid is a ***carboxylic acid***, which is a C double bonded to an O and single bonded to an OH (a "**hydroxyl**") (see above for the structure of a carboxylic acid). many, many acids in biological systems are carboxylic acids.

the "fatty" part of a fatty acid is a long-ish chain of carbons and hydrogens—a **hydrocarbon** tail, if you will. the existence and type of double bonds in these hydrocarbon chains affect their structure:

- if the hydrocarbon chain has *no* double bonds, the fatty acid is a *saturated* fatty acid (or ***saturated fat***). "saturated" means that the carbons make all the possible bonds to hydrogen that they can; the carbons are "saturated", or filled, with hydrogens.
- if the hydrocarbon chain has at least one double bond, the fatty acid is an *unsaturated* fatty acid (or ***unsaturated fat***). "unsaturated" means that the carbons are not completely saturated/filled with hydrogens: whenever a C forms a double (instead of a single) bond, it "wastes" a bond that could've been spent bonding to another H (to make it maximally saturated).
    - double bonds can be *cis* (where the substituent carbons attach to the *same* side of the double bond) or *trans* (where the substituent carbons attach to *opposite* sides of the double bond). when we say *unsaturated fat*, we assume that the double bond(s) is/are *cis*, because, as far as fatty acids go, all (hydrocarbon) double bonds found in nature are cis. we can synthetically make fats with *trans* double bonds in labs and industrial plants, though: these man-made fats are ***trans fats*** (which you may know to be notorious for their bad health effects).

[DIAGRAM HERE: saturated vs. unsaturated vs. trans (sorry, we didn't get to making this image)]

these differences in structure give rise to different properties in fats:

saturated fats (no double bonds)	**unsaturated fats** (cis double bonds)	**trans fats** (trans double bonds)
hydrocarbon tail forms straight chain → tight packing → *solid* at room temperature	hydrocarbon tail forms kinks → loose packing → *liquid* at room temperature	hydrocarbon tail forms straight chain → tight packing → *solid* at room temperature
generally from animals	generally from plants	synthetic/man-made
increases LDL ("bad") cholesterol	decreases LDL cholesterol	increases LDL cholesterol + weird for the body to deal with, since they rarely occur in nature

some bigger-picture information on different types of fats, including examples (these slides were presented in lecture): https://docs.google.com/presentation/d/1kjUc-2TffH7VJb-YA2b-P_so0zRHX1sJkNtxH61prFU/edit

polarity of molecules

BLIND SURVEY: who has heard of a polar bond? keep your hands up if you can define what a polar bond is. keep your hands up if you can define what a polar molecule/compound is.

each element on the periodic table has a different extent to which it 'likes' or is 'attracted' to electrons. one of the ways to measure this is ***electronegativity***[17]. on the *Pauling scale*, one of the most common ways

[here we stopped writing everything up because We Are Busy, sorry :(]

- polar vs. nonpolar compounds
    - hydrogen bonds in e.g. water
    - salt dissolves in water
    - oil doesn't dissolve in water/water and oil don't mix (also exemplify with hydrocarbons?)
        - soap is amphiphilic, so interacts with water *and* oil
        - [DEMO] emulsification: ex. egg yolk (mayo), starch (pasta water)
    - capsaicin in milk but not water
    - blooming aromatics like terpenoids in oil

- in the body
    - phospholipids and cholesterol make up membranes
        - phospholipid bilayer: hydrophobic heads outside, hydrophilic tails inside
    - other functions of cholesterol:
        - bile acids/salts (derived from cholesterol) emulsify dietary fats

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[17] there's also the related measures of *electron affinity* and *atomic radius*, which

lecture 2: arrow pushing, amino acids

polarity (lecture 1 cont.)

- polar vs. nonpolar compounds
    - oil doesn't dissolve in water/water and oil don't mix (also exemplify with hydrocarbons?)
        - soap is amphiphilic, so interacts with water *and* oil
        - [DEMO] emulsification: ex. egg yolk acts as an emulsifier to allow oil (nonpolar) to dissolve in vinegar (a solution of acetic acid in water; polar)
    - capsaicin in milk (includes nonpolar milk fats) but not water
    - blooming aromatics like terpenoids in oil
- in the body
    - phospholipids and cholesterol make up membranes
        - phospholipid bilayer: hydrophobic heads outside, hydrophilic tails inside

arrow pushing

- curved arrow represents the movement of two electrons; make/break bonds
    - we won't ask you to draw them yourself, but given arrows, you should be able to figure out the product

amino acids

- what is an amino acid?
    - fixed amine + carboxylic acid groups
    - zwitterionic properties
    - side chain determines chemical properties/interactions
- what is a protein?
    - polypeptides as long chain of amino acids
        - dehydration synthesis, hydrolysis

lecture 3: proteins

(see slides for more detail)

- what is a protein?
    - polypeptides as long chain of amino acids
        - dehydration synthesis, hydrolysis
    - alpha carbon and fixed chemical groups form backbone; side chains (aka “residues”) stick out from backbone
    - source of nitrogen
- (briefly) biological functions of proteins
    - ubiquity + versatility of proteins (they do Everything)
    - protein folding determined by sequence of amino acids
    - why folding is Important in determining function
        - enzymes: side chains mediating reactions
            - will talk more about enzymes later since there’s not enough time
        - structural protein in food (see: collagen becomes gelatin in chicken soup, pectin responsible for fruit crunchiness)
- non-essential vs. essential amino acids
- the rest of the slides

lecture 4: carbohydrates

(see slides for more detail)

structure: (usually) rings with hydroxyls; polar (dissolves in water!)

- monosaccharides
    - high-fructose processed foods; interaction between fructose and GI tract
- disaccharides
- polysaccharides: branching polymers, ex. starch granules, cellulose, (amylo)pectin
    - dehydration synthesis, hydrolysis (cf. polypeptides)
    - "Dietary fiber consists of non-starch polysaccharides and other plant components such as cellulose, resistant starch, resistant dextrins, inulins, lignins, chitins, pectins, beta-glucans, and oligosaccharides."

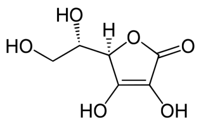
lecture 5: sugar reactivity, redox & radical reactions

non-enzymatic browning:

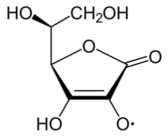
- caramelization: various sugar reactions (upon heat)
    - hydrolyses, dehydration reactions, equilibration, isomerization, etc. (see slide)
        - different caramelization temperatures for different disaccharides
    - products: flavor compounds + brown caramelans/caramelens/caramelins
- Maillard reaction: sugar + amino acid (upon heat)
    - products: flavor compounds + brown melanoidins
    - accelerated by heat (generally true for reactions) and alkalinity (because more basic conditions favor NH_2, which is more nucleophilic, over NH_3^+)

redox/radical reactions

- redox vocabulary/terminology
    - “Oxidation Is Loss of electrons, Reduction Is Gain of electrons”
    - when *carbon* is being oxidized/reduced (as in *organic* chemistry), this actually means losing/gaining bonds to atoms that are more electronegative than carbon (losing/gaining “effective” electrons)
        - methane, methanol, formaldehyde, formic acid, carbon dioxide
    - an *oxidant* oxidizes something/causes something to be oxidized; vice versa for *reductant*
        - “oxidation” doesn’t have to involve oxygen; it’s just called that because oxygen is very electronegative, so it’s a pretty common oxidant- if an atom forms a bond to oxygen, it will *probably* “lose” “effective” electrons
    - we will see Fe^{2+} ↔ Fe^{3+}, catechol ↔ quinone, etc.
- fruits/vegetables contain antioxidants etc.
- prompt: what does an *antioxidant* do? *prevent* oxidation!
- free radicals
    - free radicals (who has heard of?): unpaired electron- very unstable and reactive
    - Reactive Oxygen Species: can easily become free radicals (ex. H_2O_2 homolysis—**half-arrows**)— or are already free radicals



        - can oxidatively damage cells by oxidizing things like DNA (ex. arrow push guanine → 8-oxo-guanine)
    - vitamin C as an antioxidant that can deal with ROS (semidehydroascorbate radical is *resonance*-stabilized)



        - this is an important function of antioxidants in general! ROS oxidize things; antioxidants *prevent* this oxidation.
    - rancidification
        - who has heard the word “rancid”? who has heard of/experienced potato chips tasting bad due to exposure to oxygen?
        - half-arrows: unsaturated lipid → peroxyl radical, alkoxy radical → short-chain aldehyde & hydrocarbon
        - oxygen absorbers
- enzymatic browning of fruits via oxidation by polyphenol oxidase/catechol oxidase

- catechol oxidase catalyzes catechol → *ortho*-quinone (oxidation)
- quinones polymerize into brown melanins (also responsible for skin pigmentation!)
- cf. non-enzymatic browning: caramelization, Maillard (catalyzed by heat (or alkalinity, for Maillard), not by enzymes). prompt (review): what are the brown compounds produced by *non*-enzymatic browning? *caramelans/caramelens/caramelins, melanoidins*
- [DEMO] acid (e.g. lemon juice: citric acid, ascorbic acid (vitamin C)) inhibits PPO browning on apple by reducing *ortho*-quinone back to catechol
    - they also inhibit by binding to the enzyme; come back to this when we cover taste receptors

lecture 6: biology—taste receptors, metabolism

- don't feel bad if you've found this content difficult, it was designed for high schoolers + it's literally college material
- when you learn things like lewis structures, acids and bases, redox reactions, etc. in high school chem, keep in mind these food/biological applications as some of the applications of what you're learning!
  - i feel like a lot of high school chem is kind of rote; i wish i could've seen the Cool Actual Applications that i only now know after taking ochem and biochem
- btw feel free to explore the citations in the captions!

preview: today is more bio than chem :)

specific examples of proteins: taste receptors

- taste receptors
  - sour: H^+ channels (remember, acidic environments ↔ low pH ↔ many H^+ / acids as H^+ (proton) donors)
  - salty: Na^+ channels
    - minerals include Na^+, K^+, Ca^+, Cl^- (other ions used by cells)
  - umami: TAS1R1+3 heterodimer detects L-amino acids (especially glutamate(?))
  - bitter: TAS2R family
  - sweet: TAS1R2+3 heterodimer
    - [DEMO] at low pH (like when sour foods), miraculin (from *synsepalum dulcificum*) binds to sweet receptors
      - artificial sweeteners
    - [demo] you can just look at protein structures on PDB btw!
      - use 9NOV (bound to sucralose)
      - alpha helices and beta sheets
      - similarity of sucralose structure to sucrose
      - click to see interatomic interactions at a particular site (here, the active site/binding site)!
- proteins catalyze reactions at their *active sites*
  - the active sites above (for taste receptors) are for letting H^+ or Na^+ ions through, or for binding
  - certain enzymes require specific *cofactors* to function. see examples of common (vitamin & non-vitamin) cofactors (wikipedia)
  - ex. vitamin C as a cofactor for prolyl hydroxylase, which synthesizes collagen; vitamin C deficiency = scurvy
    - redox chain ending with vitamin C: (see right) + under reaction conditions, enzyme-bound $Fe^{2+} \rightarrow Fe^{3+}$, which deactivates the enzyme; reset $Fe^{3+} \rightarrow Fe^{2+}$
    - does anyone know the name for the disease you get when you don't have enough vitamin C? *scurvy*! (vitamin C = a-scorbic acid = anti-scurvy acid)

metabolism

- common theme: breakdown and buildup
- warning: complex pathways! *just focus on endpoints*

- TCA cycle → NADH and $FADH_2$ for ETC → ATP!
  - ETC → ATP: electron transfers as an *oxidative* pathway
  - sugars: glycolysis (→ pyruvate) and fermentation (→ lactic acid (not in TCA)) vs. gluconeogenesis
  - fatty acids: FA oxidation (→ AcCoA) vs. FA synthesis
  - amino acids: aa breakdown (→ keto vs. gluco) vs. translation
- biosynthesis of cholesterol from AcCoA (from week 1)
  - part of cell membranes (alongside phospholipids); see nonpolar part
  - cholesterol → bile salts, which emulsify dietary fats

cleanup

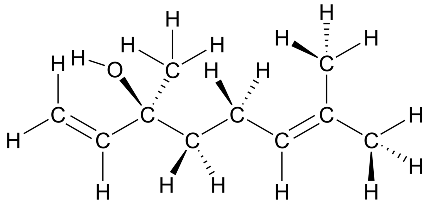
- fill out esp feedback form!
- QR codes/links (handed out at beginning) for shared doc & slides
- we will add exported pdf versions of the doc and slides to the esp documents soon :)
- time to fill out index cards

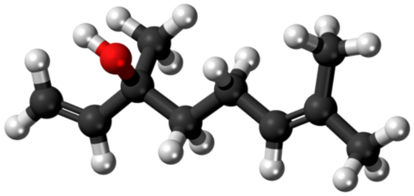
worksheets

lecture 1 worksheet[18]

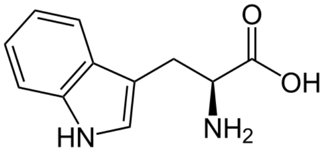
line structure

here is (kind of) a Lewis structure of a molecule, as well as a ball-and-stick model of the same molecule (bold bonds come out of the page, and hash bonds go into the page). **draw the corresponding line/skeletal structure.** (you can double check your answer by looking up *linalool*.)





what is the molecular formula (e.g. $C_wH_xN_yO_z$) of the following molecule? hint: it may be helpful to draw the full Lewis structure first. (you can double check your answer by looking up *tryptophan*.)

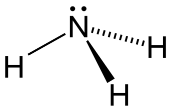


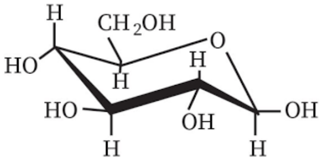
fats

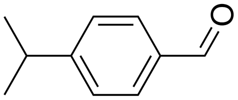
draw one example each (or more if you want) of a saturated, an unsaturated, and a trans fatty acid. predict whether each will be solid vs. liquid at room temperature, and explain why.

polarity

identify the following compounds as polar or nonpolar. which ones dissolve in water (hydrophilic)? which ones dissolve in oil (hydrophobic)? why? (the compounds are hexane, ammonia, glucose, and cuminaldehyde. glucose is a sugar from which we get energy, and cuminaldehyde is found in cumin!)







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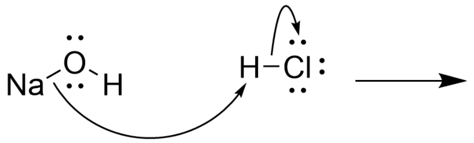
[18] all images are from wikipedia, except for the first image (original drawing) and the structure of glucose (https://www.bartleby.com/subject/science/chemistry/concepts/chair-conformation-of-glucose).

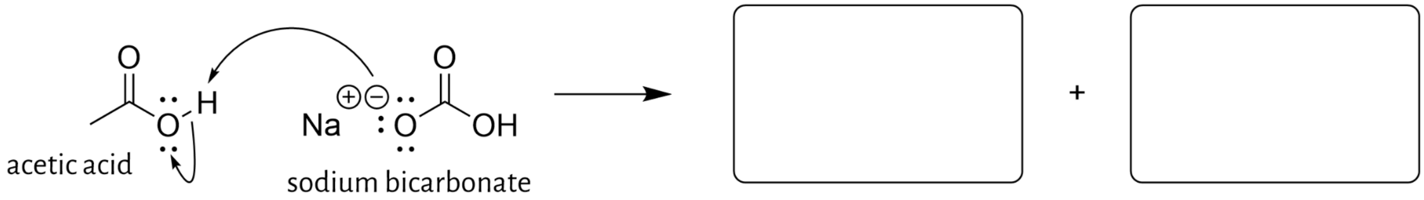
lectures 2 & 3 worksheet

arrow pushing

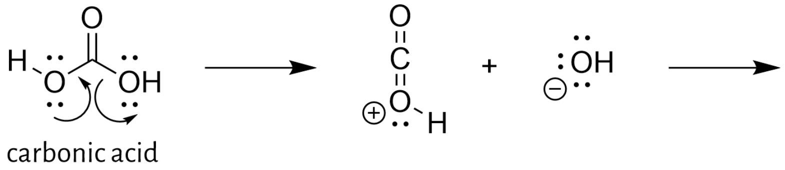
1. consider the reaction of sodium hydroxide with hydrochloric acid. given these curved arrows, **draw the products.** (hint: the products include something with a (+) charge and something with a (-) charge, which can form an ionic bond.)



2a. vinegar (acetic acid) famously reacts with baking soda (sodium bicarbonate). the first step of the reaction is shown below. **draw the products.**

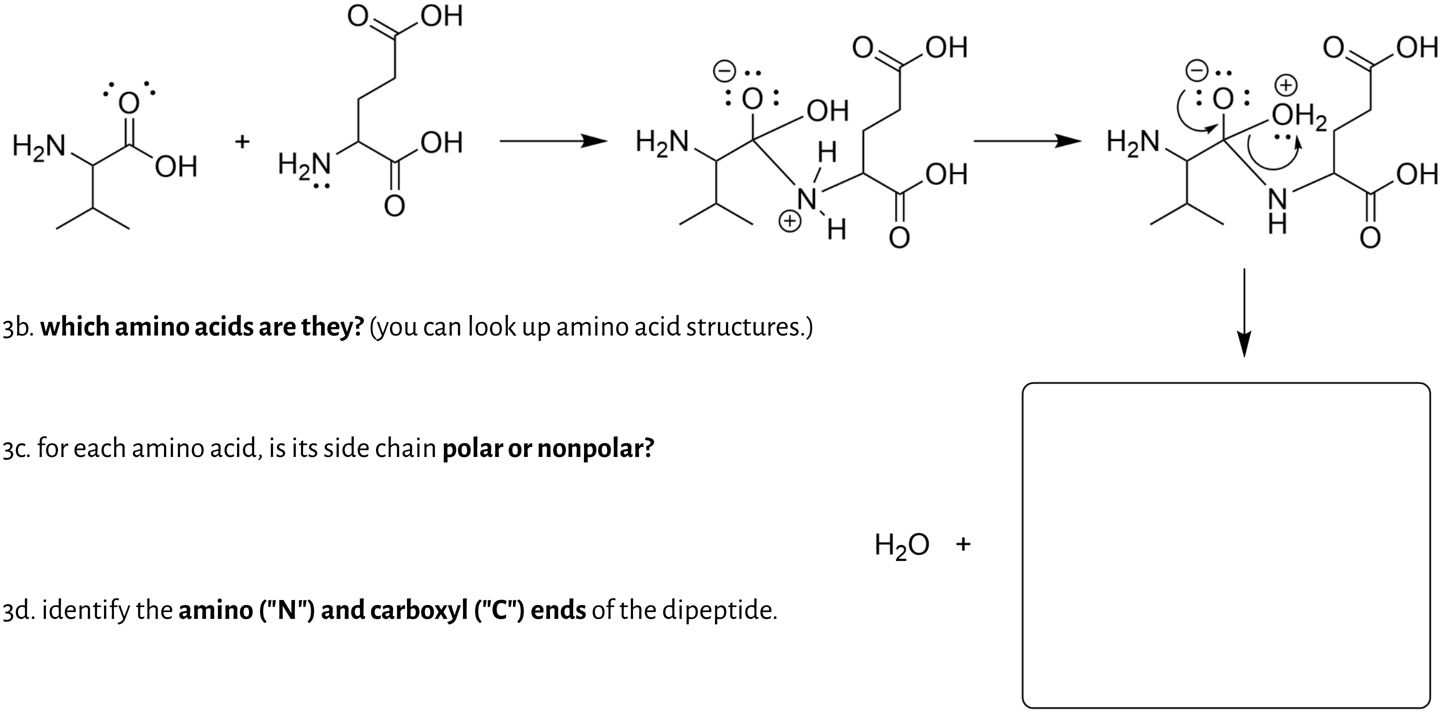


2b. one of the products is carbonic acid, which can react to form carbon dioxide and water. **draw curved arrows** on and/or between the O=C=OH+ and/or the OH- to show the mechanism for this reaction, and **draw the final products**.



amino acids and protein structure

3a. **draw curved arrows** to show the mechanism for the first two steps of this dehydration reaction between two amino acids. then, **draw the final product**, based on the given arrows (it should feature a peptide bond between the amino acids!).

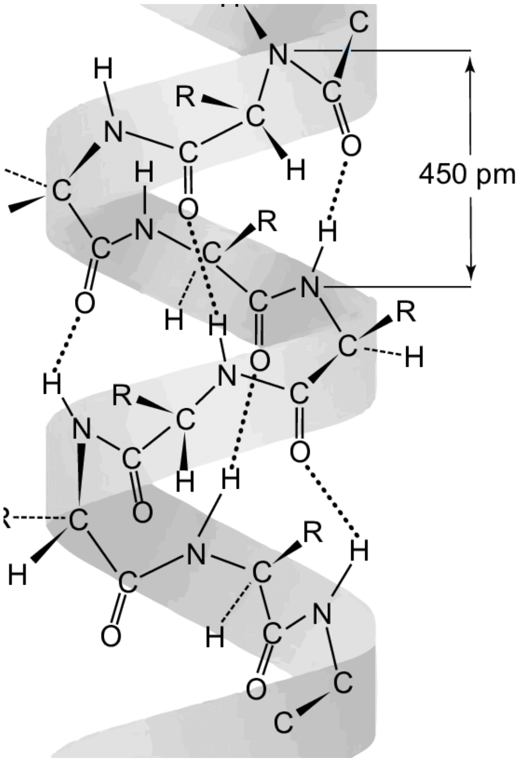


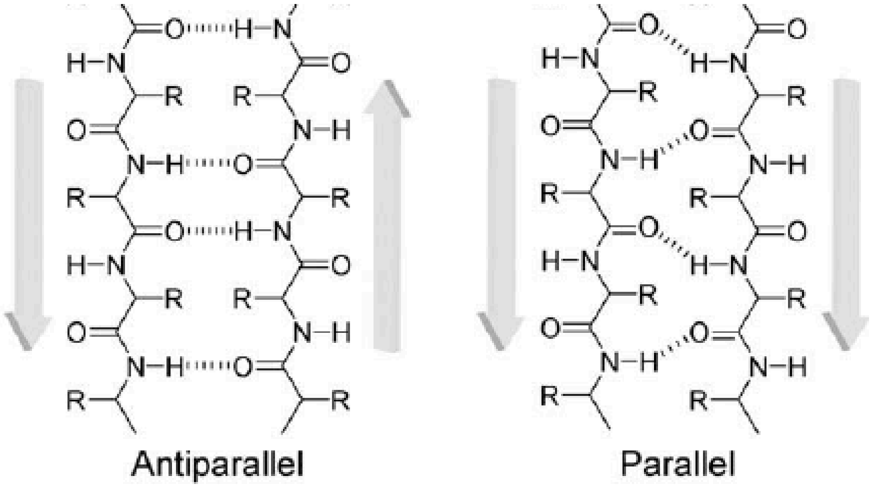
3b. **which amino acids are they?** (you can look up amino acid structures.)

3c. for each amino acid, is its side chain **polar or nonpolar?**

3d. identify the **amino ("N") and carboxyl ("C") ends** of the dipeptide.

4. in the following diagrams[19,20], **identify/label** (e.g. circle, highlight, etc.):
   a. the polypeptide backbone
   b. the side chains (hint: they are not explicitly drawn here!)
   c. the secondary structure (alpha helix or beta sheet?)
   d. the hydrogen bonds
   e. the atoms participating in the hydrogen bonds, and (for each such atom) whether they have a partial positive (δ+) or partial negative (δ-) charge




Antiparallel

Parallel

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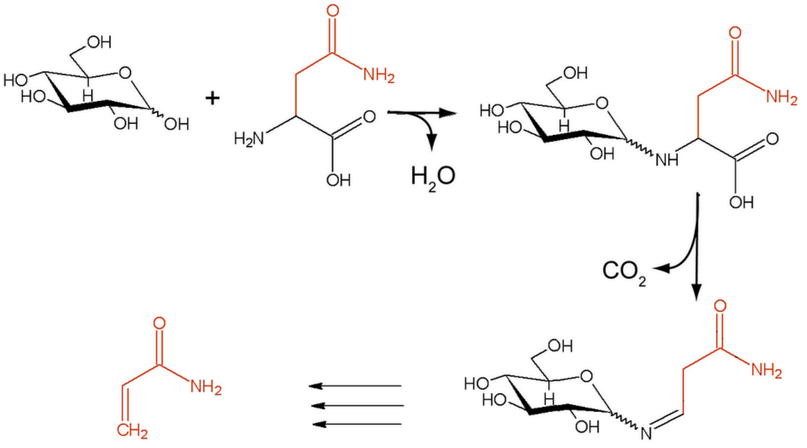
[19] https://www.sciencedirect.com/science/article/pii/S0378437118314432?via%3Dihub

[20] https://pubs.rsc.org/en/content/articlelanding/2008/jm/b711188f

lecture 5 worksheet

consider the reaction to the right.



1. what are the reactants?
    - **the first reactant ($C_6H_{12}O_6$) is:**
        a. a fatty acid
        b. an amino acid
        c. a carbohydrate
    - **the second reactant ($C_4H_8N_2O_3$) is:**
        a. a fatty acid
        b. an amino acid
        c. a carbohydrate
    - **for each reactant, what specific fatty acid/amino acid/carbohydrate is it?**
      see the last page for a list of structures and their corresponding names.

2. **what type of reaction is this?** (hint: for each option below, think through what the reactant(s) would be!)
    a. dehydration synthesis of amino acids
    b. hydrolysis of peptide bond
    c. dehydration synthesis of sugars
    d. hydrolysis of glycosidic bond
    e. caramelization
    f. Maillard reaction

3. in the top right of the image, **circle** the carbon that gets removed to form CO_2.**this carbon gets...**
    a. oxidized
    b. reduced

4. remember, reduction reactions and oxidation reactions come in pairs ("redox" reactions)! therefore:
    - if your answer to (3) was 'oxidized', **circle the oxygen atom that gets reduced.**
    - if your answer to (3) was 'reduced', **circle the oxygen atom that gets oxidized.**

5. **in what ways did we see vitamin C get used?** select all that apply.
    a. as a flavor compound
    b. as a reductant
    c. as an oxidant
    d. as an antioxidant
    e. as an inhibitor
    f. as a cofactor

citations: [21] [22] [23] [24]

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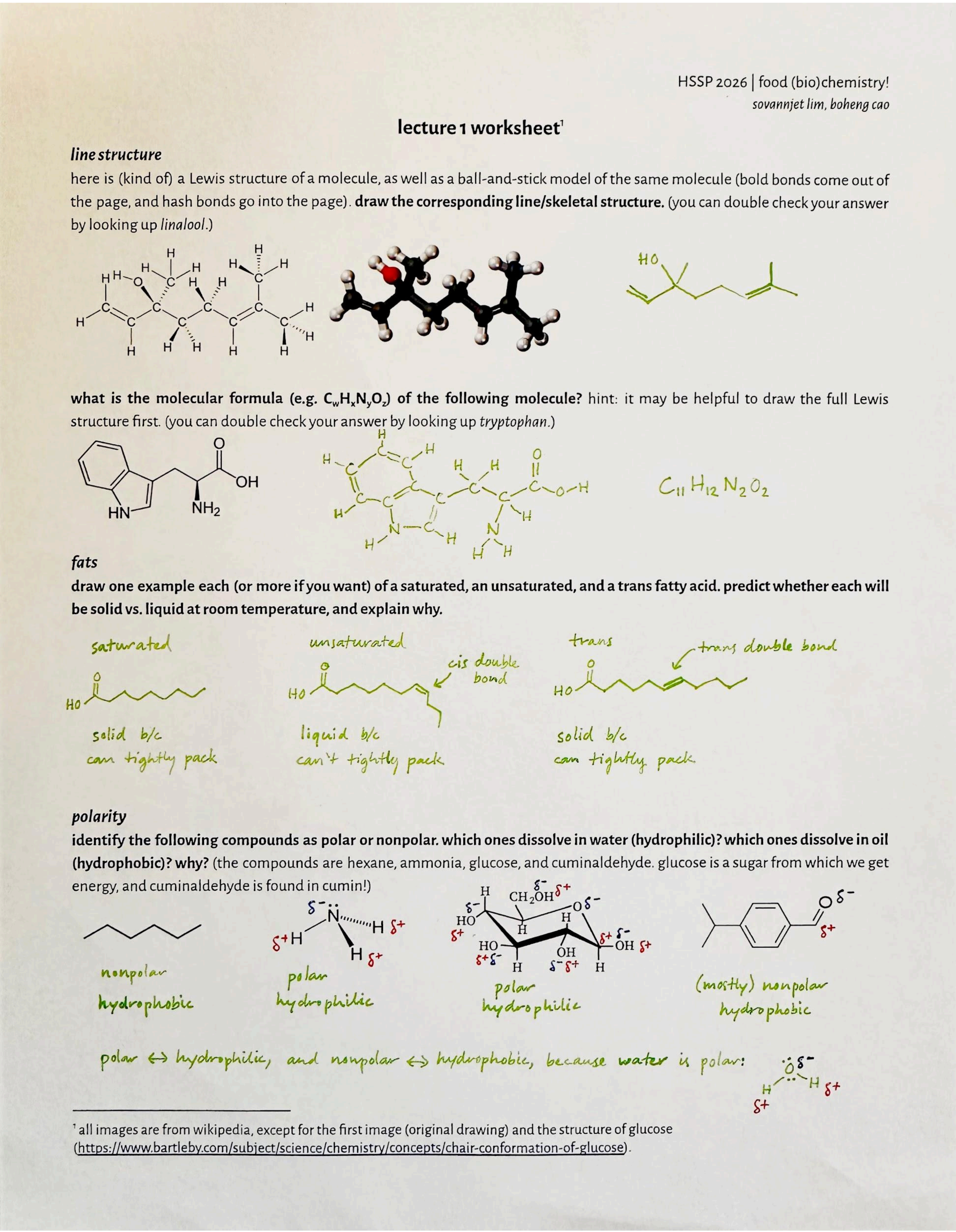
[21] https://en.wikipedia.org/wiki/Food_browning

[22] https://pubs.rsc.org/en/content/articlelanding/2014/ob/c3ob42339e

[23] https://chem.libretexts.org/Bookshelves/Organic_Chemistry/Organic_Chemistry_III_%28Morsch_et_al.%29/25%3A_Carbohydrates/25.05%3A_Cyclic_Structures_of_Monosaccharides_-_Anomers

[24] https://www.technologynetworks.com/applied-sciences/articles/essential-amino-acids-chart-abbreviations-and-structure-324357

worksheet 1 answer key



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sovannjet lim, boheng cao

lecture 1 worksheet[1]

line structure

here is (kind of) a Lewis structure of a molecule, as well as a ball-and-stick model of the same molecule (bold bonds come out of the page, and hash bonds go into the page). **draw the corresponding line/skeletal structure.** (you can double check your answer by looking up *linalool*.)

what is the molecular formula (e.g. $C_wH_xN_yO_z$) of the following molecule? hint: it may be helpful to draw the full Lewis structure first. (you can double check your answer by looking up *tryptophan*.)

$C_{11}H_{12}N_2O_2$

fats

draw one example each (or more if you want) of a saturated, an unsaturated, and a trans fatty acid. predict whether each will be solid vs. liquid at room temperature, and explain why.

saturated

solid b/c can tightly pack

unsaturated

cis double bond

liquid b/c can't tightly pack

trans

trans double bond

solid b/c can tightly pack

polarity

identify the following compounds as polar or nonpolar. which ones dissolve in water (hydrophilic)? which ones dissolve in oil (hydrophobic)? why? (the compounds are hexane, ammonia, glucose, and cuminaldehyde. glucose is a sugar from which we get energy, and cuminaldehyde is found in cumin!)

nonpolar
hydrophobic

polar
hydrophilic

polar
hydrophilic

(mostly) nonpolar
hydrophobic

polar ↔ hydrophilic, and nonpolar ↔ hydrophobic, because water is polar:

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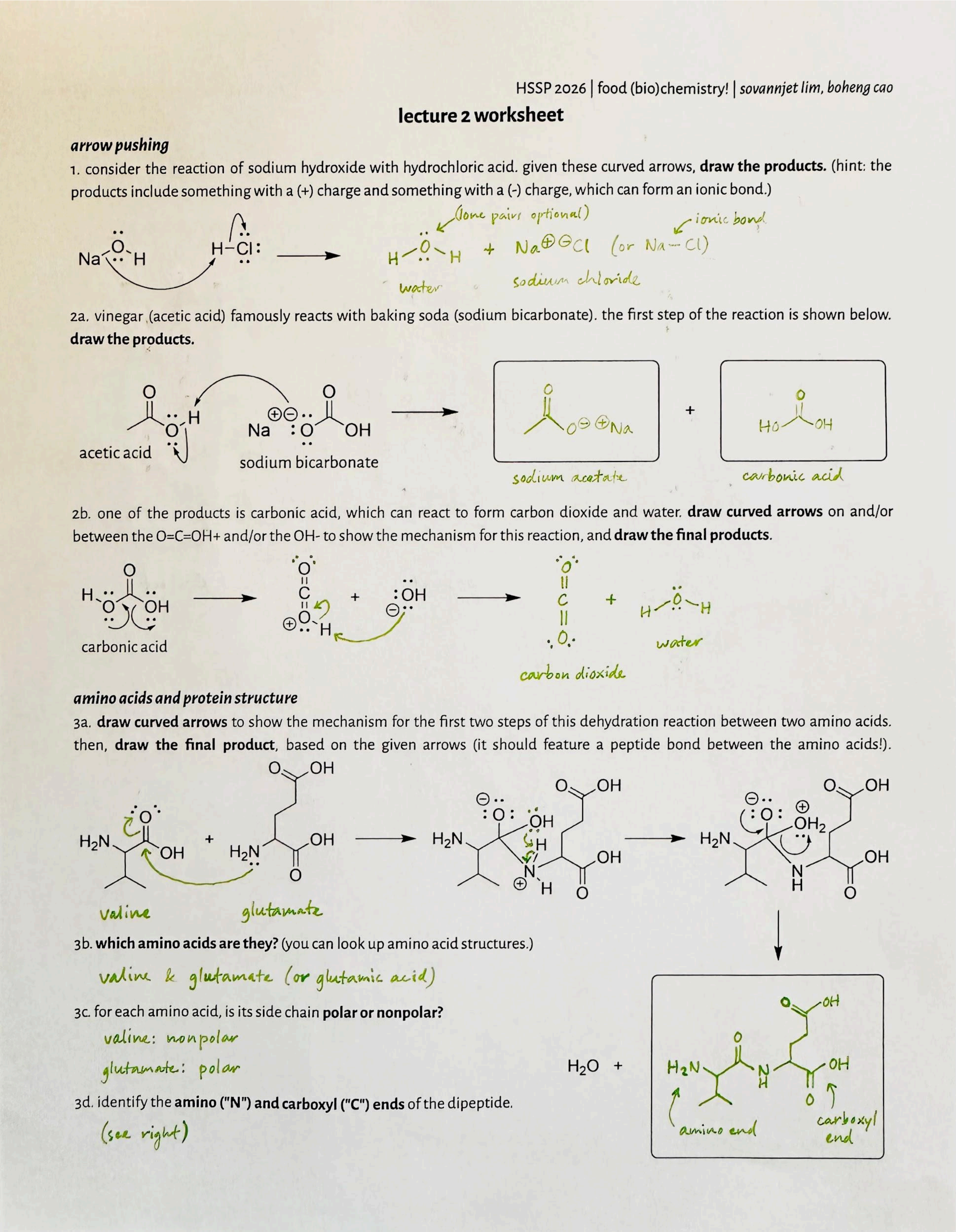
[1] all images are from wikipedia, except for the first image (original drawing) and the structure of glucose (https://www.bartleby.com/subject/science/chemistry/concepts/chair-conformation-of-glucose).

worksheet 2 & 3 answer key



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lecture 2 worksheet

arrow pushing

1. consider the reaction of sodium hydroxide with hydrochloric acid. given these curved arrows, **draw the products.** (hint: the products include something with a (+) charge and something with a (-) charge, which can form an ionic bond.)

(lone pairs optional)

ionic bond

H_2O + $Na^{\oplus}\,{}^{\ominus}Cl$ (or Na—Cl)

water

sodium chloride

2a. vinegar (acetic acid) famously reacts with baking soda (sodium bicarbonate). the first step of the reaction is shown below. **draw the products.**

acetic acid

sodium bicarbonate

sodium acetate

carbonic acid

2b. one of the products is carbonic acid, which can react to form carbon dioxide and water. **draw curved arrows** on and/or between the O=C=OH+ and/or the OH- to show the mechanism for this reaction, and **draw the final products**.

carbonic acid

carbon dioxide

water

amino acids and protein structure

3a. **draw curved arrows** to show the mechanism for the first two steps of this dehydration reaction between two amino acids. then, **draw the final product**, based on the given arrows (it should feature a peptide bond between the amino acids!).

valine

glutamate

3b. **which amino acids are they?** (you can look up amino acid structures.)

valine & glutamate (or glutamic acid)

3c. for each amino acid, is its side chain **polar or nonpolar?**

valine: nonpolar

glutamate: polar

3d. identify the **amino ("N") and carboxyl ("C") ends** of the dipeptide.

(see right)

H_2O +

amino end

carboxyl end

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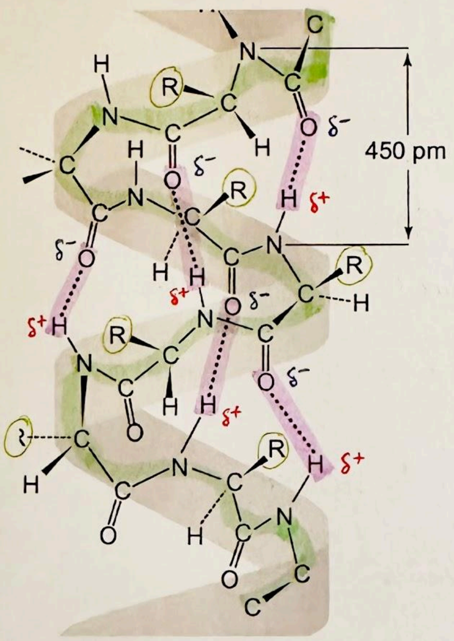
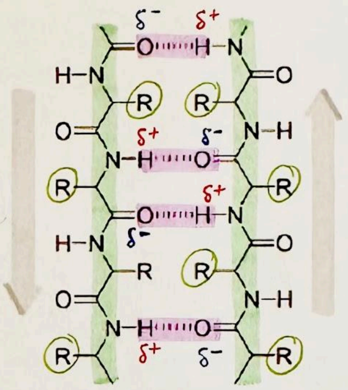
4. in the following diagrams[1,2], **identify/label** (e.g. circle, highlight, etc.):
   - a. the polypeptide backbone
   - b. the side chains (hint: they are not explicitly drawn here!)
   - c. the secondary structure (alpha helix or beta sheet?)
   - d. the hydrogen bonds
   - e. the atoms participating in the hydrogen bonds, and (for each such atom) whether they have a partial positive (δ+) or partial negative (δ-) charge

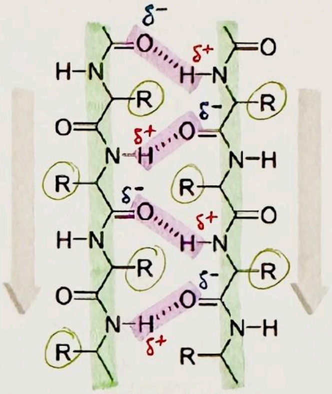


α-helix



Antiparallel

β-sheet



Parallel

β-sheet

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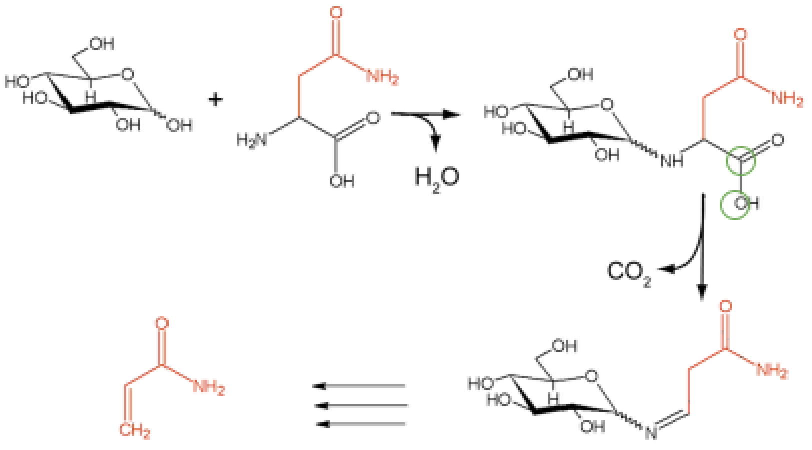
[1] https://www.sciencedirect.com/science/article/pii/S0378437118314432?via%3Dihub

[2] https://pubs.rsc.org/en/content/articlelanding/2008/jm/b711188f

worksheet 5 answer key

consider the reaction to the right.



1. what are the reactants?
   - **the first reactant ($C_6H_{12}O_6$) is:**
     - a. a fatty acid
     - b. an amino acid
     - [✓ c. a carbohydrate]
   - **the second reactant ($C_4H_8N_2O_3$) is:**
     - a. a fatty acid
     - [✓ b. an amino acid]
     - c. a carbohydrate
   - **for each reactant, what specific fatty acid/amino acid/carbohydrate is it?**

     see the last page for a list of structures and their corresponding names.

     the carbohydrate is **glucose**; the amino acid (a.a.) is **asparagine**.

2. **what type of reaction is this?** (hint: for each option below, think through what the reactant(s) would be!)

a. dehydration synthesis of amino acids	a.a. + a.a. → dipeptide
b. hydrolysis of peptide bond	dipeptide → a.a. + a.a. (or *n*-peptide → a.a. + (*n*-1)-peptide)
c. dehydration synthesis of sugars	monosaccharide + monosaccharide → disaccharide (or *m*-saccharide + *n*-saccharide → (*m*+*n*)-saccharide)
d. hydrolysis of glycosidic bond	disaccharide → monosaccharide + monosaccharide (or *n*-saccharide → *m*-saccharide + (*n*–*m*)-saccharide)
e. caramelization	sugar → flavor compounds + caramelans, caramelens, caramelins
[✓ f. Maillard reaction]	sugar (**carbohydrate**) + protein (**a.a.'s**) → flavor cmpds. + melanoidins

3. in the top right of the image, **circle** the carbon that gets removed to form CO_2 (see top right of image). **this carbon gets...**
   - [✓ a. oxidized]
   - b. reduced

4. remember, reduction reactions and oxidation reactions come in pairs ("redox" reactions)! therefore:
   - if your answer to (3) was 'oxidized', **circle the oxygen atom that gets reduced.** (see top right of image)
   - if your answer to (3) was 'reduced', **circle the oxygen atom that gets oxidized.**

5. **in what ways did we see vitamin C get used?** select all that apply.

a. as a flavor compound	
[✓ b. as a reductant]	vitamin C reduces *o*-quinone back to catechol
c. as an oxidant	
[✓ d. as an antioxidant]	vitamin C removes ROS, which are (damaging) oxidants
[✓ e. as an inhibitor]	vitamin C inhibits catechol oxidase (and therefore browning)
f. as a cofactor	we plan to show vitamin C as a cofactor in lecture 6 !