Unit 1

Structure Determination

1.1 Intro + EA

- Teaching team.

  - Prof. Masha Elkin.
  - Prof. Steve Buchwald.
  - 8 Teaching Fellows (TFs).

- Masha Elkin begins. Steve Buchwald and all TFs introduce themselves. Special roles:

  - Head TF: Minh Le.
  - Electronic TF (contact with questions on Canvas, Piazza, BACON): Angel Garcia-Ramirez.

- In this class, you will learn. . .

  - New things in organic chemistry;
  - Old things at a deeper level;
  - Real-world applications of chemistry.

- Why study organic chemistry?

  - Chemists manipulate matter, and that's awesome!
  - By "manipulate matter," we mean making molecules, breaking molecules, making polymers, making detergents, and making sure that all of these things break down in the environment :)

- Core questions.

  - *How* do we make molecules?
  - What molecules *should* we make?

- Course logistics.

  - Seven (7) units total (2 big units before the halfway mark & 5 smaller units after).
  - The units.
    - Unit 1: How do we know what molecule(s) we have?
    - Unit 2: How do electrons move?
    - Units 3-7: How do we make molecules? How do reactions work?
  - Exams after units 1, 2, 4, and 6; final exam after unit 7.
  - Questions? Ask your TF first, then the Head TF, then the profs (Masha & Steve).

- Prerequisites.

  - Official prerequisites: 5.12 (equivalent to Orgo I, in case you took it elsewhere) & Gen Chem.
  - Recommended reading for review: Chapters 1-2 of the main textbook, referred to in these notes as Clayden et al. (2012).

- Grading.

  - Your grade will (hopefully) be a reflection of your learning.
  - There are no curves in this class or at MIT, so *everyone can get an A!!!*
  - How to improve your grade: Do problems!
    - ■ Problem sets (PSets) and recitation worksheets will be provided.
    - ■ You may also do as many textbook problems as you want. Feel free to buy the solutions manual, or borrow a copy from the ChemEd office[1] to check your answers.

- How to learn organic chemistry.

  - Analogy: Learning Orgo is like learning a language.
    - ■ Basic vocab and grammar that must be memorized. Examples: Drawing structures, curved arrow formalism, etc.
    - ■ Recognizing patterns and trends. Examples: Nucleophiles tend to have lone pairs (or be other regions of high electron density).
    - ■ Developing intuition.
    - ■ Practice, practice, practice! (Focus on drawing structures.)
  - Tips for success.
    - ■ Be active and participate in lecture, recitation, etc. Take notes while you're here!
    - ■ Practice **metacognition**, i.e., learn how you learn.
      - ➢ Do you learn best in a crowded coffee shop, or in your own room? Would you rather recopy your notes, or read the textbook?
      - ➢ Note that what works for somebody else may not work for you, and vice versa!
      - ➢ Invest the time and effort that *you* need to succeed. This may be more (or less) than other students, and that's ok!
    - ■ Communicate with *the whole* teaching team. They're here to help!!!
      - ➢ Seek out accommodations as needed: It's the student's responsibility to ask.

- **Metacognition**: Being aware of your own understanding.

- We now begin the content for Unit 1.

- Goal: Learn how to determine the chemical structure of a given organic compound.

- Why do we need to determine structures?

Figure 1.1: Why we study structure determination.

  - With the naked eye, organic chemists see a flask with a colorless liquid. But we draw the skeletal diagram for benzene (which is a colorless liquid). What tools enable us to convert from the flask to the structure?

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[1]Located in 6-203.

    – Here's another reason: Suppose we run a brand new chemical reaction. Organic chemists do this all the time in research! How do we now what the product is? How do we know which atoms it contains, and in what arrangement?

- Structure determination workflow.

    1. Identify the atoms present.

        – Questions to answer: What is the molecular formula?
        – Relevant tools: Elemental analysis (EA) and mass spectrometry ("mass spec" or MS).

    2. Identify the functional groups and substructures present.

        – Questions to answer: Do we have ketones? Esters? Alcohols? Rings?
        – Relevant tools: MS, infrared spectroscopy (IR), and nuclear magnetic resonance (NMR).[2]

    3. Identify how all the functional groups fit together.

        – Questions to answer: Are they close? Far apart? Ortho/meta/para? What stereochemistry?
        – Relevant tools: NMR and X-ray diffraction.

- We now begin talking about EA.

    – History: Began development in the 1820s.

    – Purpose: Determine which elements are present, and in what quantities (in a given sample).

- In this course, we will apply EA to compounds containing carbon, hydrogen, and oxygen *exclusively*.

    – To reiterate, in an EA problem for this course, we will *not* have to worry about any other elements.

    – The typical EA technique for such compounds is **combustion analysis**.

- **Combustion analysis**: Burn the sample and measure the products.

    – All C in the sample becomes CO_2.

    – All H in the sample becomes H_2O.

    – O is then determined via process of elimination, explained as follows.

- Advanced techniques (beyond the scope of this class): Nitrogen to NO or NO_2, sulfur to SO_2, etc.

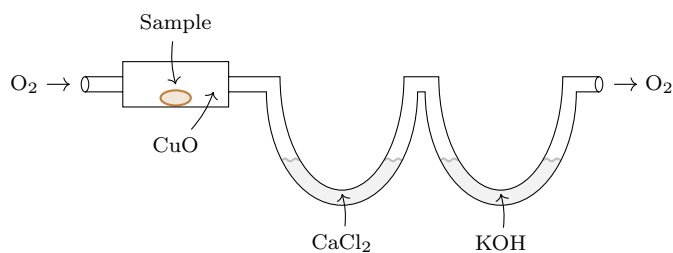- A schematic of combustion analysis.

Figure 1.2: Combustion analysis schematic.

    – Burn the sample in the presence of an oxidant such as cupric oxide (CuO).

    – Flow O_2 into the combustion chamber to facilitate burning as well.

    – The combusted gas then flows through a series of reaction containers.

        ■ The first one contains a desiccant (like $CaCl_2$) that absorbs the water.

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[2] NMR is an organic chemist's best friend!

- ■ The second one contains a base (like KOH) that absorbs the CO_2.
  - – The remaining oxygen flows out the end.

- The *analysis* part of combustion analysis.

  - – The amount of H is equal to the change in mass of the $CaCl_2$.

  $$\Delta\text{mass}(CaCl_2) = \text{mass}(H_2O) \rightarrow \text{ratio}(H)$$

  - – The amount of C is equal to the change in mass of the KOH.

  $$\Delta\text{mass}(KOH) = \text{mass}(CO_2) \rightarrow \text{ratio}(C)$$

 - – The amount of O is equal to the change in mass of the sample.

  $$\text{mass(sample)} - \text{mass}(H) - \text{mass}(C) = \text{mass}(O) \rightarrow \text{ratio}(O)$$

  - – Result: We get an **empirical formula** of the form $C_x H_y O_z$. Remember that this is *not* (necessarily) the **molecular formula**; it is *only* a ratio of elements.

- EA example: Let's burn $0.5\,\text{g}$ of propanol (C_3H_8O).

  - – Suppose we obtain $0.600\,\text{g}\ H_2O$ and $1.09\,\text{g}\ CO_2$.
  - – This means that there was $0.067\,\text{g}$ (H) and $0.300\,\text{g}$ (C) in the sample. The remaining $0.133\,\text{g}$ must then be due to O.
  - – Therefore, the elements exist in a 3:8:1 (C:H:O) ratio.
  - – Bonus: Convert the masses to a ratio via stoichiometry.
    - ■ $0.600\,\text{g}\ H_2O \times \dfrac{1\,\text{mol}\ H_2O}{18.02\,\text{g}\ H_2O} \times \dfrac{2\,\text{mol}\ H}{1\,\text{mol}\ H_2O} \times \dfrac{1.01\,\text{g}\ H}{1\,\text{mol}\ H} = 0.067\,\text{g}$ (H)
    - ■ $1.09\,\text{g}\ CO_2 \times \dfrac{1\,\text{mol}\ CO_2}{44.01\,\text{g}\ CO_2} \times \dfrac{1\,\text{mol}\ C}{1\,\text{mol}\ CO_2} \times \dfrac{12.01\,\text{g}\ C}{1\,\text{mol}\ C} = 0.300\,\text{g}$ (C)
    - ■ $0.5\,\text{g}$ propanol $- 0.067\,\text{g}$ (H) $- 0.300\,\text{g}$ (C) $= 0.133\,\text{g}$ (O)

- A note on the previous example.

| Name	Propanol	Methyl ethyl ether	Formaldehyde	Acetic acid	Glucose
Structure					
Emp. formula	C_3H_8O	C_3H_8O	CH_2O	CH_2O	CH_2O
Mol. formula	C_3H_8O	C_3H_8O	CH_2O	$C_2H_4O_2$	$C_6H_{12}O_6$

Table 1.1: Questions that EA can't answer.

  - – EA has given us the empirical formula, but it has *not* confirmed that the sample is propanol. For example, methyl ethyl ether has the same empirical formula!
  - – Additionally, we don't yet have the molecular formula. Consider, for instance, the breadth of compounds with empirical formula CH_2O!
  - – Takeaway: EA gives you the empirical formula; we need MS to get the molecular formula (we'll see this on Friday), and we may need even more to get the atomic connectivity.

- Application of EA to real-world chemistry.

  - – A home furnace burns natural gas — which is mostly methane (CH_4) — for heat.

- **Ideal combustion**[3] corresponds to the reaction

$$CH_4 + O_2 \longrightarrow CO_2 + H_2O$$
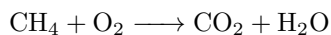
- Real-world combustion is incomplete; you make

$$CH_4 + air \longrightarrow CO_2 + H_2O + NO_2 + CO$$
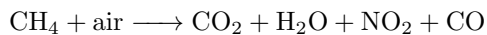
- When a technician comes to your home, they analyze the flue gas (i.e., your furnace exhaust).
    - Their analysis could determine that our combustion has too much O_2, which is called "air rich." This is inefficient and doesn't yield enough heat.
    - They could also determine that you have too much CO_2 and CO, which is called "fuel rich." This yields too much soot and CO. CO can be dangerous and lead to carbon monoxide poisoning, which makes you sleepy before it kills you.
- To measure this flue gas, though, they have a little handheld elemental analysis device!

• Note that there is a relation between ideal/real-world combustion and the CuO oxidant in Figure 1.2: The CuO ensures that when we combust our EA sample, all the carbon is fully oxidized to CO_2! Without it, some CO would be formed, and our stoichiometry would be thrown off.

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[3]You can learn more about in a chemical engineering/ChemE course.