

**The four facets of  $^1\text{H}$  NMR spectroscopy:**

1. The number of signal sets (Section 13.6)
  - The number of signal sets tells how many types of symmetry-unique hydrogen are present
  - Symmetry-duplicate hydrogens give the same signal sets
2. The chemical shifts (where the signals appear) (Section 13.5) (Most complex facet)
  - The chemical shifts reflect the chemical environment of each type of hydrogen
    - a. Whether attached to an  $\text{sp}^3$  or and  $\text{sp}^2$  carbon
    - b. What kind of functional groups might be attached to the carbon on which the hydrogen is attached.
    - c. Whether attached to carbon versus to oxygen or nitrogen
3. The integration (size/area) of each signal set (Section 13.7) (Simplest facet, once you know how)
  - The integrated area for each signal set reflects how many hydrogens are responsible.
    - a.  $3\text{H} \rightarrow \text{CH}_3$  group (or  $2\text{H}$  and  $1\text{H}$  groups superimposed)
    - b.  $2\text{H} \rightarrow \text{CH}_2$  group (or two nonequivalent  $1\text{H}$  groups superimposed)
    - c.  $1\text{H} \rightarrow \text{CH}$  or  $\text{OH}$  group
4. The splitting (number of lines) in each signal set (Section 13-8)
  - The splitting provides information about what is connected to a given carbon
    - a.  $N$  lines  $\rightarrow N-1$  "neighbor"  $\text{H}$ 's (when working from spectrum to structure)
    - b.  $N$  neighbors  $\rightarrow N+1$  lines (when predicting spectrum from structure)

**Summary of Steps in Beginner  $^1\text{H}$  NMR Interpretation:**

1. If provided with a chemical formula, calculate how many elements of unsaturation are present
  - This helps to put you on the alert for the presence of double bonds, rings, or aromatics
2. **Count how many signal sets** you have.
  - **This will tell you how many types of hydrogen-bearing carbons** you have.
  - Hydrogens attached to symmetry-equivalent carbons will give equivalent signals)
  - Clean  $\text{CH}_3$  or  $\text{CH}_2$  signal sets will normally have reasonable shape symmetry
  - If you have asymmetric looking signals, there is a good chance that two or more different signal sets may be overlapping
3. Check the integration of each signal set.
  - $3\text{H} \rightarrow \text{CH}_3$  group     $2\text{H} \rightarrow \text{CH}_2$  group     $1\text{H} \rightarrow \text{CH}$  or  $\text{OH}$  group
  - The above are true if there isn't any accidental overlapping
  - Clean  $\text{CH}_3$  or  $\text{CH}_2$  signal sets will normally have reasonable shape symmetry
    - a. So, for example, if you have a nice symmetric  $3\text{H}$  signal, conclude you have a  $\text{CH}_3$
    - b. But if you have a complex, unsymmetric  $3\text{H}$ , do not assume it's really a  $\text{CH}_3$ .
  - Effective recognition and integration of signal sets can help you know how many  $\text{CH}_3$ 's and  $\text{CH}_2$ 's you have in your molecule
4. **Check diagnostic "chemical shift" windows** of the lines
  - Use yes-or-no checklist regarding the presence of key functional groups
  - Things can get more complicated if two or more functional groups are both affecting a common signal set.
  - Chemical shift information can quickly tell you whether hydrogens are attached to arenes or alkenes, and tell whether a  $\text{CH}_2$  or  $\text{CH}_3$  or  $\text{CH}$  signal set is attached to a single-bond oxygens or a carbonyl or an aromatic.

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5. Check the **splitting** of each signal set.
    - A signal set with N lines means that there are N-1 hydrogens attached to carbons directly connected to the carbon that holds the signal set hydrogens
    - The splitting tells you nothing about the signal set itself (for example, whether it is a CH<sub>3</sub> or a CH<sub>2</sub> group). But it can tell you for example whether a CH<sub>3</sub> group (for example) is connected to a CH<sub>2</sub> group or a CH group, or perhaps to an oxygen or a carbonyl carbon that doesn't have any directly attached hydrogens.
    - Etc.
  6. Try to find any sure things that you can as soon as you can.
  7. Try to use integration to find any clean 3H signals that indicate CH<sub>3</sub> groups. Then use splitting and/or chemical shifts to track down what the CH<sub>3</sub> group is connected to, etc..

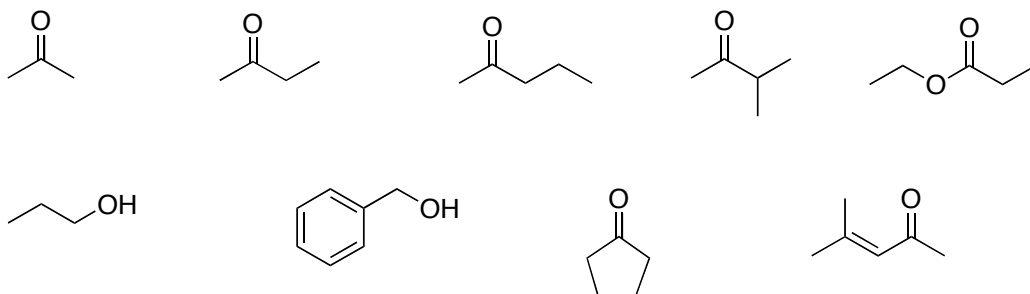
#### Other Practical Tips

1. Try to recognize any easy and obvious sure-thing components, for example:
  - a. Aryl groups (chemical shift in the 7's, a 4H or 5H integral depending on whether di- or mono-substituted)
  - b. CH<sub>3</sub> methyl groups (based on clean 3H integration)
  - c. Isopropyl groups (6H doublet)
  - d. Alcohol OH: integrates for only 1H, and normally doesn't have the splitting that a CH hydrogen does
2. Try to work from end(s) toward the middle
  - If you know you have a CH<sub>3</sub> group, you can write it down for sure, and then try to figure out via splitting and/or chemical shifts what it's connected to, etc.
3. Recognizing "end groups" can give you an idea whether you have a straight chain or have branching
  - CH<sub>3</sub>
  - Cl, Br
  - OH
  - C<sub>6</sub>H<sub>5</sub>

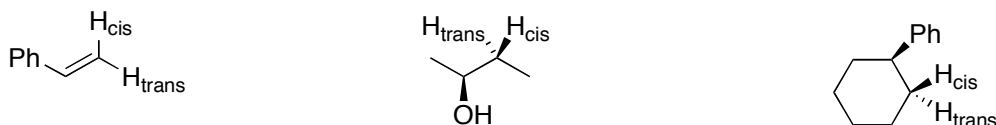
#### The Number of Signal Sets (Section 13-6)

1. Nonequivalent H's have different chemical environments and give different signals
2. Symmetry-equivalent H's have the same chemical environment and give the same signal
  - Thus the number of signal sets tells you how many different types of hydrogens are present
3. On an **achiral** molecule (alkenes and rings excepted), hydrogens on a common carbon will be equivalent.
  - all three H's on a CH<sub>3</sub> group will be equivalent
  - both H's on a CH<sub>2</sub> group will be equivalent.

Example: How many H-NMR Signal Sets Would each of the following produce?



4. For chiral molecules, substituted rings, and alkenes, cis-trans relationships can often make the two hydrogens in a  $\text{CH}_2$  group non-equivalent

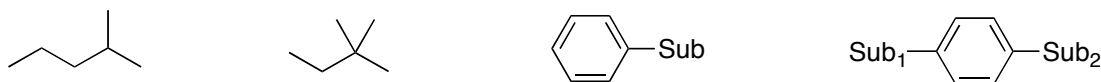


5. **Beware of overlaps!**

- Often two signal sets will show at about the same place. If you think you have a  $\text{CH}_3$  group when in fact it's overlapping  $\text{CH}_2$  and  $\text{CH}$  signals, you can get very confused...
- Overlaps normally don't have the clean symmetry that a clean signal set has

6. **Beware of Symmetry Duplication**

- Isopropyl groups are most common, and t-butyl groups on occasion
  - Integrations of 6H or 9H can help recognize these



**Integration** (Section 13-7)

1. All hydrogens give an equal amount of signal
  - The area produced is measured or "integrated" by the spectrometer
  - The measured area is normally referred to as the "integral"
2. When there is symmetry duplication of a hydrogen, the resulting signal will be multiplied accordingly!
  - Since all three H's on a  $\text{CH}_3$  group are equivalent, they will sum to provide a signal set that integrates for 3H
3. Technical notes:
  - a. The key is not the signal height, but rather the signal **area**.
  - b. The signal **area** is measured by "integration lines". Make sure to differentiate integration marks, and what they mean, from signal lines themselves.

**4. The relative areas of the signal-set integrals directly correlates the ratios of H's**

- The integrals **must be simple whole-number ratios** (2:1, 3:1, 3:2, etc..)
- You can't have half a hydrogen or one-third of a hydrogen atom!

5. Clean sets involving equivalent H's give clean, symmetric signal sets:

- 1H  $\rightarrow$  CH or OH
- 2H  $\rightarrow$  CH<sub>2</sub>
- 3H  $\rightarrow$  CH<sub>3</sub>
- 6H  $\rightarrow$  2 equivalent CH<sub>3</sub> groups
- 5H in aryl region  $\rightarrow$  monosubstituted benzene (even if not clean set)
- 4H in aryl region  $\rightarrow$  disubstituted benzene (even if not clean set)

6. Unsymmetrical messy sets involving overlapping signal sets: (these will routinely not look nice and symmetric...)

- 3H  $\rightarrow$  CH<sub>2</sub> overlapping an OH or CH
- 4H  $\rightarrow$  two overlapping but not exactly equivalent CH<sub>2</sub> groups; or a CH<sub>3</sub> overlapping an OH or CH
- 5H  $\rightarrow$  common in the 7's, for 5 overlapping arene H's; also common in the 1's, when a CH<sub>3</sub> and CH<sub>2</sub> overlap

7. Recognizing 3H  $\rightarrow$  methyl groups, or 6H  $\rightarrow$  isopropyl groups is really helpfulWays to Determine the Integration (Focus on the types of spectra that you'll see for test)

- Identify the integration line as opposed to the actual spectrum itself

- Measure the raw areas for each signal set
  - For class/test problems, use the grid lines
  - For lab, the spectrometer will often measure an integral number for you
  - For class or lab, if you prefer to use a ruler to measure, that's common to
- Convert the raw areas into relative area ratios (Example, Handout problem 1)

Raw areas:

Three Ways to do this:

- Divide any raw area by the smallest raw area

<u>Ratio</u>	<u>Means</u>	<u>Ratio</u>	<u>Means</u>	<u>Ratio</u>	<u>Means</u>	<u>Ratio</u>	<u>Means</u>
1		1.5		2		3	

- Since all of our class/test NMR's will have 10 gridlines, you can take 10 gridlines/actual number of hydrogens (if formula is provided) to figure out the gridlines-per-hydrogen ratio
  - You can then use this to convert your raw integrals into actual Hydrogen counts

Ex: 10 grids/7 H's = 1.4 grids/1 H

- Since all of our class/test NMR's will have 10 gridlines, you can set up a ratio to solve for actual H's in a given signal set:

Ex:  $\frac{2.9 \text{ grids}}{10 \text{ grids}} = \frac{x \text{ H's}}{7 \text{ H's}}$

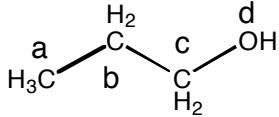
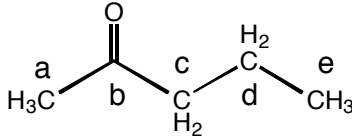
**Splitting (Section 13.8)**

- The number of lines in a signal set tell us nothing about the C-H's themselves that cause the signal (whether it's a CH<sub>3</sub> or CH<sub>2</sub> group, whether it's an sp<sup>3</sup> or sp<sup>2</sup> carbon, whether it's allylic or oxygenated...).
- But the splitting tells us something else that is really useful: what kind of CH groups are attached to the group of interest! Splitting tells us nothing about the group itself, but it does provide great information about neighbor groups.

**Rules of "Splitting"**

- N-1 Rule: N lines → N-1 neighbor H's** (H's directly attached to carbons attached to the C-H group causing the signal)
  - The N-1 Rule is useful when working from spectrum to actual structure
- N+1 Rule: N neighbor H's → N+1 lines**
  - The N+1 Rule is useful when predicting a spectrum for a structure

**N+1 Rule (Given structure, how many lines a spectrum should give)**


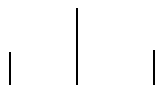
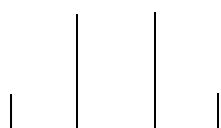
										
Neighbors	2	3+2	2	0	Neighbors	0	-	2	2+3	2
Lines	3	6	3	1	Lines	1	-	3	6	3

(Notice: OH doesn't split...)

**N-1 Rule (Given spectrum, how many neighbors a structure should have)**

	Lines	1 (s)inglet		Lines	2 (d)oublet
	Neighbors	0		Neighbors	1
	Lines	3 (t)riplet		Lines	4 (q)uartet
	Neighbors	2		Neighbors	3
					etc.

- Physics Origin: hydrogens are quantized little magnets. Having neighbor hydrogens is equivalent to having local magnets that can either reinforce the external field (spin up) or counteract the external magnetic field (spin down).
  - The number of lines and the relative intensity of the lines reflects simple statistical possibilities in terms of neighbor hydrogen magnets being spin up or spin down.
    - With one neighbor magnet, the probability of spin up vs spin down is comparable → 1:1 doublet
    - With two neighbor magnets, they can be spin up/down in three different arrangements of 1:2:1 probability → 1:2:1 triplet
    - Etc.

Lines Neighbors	2 (d)oublet 1 neighbor	3 (t)riplet 2 neighbors	4 (q)uartet 3 neighbors
			
Neighbor Hydrogen Spin States	↑     ↓	↑↑   ↓↑   ↓↓ ↑↓	↑↑↑   ↓↑↑   ↓↓↑   ↓↓↓ ↑↑↓   ↓↓↑ ↑↑↓   ↓↓↑

- Neighbor C-H hydrogens participate in splitting (always)

3. Neighbor OH hydrogens usually don't participate in splitting (~75% of the time). But sometimes they do (about 25% of the time).

- They can have widely varying and rapidly changing hydrogen-bonding arrangements
- Splitting from H's further distant than neighbor carbons sometimes occurs, but usually the amount of splitting is too small to worry about
  - Splitting nicknames:
    - 1 line = singlet (s)    2 lines = doublet (d)    3 lines = triplet (t)
    - 4 lines = quartet (q)    5 lines = pentet (p)    >5 lines = multiplet (m)
  - Limitation to the N-1/N+1 rules: it is only reliable if all of the neighbor hydrogens are equivalent. However, the rules actually are accurate only if the neighbor H's are equivalent.

• The rule can break down when some of the neighbor H's differ significantly from each other

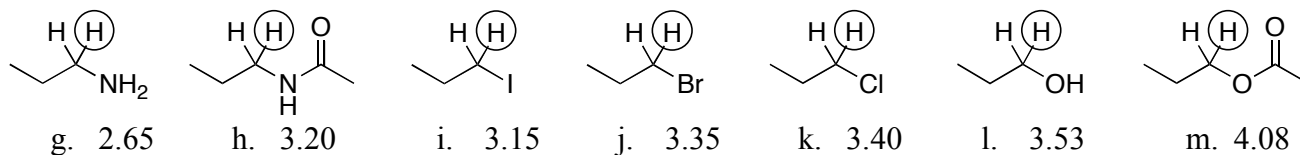
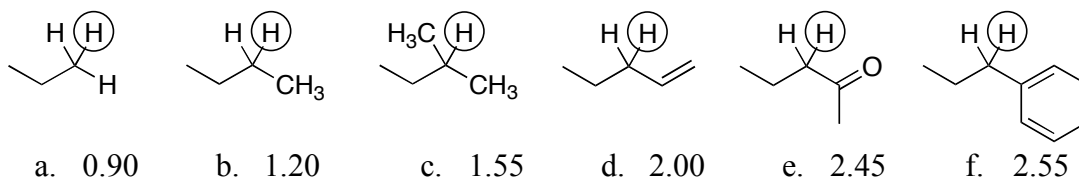
- The more nonequivalent the neighbor hydrogens, the less the N-1/N+1 rules apply
  - Neighbor hydrogens on acyclic and  $sp^3$  carbons tend to be pretty similar
  - Alkenes or aldehyde hydrogens (on  $sp^2$  carbons) tend to split rather differently than hydrogens on  $sp^3$  carbons
  - Splitting involving cis versus trans hydrogens on rings or alkenes tend to split rather differently from each other and from hydrogens on acyclic  $sp^3$  systems.
  - Chiral centers can mess up the splitting even on acyclic systems

**“Chemical Shifts” of the Signal Sets (Section 13.5)**

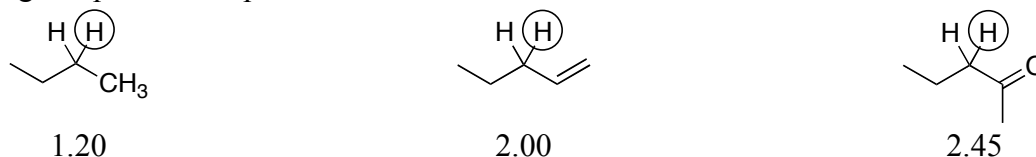
- The following apply when only one functional group is impacting
- If two or more are impacting, then signal sets can appear outside of these windows

1's (0.7-2.0)	$sp^3$ hybridized C-H's, with <b><u>no attached Functional Groups</u></b> <ul style="list-style-type: none"> <li>• <b><u>Note:</u></b> Many molecules with non-functional alkyl portions will give a lot of signal in this area.</li> <li>• <b><u>This is the default place for <math>sp^3</math> C-H's, when no functional group is shifting them to higher number</u></b></li> </ul>
2's (1.8-3.1)	<b><u>Allylic</u></b> $sp^3$ hybridized C-H's ( $sp^3$ hybridized C-H's that has a double bond attached to the $sp^3$ hybridized C). Allylic signals routinely appear when one of the following double-bonded functional groups is present: <ul style="list-style-type: none"> <li>• +1 Adjustment factor</li> <li>• <b><u>carbonyls</u></b>, (ketones, esters, aldehydes, acids, amides)</li> <li>• <b><u>alkenes</u></b>, or</li> <li>• <b><u>aromatics</u></b></li> </ul>
3's (2.8-4.5)	<b><u>Oxygenated</u></b> $sp^3$ hybridized C-H's (halogenated and nitrogenated alkyl C-H's will also come in this window, although no candidates for today's lab). Oxygenated $sp^3$ -carbons are routinely present for the following functional groups that contain oxygen single bonds: <ul style="list-style-type: none"> <li>• +2 Adjustment factor</li> <li>• <b><u>alcohols</u></b>,</li> <li>• <b><u>ethers</u></b>, or</li> <li>• <b><u>esters</u></b></li> </ul>
5's (4.8-6.8)	<b><u>Alkene</u></b> $sp^2$ hybridized C-H's
7's (6.5-8.4)	<b><u>Aromatic</u></b> $sp^2$ hybridized C-H's
9's (9.0-10.0)	<b><u>Aldehyde</u></b> $sp^2$ hybridized C-H's
0-12 (anywhere!)	<b><u>Alcohol/Acid</u></b> O-H hydrogens (N-H hydrogens likewise) <ul style="list-style-type: none"> <li>• <b><u>alcohols</u></b>, (normally 1.5-3.0)</li> <li>• <b><u>carboxylic acids</u></b></li> </ul>

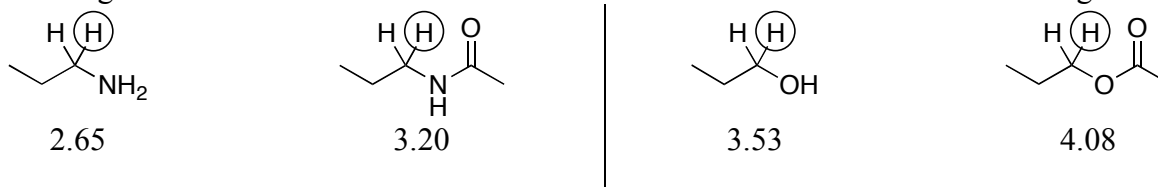
1. Replacement of H by more electronegative atom/group “deshields” a proton and moves it “downfield”, to a higher number
  - a. “methine” (CH)  $\rightarrow$  “methylene” (CH<sub>2</sub>)  $\rightarrow$  “methyl” (CH<sub>3</sub>) (case “a” vs “b” vs “c”)
    - sequential replacement of hydrogens by more electronegative carbons moves the signal “downfield”
  - b. See the electronegativity pattern as you go from: H (0.9) – C (1.2) – N (2.6) – I (3.2) – Br (3.3) – Cl (3.4) to O (3.5) (case “a” vs “b” vs “g” vs “i-l”)
    - sequential replacement of hydrogens (or carbons) by any more electronegative substituents moves a signal “downfield”
  - c. See the electronegativity pattern between amine (2.7) versus amide (3.2) (case “g” vs “h”), and alcohol/ether oxygen (3.5) versus ester oxygen (4.1) (case “l” vs “m”)
    - the electron-withdrawing carbonyl attachment on the nitrogen or oxygen makes it effectively more electronegative and moves the signal “downfield”



2. The allylic factor has the same basis:  $sp^2$  carbons are more electronegative than  $sp^3$  carbons, so replacing an  $sp^3$  with an  $sp^2$  "deshields"



3. An electron-withdrawing carbonyl on a heteroatom makes the heteroatom effectively more electronegative. So ester versus ether and amide versus amine has the same electronegativity basis.

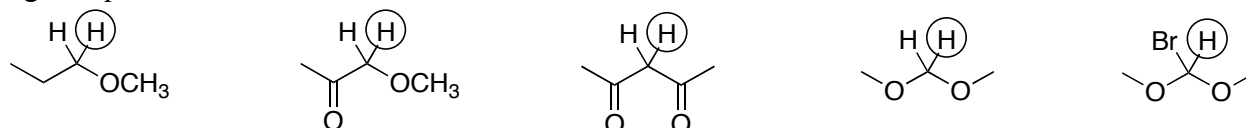


4. **Additivity values can be used to predict chemical shifts when two or more functional groups are acting**

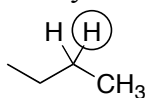
Vinyl	Carbonyl ("Acyl")	Aryl	Amino	Amido	Halo	Hydroxy/ Alkoxy	Carbonyloxy
0.8	1.2	1.3	1.5	2	2.2	2.3	2.8

- Default reference points:  $CH_3$  0.90       $CH_2$  1.20       $CH$  1.50
- Memorize the following qualitative additivity values:
  - Double-bonded carbons (vinyl, acyl, aryl)  $\rightarrow +1$
  - Oxygen or Halogen  $\rightarrow +2$

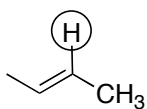
Predict the chemical shifts for the circled hydrogens, using the specific chart additivity values and using the qualitative memorized ones:



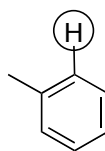
5. Strong hybridization effect: hydrogens on  $sp^2$  carbons routinely above 5, those on  $sp^3$  carbons normally come below 5.



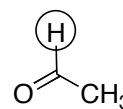
1.20



5.4

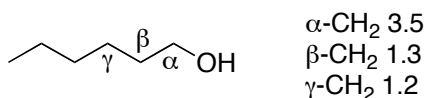


7.1



9.7

6. Functional Groups further away have reduced but sometimes significant impact.
- Direct “ $\alpha$ ” attached functional groups have a large impact
  - When the functional group is “ $\beta$ ” it makes a difference, but not large
  - When the functional group is “ $\gamma$ ” or further, it makes no difference
  - Sometimes a couple of “ $\beta$ ” substituents can add up and push a signal set out of it’s normal window



Key: The impact of two or more functional groups can sometimes deceptively push a signal into a window that you assume means something else

- A signal in the 3’s normally implies an oxygenated (or halogenated) carbon. But it could also result from a double allylic carbon with two carbonyls attached.
- A signal in the 5’s is normally implies an alkene, but it might also result from an  $sp^3$ -hybridized carbon that has two oxygen attachments.
- Etc.

### 7. Recognize OH’s.

- An OH can come anywhere, and can easily cause you to make a mistaken conclusion about a feature group. For example, if you have an OH and it comes in the 2’s, and you conclude that you have an allylic C-H, that might send you down a bad blind alley. Or if you have an OH that appears in the 5’s, you might falsely deduce that you have an alkene, etc.. Thus it is really helpful to recognize OH’s when they appear so that they don’t confuse you.
- Three recognition factors for OH signals:
  - They always **integrate for 1H**, never for 2H or 3H
  - They often **appear as singlets, often somewhat broad**. C-H signals tend to be sharper, and any C-H signal set that integrates for 1H will have significant splitting. The only way to have a 1H that doesn’t split is for it to be an OH.
  - They come anywhere, but often in the 1.5-3.0 range
  - If you have an OH signal, of course you will also have some C-H signals in the 3.0-4.5 area.

### 8. Check each of the zones. Each one gives you a tentative yes or no answer about the presence of absence of the featured group.

- Do I have something in the 9’s? If yes → aldehyde
- Do I have something in the 7’s? (Other than a solvent singlet...)? If yes → aromatic
- Do I have something in the 5’s? If yes → alkene
- Do I have something in the 3’s? If yes → alcohol, ether, or ester (or OH)
- Do I have something in the 2’s? If yes → ketone, aromatic, or alkene (or OH)
- Do I have something in the 1’s? If yes → some nonfunctional alkyl carbons (or OH)

**Caution: Mistaken conclusions can sometimes be drawn from two sources:**

- An OH in the 2's or 3's or 5's, from which you falsely conclude that you be allylic or oxygenated or vinylic
- A signal that appears where it does because of the effect of two (or more) functional groups, rather than just one.

**Standard Summary Format and Predicting H-NMR's** There is a standard summary report format for H-NMR's which addresses chemical shift, integration, and splitting. Normally an interpretation/correlation with the actual structure is also included.

Ex:  $\text{CH}_3\text{OCH}_2\text{CH}_2\text{CH}_2\text{C}(\text{O})\text{CH}_3$  (I'll number the carbons from left to right...)

Standard report format (approximate chemical shift range, integration, splitting, and interpretation of which signal correlates to which group in the structure...)

3's, 3H, s ( $\text{CH}_3$ -1)

3's, 2H, t ( $\text{CH}_2$ -2)

1's, 2H, p ( $\text{CH}_2$ -3)

2's, 2H, t ( $\text{CH}_2$ -4)

2's, 3H, s ( $\text{CH}_3$ -6)

- Beware of Overlapping.** Overlapping is most routine in the benzene area (7's), and also in the alkyl area (1's), but happens elsewhere as well. OH signals also often overlap other signals.

**Review + Summary**

- Use your formula to count elements of unsaturation
- Count **how many signal sets** you have.
- Check the **integration** of each signal set.
  - 3H  $\rightarrow$   $\text{CH}_3$  group      2H  $\rightarrow$   $\text{CH}_2$  group      1H  $\rightarrow$  CH or OH group
- Check the **splitting** of each signal set.
  - N lines  $\rightarrow$  N-1 neighbor hydrogens
- Check **"chemical shift" windows** of the lines to provide information regarding the **presence or absence of key functional groups** in your molecule.
  - ☐ Beware of misinterpreting overlapping signals
  - ☐ Beware of being confused by signal sets caused by OH's or caused by two or more functional groups impacting chemical shift
  - ☐ Steps 4 and 5 are definitely interchangeable
- Use **"tracking" to work from known components (normally  $\text{CH}_3$  end groups, or  $\text{C}_6\text{H}_5$  end group, or OH end groups) down the chain**
  - Integration can tell you whether it's a  $\text{CH}_3$ ,  $\text{CH}_2$ , or CH causing a particular signal set
  - Chemical shift and/or splitting can then tell you what else may be attached to that carbon
- End-Check:** Check that the structure you believe you actually have would give the number of signal sets you have, the chemical shifts you have, the integrations you have, and the splittings that you have. If not, your structure needs to be corrected!