Many atomic nuclei behave as if they spin on an axis of rotation:
- Nuclei are positively charged
- These spinning nuclei generate tiny magnetic fields
- Tiny magnets interact with an external magnetic field, denoted $B_0$
- Proton ($^1H$) and carbon ($^{13}C$) are the most important nuclear spins to organic chemists

Nuclear spins are oriented randomly in the absence (a) of an external magnetic field but have a specific orientation in the presence (b) of an external field, $B_0$:
- Some nuclear spins are aligned parallel to the external field
  - Lower energy orientation
  - More likely
- Some nuclear spins are aligned antiparallel to the external field
  - Higher energy orientation
  - Less likely

When nuclei that are aligned parallel with an external magnetic field are irradiated with the proper frequency of electromagnetic radiation, the energy is absorbed and the nuclei "spin-flips" to the higher-energy antiparallel alignment:
- Nuclei that undergo "spin-flips" in response to applied radiation are said to be in resonance with the applied radiation - nuclear magnetic resonance
- Frequency necessary for resonance depends on strength of external field and the identity of the nuclei
The energy difference $\Delta E$ between nuclear spin states depends on the strength of the applied magnetic field:
- Absorption of energy with frequency $\nu$ converts a nucleus from a lower to a higher spin state.
- $\Delta E = 8.0 \times 10^{-6}$ kJ/mol for magnetic field strength of 4.7 T.
- For field strength of 4.7 T a radiofrequency (rf) of $\nu = 200$ MHz is required to bring $^1$H nuclei into resonance.
- For a field strength of 4.7 T a radiofrequency (rf) of $\nu = 50$ MHz is required to bring $^{13}$C nuclei into resonance.

Many nuclei exhibit NMR phenomenon:
- All nuclei with odd number of protons.
- All nuclei with odd number of neutrons.
- Nuclei with even numbers of both protons and neutrons do not exhibit NMR phenomenon.

### Nuclear Magnetic Resonance Spectroscopy

#### The NMR Behavior of Some Common Nuclei

<table>
<thead>
<tr>
<th>Magnetic nuclei</th>
<th>Nonmagnetic nuclei</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^1$H</td>
<td>$^{13}$C</td>
</tr>
<tr>
<td>$^{13}$C</td>
<td>$^{16}$O</td>
</tr>
<tr>
<td>$^2$H</td>
<td>$^{32}$S</td>
</tr>
<tr>
<td>$^{14}$N</td>
<td>$^{31}$P</td>
</tr>
</tbody>
</table>

The absorption frequency is not the same for all $^1$H and $^{13}$C nuclei:
- Nuclei in molecules are surrounded by electrons.
- Electrons set up tiny local magnetic fields that act in opposition to the applied field, shielding the nucleus from the full effect of the external magnetic field.
- The effective field actually felt by the nucleus is the applied field reduced by the local shielding effects.

$$B_{\text{effective}} = B_{\text{applied}} - B_{\text{local}}$$
The Nature of NMR Absorptions

Because the three hydrogens in each methyl group of methyl acetate have the same electronic environment they are shielded to the same extent and are said to be equivalent

- Chemically equivalent nuclei always show the same absorption
- The three hydrogens in each methyl group have the same $^1H$ NMR signal

The $^1H$ NMR spectrum of methyl acetate shows two peaks, one for each of the two chemically distinct hydrogen atoms in the molecule.
The Nature of NMR Absorptions

Schematic operation of a basic NMR spectrometer

- NMR spectroscopy requires more time (about $10^{-3}$ s) compared to IR spectroscopy (about $10^{-13}$ s).
- If two rapidly interconverting species are present in a sample, IR spectroscopy will record spectra for both but the slower NMR spectroscopy will record a "time-averaged" spectrum.
- "Time-averaging" of NMR spectra can be used to measure reaction rates and activation energies of very fast processes.

$E_{\text{act}} = 45 \text{ kJ/mol}$

$^1H$ NMR: 1 peak at 25 °C
2 peaks at −90 °C

The NMR Chart

- The downfield, deshielded side is on the left, and requires a lower field strength for resonance.
- The upfield, shielded side is on the right, and requires a higher field strength for resonance.
- The tetramethylsilane (TMS) absorption is used as a reference point.
### Chemical Shifts

**Chemical shift**
- Position on NMR chart at which a nucleus absorbs
  - The chemical shift of TMS is set as zero point
  - Other absorptions normally occur downfield
  - NMR charts calibrated using delta (δ) scale
    - $1 \delta = 1$ part per million of operating frequency
  - Chemical shift of an NMR absorption in δ units is constant, regardless of the operating frequency of the spectrometer

$$\delta = \frac{\text{Chemical shift (number of Hz downfield from TMS)}}{\text{Spectrometer frequency in MHz}}$$

### Chemical Shifts

Narrow NMR absorption range
- 0 to 10 δ for 1H NMR
- 0 to 220 δ for 13C NMR

Higher magnetic field instruments have greater dispersion of NMR signals
- Two signals that are 20 Hz apart (0.1 ppm) at 200 MHz are 50 Hz (0.1 ppm) apart at 500 MHz
- Accidental overlap of nonequivalent signals decreases with increasing field strength

### 11.4 13C NMR Spectroscopy: Signal Averaging and FT-NMR

Carbon-13 is only naturally occurring carbon isotope with a nuclear spin
- Natural abundance of 13C is 1.1%
- Low abundance of 13C is overcome by signal averaging and Fourier-transform NMR (FT-NMR)

### 13C NMR Spectroscopy: Signal Averaging and FT-NMR

- **Signal averaging**
  - Numerous individual runs are added together and averaged such that random background noise cancels to zero and NMR signals are enhanced, substantially increasing sensitivity

- **FT-NMR**
  - Sample is irradiated with entire range of useful frequencies
  - All 1H or 13C nuclei in the sample resonate at once giving complex, composite signal that is mathematically manipulated by Fourier transforms to segregate individual signals
Carbon-13 NMR spectra of pentan-1-ol. Spectrum (a) is a single run, showing background noise. Spectrum (b) is an average of 200 runs.

**Factors that affect chemical shifts:**
1. Chemical shift affected by nearby electronegative atoms
   - Carbons bonded to electronegative atoms absorb downfield from typical alkane carbons
2. Hybridization of carbon atoms
   - \(sp^3\)-hybridized carbons generally absorb from 0 to 90 ppm
   - \(sp^2\)-hybridized carbons generally absorb from 110 to 220 ppm
   - \(C=O\) carbons absorb from 160 to 220 ppm

**Characteristics of \(^{13}\text{C}\) NMR Spectroscopy**

\(^{13}\text{C}\) spectrum for butan-2-one
- Butan-2-one contains 4 chemically nonequivalent carbon atoms
- Carbonyl carbons (C=O) are always found at the low-field end of the spectrum from 160 to 220 ppm.

\(^{13}\text{C}\) NMR spectrum of \(p\)-bromoacetophenone shows only six absorptions, even though the molecule contains eight carbons. A molecular plane of symmetry makes ring carbons 4 and 4\(^{'}\) and ring carbons 5 and 5\(^{'}\) equivalent. Thus, six ring carbons show only four absorptions.
At what approximate positions would you expect ethyl acrylate, H₂C=CHCO₂CH₂CH₃, to show ¹³C NMR absorptions?

Strategy
- Identify the distinct carbons in the molecule, and note whether each is alkyl, vinylic, aromatic, or in a carbonyl group. Then predict where each absorbs, using Figure 11.7 as necessary.

Solution
- Ethyl acrylate has five distinct carbons: two different C=C, one C=O, one C(O)-C, and one alkyl C. From Figure 11.7, the likely absorptions are:
  - The actual absorptions are at 14.1, 60.5, 128.5, 130.3, and 166.0 δ.

Distortionless Enhancement by Polarization Transfer (DEPT-NMR) experiment
- Run in three stages
  1. Ordinary broadband-decoupled spectrum
     - Locates chemical shifts of all carbons
  2. DEPT-90
     - Only signals due to CH carbons appear
  3. DEPT-135
     - CH₃ and CH resonances appear positive
     - CH₂ signals appear as negative signals (below the baseline)
- Used to determine number of hydrogens attached to each carbon
DEPT $^{13}$C NMR Spectroscopy

Summary of signals in the three stage DEPT experiment

<table>
<thead>
<tr>
<th>Broadband-decoupled</th>
<th>DEPT-90</th>
<th>DEPT-135</th>
</tr>
</thead>
<tbody>
<tr>
<td>C, CH, CH$_2$, CH$_3$</td>
<td>CH</td>
<td>CH$_2$, CH are positive</td>
</tr>
<tr>
<td></td>
<td></td>
<td>CH$_2$ is negative</td>
</tr>
</tbody>
</table>
C                     | Subtract DEPT-135 from broadband-decoupled spectrum |
CH                    | DEPT-90 |
CH$_2$                | Negative DEPT-135 |
CH$_3$                | Subtract DEPT-90 from positive DEPT-135 |

Worked Example 11.2

Assigning a Chemical Structure from a $^{13}$C NMR Spectrum

Propose a structure for an alcohol, C$_4$H$_{10}$O, that has the following $^{13}$C NMR spectral data:

- Broadband-decoupled $^{13}$C NMR: 19.0, 31.7, 69.5 $\delta$
- DEPT-90: 31.7 $\delta$
- DEPT-135: positive peak at 19.0 $\delta$, negative peak at 69.5 $\delta$

Strategy

- Begin by noting that the unknown alcohol has four carbon atoms, yet has only three NMR absorption, which implies that two carbons must be equivalent.
- Two of the absorptions are in the typical alkane region (19.0 and 31.7 $\delta$) while one is in the region of a carbon bonded to an electronegative atom (69.5 $\delta$) – oxygen in this instance.
- The DEPT-90 spectrum tells us that the alkyl carbon at 31.7 $\delta$ is tertiary (CH); the DEPT-135 spectrum tells us that the alkyl carbon at 19.0 $\delta$ is a methyl (CH$_3$) and that the carbon bonded to oxygen (69.5 $\delta$) is secondary (CH$_2$).
- The two equivalent carbons are probably both methyls bonded to the same tertiary carbon, (CH$_3$)$_2$CH-
Worked Example 11.2
Assigning a Chemical Structure from a $^{13}$C NMR Spectrum
Solution
• We can now put the pieces together to propose a structure:

![2-Methylpropan-1-ol structure](image)

11.7 Uses of $^{13}$C NMR Spectroscopy
$^{13}$C NMR spectroscopy provides information about:
• The number of nonequivalent carbons atoms in a molecule
• The electronic environment of each carbon
• How many protons are bonded to each carbon

Uses of $^{13}$C NMR Spectroscopy
$^{13}$C NMR spectroscopy can verify that E2 elimination of an alkyl halide gives the more substituted alkene (Zaitsev’s rule)

![Reaction scheme](image)

1-Chloro-1-methylcyclohexane (trisubstituted) Methylene cyclohexane (disubstituted)
• 1-Methylcyclohexene has five $sp^3$-carbon resonances in the 20 to 50 $\delta$ range and two $sp^2$-carbon resonances in the 100 to 150 $\delta$ range
• Methylene cyclohexene, due to symmetry, has only three $sp^3$-carbon resonance peaks and two $sp^2$-carbon resonance peaks
11.8 $^1$H NMR Spectroscopy and Proton Equivalence

$^1$H NMR spectroscopy determines how many kinds of electronically nonequivalent hydrogens are present in a molecule.

- Equivalence or nonequivalence of two protons determined by replacing each H by an X group.
- Four possibilities:
  1. Protons are chemically unrelated and thus nonequivalent
  2. Protons are chemically identical and thus electronically equivalent.
     - Chemically identical protons are said to be homotopic.
  3. Protons are electronically equivalent but not identical.
     - The two –CH$_2$ – hydrogens on C2 of butane (as well as the two C3 hydrogens) are not identical because replacing one or the other would lead to a new chirality center.
     - Non-identical but electronically equivalent protons are said to be enantiotopic.
     - Different enantiomers would result if pro-R or pro-S hydrogen were replaced.
     - Prochiral hydrogens are electronically equivalent and thus have the same NMR absorption.
  4. Replacement of a hydrogen gives a unique diastereomer with a second chirality center.
     - Such hydrogens are diastereotropic.
     - Diastereotropic hydrogens are neither electronically or chemically equivalent and will most likely show different $^1$H NMR absorptions.
Most $^1$H NMR chemical shifts occur within the 0 to 10 $\delta$ range except for carboxylic acid O-H absorptions which usually occur within the 11-12 $\delta$ range.

**Table 11.2**

<table>
<thead>
<tr>
<th>Region</th>
<th>Chemical Shift ($\delta$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aromatic</td>
<td>7.0-8.0</td>
</tr>
<tr>
<td>Vinylic</td>
<td>5.5-6.5</td>
</tr>
<tr>
<td>Halogen</td>
<td>4.0-5.0</td>
</tr>
<tr>
<td>Alkylic</td>
<td>3.0-4.0</td>
</tr>
<tr>
<td>Saturated</td>
<td>2.0-3.0</td>
</tr>
</tbody>
</table>

**Worked Example 11.3**

**Predicting Chemical Shifts in $^1$H NMR Spectra**

Methyl 2,2-dimethylpropanoate, (CH$_3$)$_2$CCO$_2$CH$_3$, has two peaks in its $^1$H NMR spectrum. What are their approximate chemical shifts?

**Strategy**

- Identify the types of hydrogens in the molecule and note whether each is alkyl, vinylic, or next to an electronegative atom. Then predict where each absorbs, using Table 11.3 if necessary.
Worked Example 11.3

Predicting Chemical Shifts in $^1$H NMR Spectra

Solution

- The –OCH$_3$ protons absorb around 3.5 to 4.0 $\delta$ because they are on carbon bonded to oxygen. The (CH$_3$)$_3$C- protons absorb near 1.0 $\delta$ because they are typical alkane-like protons.

11.10 Integration of $^1$H NMR Absorptions: Proton Counting

The area under each $^1$H NMR peak is proportional to the number of protons causing that peak.

- Integrating (electronically measuring) the area under each peak makes it possible to determine the relative number of each kind of proton in a molecule.
- Integrating the peaks of 2,2-dimethylpropanoate in a “stair-step” manner shows that they have 1:3 ratio, corresponding to the ratio of the numbers of protons (3:9).

Spin-Spin Splitting in $^1$H NMR Spectra

Multiple absorptions, called spin-spin splitting, are caused by the interaction (coupling) of the spins of nearby nuclei.

- Tiny magnetic fields produced by one nucleus affects the magnetic field felt by neighboring nuclei.
  - If protons align with the applied field the effective field felt by neighboring protons is slightly larger.
  - If protons align against the applied field the effective field felt by neighboring protons is slightly smaller.

11.11 Spin-Spin Splitting in $^1$H NMR Spectra

The absorption of a proton can split into multiple peaks called a multiplet.

- $^1$H NMR spectrum of bromoethane shows four peaks (a quartet) at 3.42 $\delta$ for –CH$_2$Br protons and three peaks (a triplet) at 1.68 $\delta$ for –CH$_3$ protons.
Each $-\text{CH}_2\text{Br}$ proton of $\text{CH}_3\text{CH}_2\text{Br}$ has its own nuclear spin which can align either with or against the applied field, producing a small change in the effective field experienced by the $-\text{CH}_3$ protons

- **Three** possible spin states (combinations)
  1. Both protons spin in alignment with applied field
     - Effective field felt by neighboring $-\text{CH}_3$ protons is larger
     - Applied field necessary to cause resonance is reduced
  2. One proton spin is aligned with and one proton spin is aligned against the applied field (two possible combinations)
     - No effect on neighboring protons
  3. Both proton spins align against applied field
     - Effective field felt by neighboring $-\text{CH}_3$ is smaller
     - Applied field necessary to cause resonance is increased

Spin-Spin Splitting in $^1\text{H}$ NMR Spectra

Each $-\text{CH}_3$ proton of $\text{CH}_3\text{CH}_2\text{Br}$ has its own nuclear spin which can align either with or against the applied field, producing a small change in the effective field experienced by the $-\text{CH}_2\text{Br}$ protons

- **Four** possible spin states (combinations)
  1. All proton spins are aligned with applied field
     - Effective field felt by neighboring $-\text{CH}_2\text{Br}$ protons is larger
     - Applied field necessary to cause resonance is reduced
  2. Two proton spins are aligned with and one proton spin is aligned against the applied field (three possible combinations)
     - Effective field felt by neighboring $-\text{CH}_2\text{Br}$ protons is slightly larger
     - Applied field necessary to cause resonance is slightly reduced
  3. Two proton spins are aligned against and one proton spin is aligned with the applied field (three possible combinations)
     - Effective field felt by neighboring $-\text{CH}_2\text{Br}$ protons is slightly smaller
     - Applied field necessary to cause resonance is slightly increased
  4. All proton spins align against applied field
     - Effective field felt by neighboring $-\text{CH}_3$ is smaller
     - Applied field necessary to cause resonance is increased

The origin of spin-spin splitting in bromoethane. The nuclear spins of $-\text{CH}_2\text{Br}$ protons, indicated by horizontal arrows, align either with or against the applied field, causing the splitting of $-\text{CH}_3$ absorptions into a triplet.
The origin of spin-spin splitting in bromoethane. The nuclear spins of $–\text{CH}_3$ protons, indicated by horizontal arrows, align either with or against the applied field, causing the splitting of $–\text{CH}_2\text{Br}$ absorptions into a quartet.

**Spin-Spin Splitting in $^1\text{H}$ NMR Spectra**

### Coupling constant
- The distance between peaks in a multiplet
- Denoted $J$
- Measured in hertz
- Generally fall into range 0 to 18 Hz
- Same coupling constant is shared by both groups of hydrogens whose spins are coupled
- Coupling constants are independent of spectrometer field strength

**n + 1 rule**
- Protons that have $n$ equivalent neighboring protons show $n + 1$ peaks in their $^1\text{H}$ NMR spectrum
  - The septet is caused by splitting of the $–\text{CHBr}$ proton signal at 4.28 δ by six equivalent neighboring protons on the two methyl groups ($n = 6$ leads to $6+1 = 7$ peaks)
  - The doublet at 1.71 δ is due to signal splitting of the six equivalent methyl protons by the single $–\text{CHBr}$- proton ($n = 1$ leads to 2 peaks)

**Spin-Spin Splitting in $^1\text{H}$ NMR Spectra**

**TABLE 11.4**

<table>
<thead>
<tr>
<th>Number of equivalent adjacent protons</th>
<th>Multiplet</th>
<th>Ratio of intensities</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>Singlet</td>
<td>1</td>
</tr>
<tr>
<td>1</td>
<td>Doublet</td>
<td>1:1</td>
</tr>
<tr>
<td>2</td>
<td>Triplet</td>
<td>1:2:1</td>
</tr>
<tr>
<td>3</td>
<td>Quartet</td>
<td>1:3:3:1</td>
</tr>
<tr>
<td>4</td>
<td>Quintet</td>
<td>1:4:6:4:1</td>
</tr>
</tbody>
</table>
Summary of spin-spin splitting in $^1$H NMR:
1. Chemically equivalent protons do not show spin-spin splitting

\[
\begin{align*}
\text{Three C-H protons are} & \quad \text{chemically equivalent: no splitting occurs.} \\
\text{Four C-H protons are} & \quad \text{chemically equivalent: no splitting occurs.}
\end{align*}
\]

2. The signal of a proton with $n$ equivalent neighboring protons is split into a multiplet of $n + 1$ peaks with coupling constant $J$

\[
\begin{align*}
\text{Splitting observed} & \quad \text{Splitting not usually observed}
\end{align*}
\]

Spin-Spin Splitting in $^1$H NMR Spectra

Why no $^{13}$C NMR splitting
- No carbon-carbon spin coupling because low natural abundance of $^{13}$C makes it unlikely that two $^{13}$C nuclei will be adjacent in a molecule
- No carbon-hydrogen spin coupling because of broadband decoupling
  - Molecule is irradiated with a pulse of rf energy to cover carbon and hydrogen resonance frequencies simultaneously
  - Hydrogens spin-flip so rapidly that their local magnetic fields average to zero

$^1$H NMR spectrum of $p$-methoxypropiophenone
- Downfield absorptions at 6.91 and 7.93 $\delta$ are due to four aromatic ring protons of two kinds, each of which is split into a doublet by its neighbor
- $-\text{OCH}_3$ signal is unsplit at 3.84 $\delta$
- $-\text{CH}_2-$ protons next to carbonyl appear as a quartet at 2.93 $\delta$ coupled to neighboring $-\text{CH}_3$ protons which appear as a triplet at 1.20 $\delta$

Propose a structure for a compound, C$_5$H$_{12}$O, that fits the following $^1$H NMR data:
- 0.92 $\delta$ (3 H, triplet, $J = 7$ Hz)
- 1.20 $\delta$ (6 H, singlet)
- 1.50 $\delta$ (2 H, quartet, $J = 7$ Hz)
- 1.64 $\delta$ (1H, broad singlet)
Strategy

- Look at each absorption individually.
  - The three-proton absorption at 0.92 $\delta$ is due to a methyl group in an alkane-like environment, and the triplet splitting pattern implies that the $-\text{CH}_3$ is next to a $-\text{CH}_2$. Thus, our molecule contains an ethyl group, $\text{CH}_3\text{CH}_2-$. 
  - The six-proton singlet at 1.20 $\delta$ is due to two equivalent alkane-like methyl groups attached to a carbon with no hydrogens, $(\text{CH}_3)_2\text{C}-$, and the two-proton quartet at 1.50 $\delta$ is due to the $-\text{CH}_2$ of the ethyl group.
  - All 5 carbons and 11 of the 12 hydrogens in the molecule are now accounted for. The remaining hydrogen, which appears as a broad one-proton singlet at 1.64 $\delta$, is probably due to an $-\text{OH}$ group, since there is no other way to account for it.
  - Putting the pieces together gives the structure: 2-methylbutan-2-ol

Worked Example 11.4

Assigning a Chemical Structure from a $^1$H NMR Spectrum

Solution

- The $^1$H NMR spectrum of toluene shows the accidental overlap of the five nonequivalent aromatic ring protons.
- One signal can be split by two or more nonequivalent kinds of protons.
- Not predicted by $n + 1$ rule
More Complex Spin-Spin Splitting Patterns

\(^1\text{H} \text{ NMR spectrum of } \text{trans-cinnamaldehyde}\)

- Five aromatic proton signals (black) overlap into complex pattern with large peak at 7.42 \(\delta\) and broad peak at 7.57 \(\delta\).
- Aldehyde proton signal at C1 appears in the normal downfield position at 9.69 \(\delta\) and is split into a doublet with \(J = 6\) Hz by the adjacent proton at C2.
- Vinylic proton at C3 is next to the aromatic ring and is shifted downfield from the normal vinylic region. This C3 proton signal appears as a doublet centered at 7.49 \(\delta\). Because it has one neighbor proton at C2, its signal is split into a doublet, with \(J = 12\) Hz.

More Complex Spin-Spin Splitting Patterns

\(\text{C2 proton of trans-cinnamaldehyde}\)

- Multiple coupling of C2 proton gives "doublet of doublets".
- Splitting pattern illustrated by tree diagram:
  - C3 proton splits C2 proton signal into doublet \((J_{2,3} = 12\) Hz\) which is split by C1 aldehyde proton into new doublets \((J_{1,2} = 6\) Hz\) producing four-line spectrum.

11.13 Uses of \(^1\text{H} \text{ NMR Spectroscopy}\)

**Hydroboration/oxidation of methylenecyclohexane**

\[
\begin{array}{c}
\text{CH}_2
\
\text{C}
\end{array}
\xrightarrow{1. \text{BH}_3, \text{THF}}
\begin{array}{c}
\text{CH}_2\text{OH}
\
\text{C}
\end{array}
\]

Methylenecyclohexane

**Cyclohexylmethanol**

\[
\begin{array}{c}
\text{CH}_2
\
\text{C}
\end{array}
\xrightarrow{2. \text{H}_2\text{O}_2, \text{OH}^-}
\begin{array}{c}
\text{CH}_3
\
\text{C}
\end{array}
\]

1-Methylcyclohexanol

Uses of \(^1\text{H} \text{ NMR Spectroscopy}\)

\(^1\text{H} \text{ NMR of reaction product (a)}\) shows a two-proton multiplet at 3.40 \(\delta\) indicating the product has a \(-\text{CH}_2\) group bonded to an electronegative oxygen atom (\(-\text{CH}_2\text{OH}\)).

Absence of quaternary \(-\text{CH}_3\) signal in \(^1\text{H} \text{ NMR} \) of reaction product clearly shows that alternative reaction product (b) is not formed by the hydroboration/oxidation of methylenecyclohexane.

**Reaction product**

**Alternative product (not formed)**
Magnetic Resonance Imaging (MRI)

*Magnetic Resonance Imaging* (MRI) is a diagnostic technique of enormous value to the medical community. MRI takes advantage of the magnetic properties of certain nuclei, typically hydrogen, and of the signals emitted when those nuclei are stimulated by radiofrequency energy. Signals detected by MRI vary with the density of hydrogen atoms and with the nature of their surroundings, allowing identification of different types of tissue and even allowing the visualization of motion.

MRI of this left knee shows the presence of a ganglion cyst.