L6 and L7
Sound Intensity, Sound Level/Loudness (Decibels), The Ear
## The Physical and Acoustical Background

### Table II

Measured greatest power outputs of some musical instruments

<table>
<thead>
<tr>
<th>Instrument</th>
<th>Power Output, Watts</th>
</tr>
</thead>
<tbody>
<tr>
<td>Large orchestra</td>
<td>67</td>
</tr>
<tr>
<td>Bass drum</td>
<td>25</td>
</tr>
<tr>
<td>Snare drum</td>
<td>12</td>
</tr>
<tr>
<td>Cymbals</td>
<td>9.5</td>
</tr>
<tr>
<td>Trombone</td>
<td>6.4</td>
</tr>
<tr>
<td>Piano</td>
<td>0.44</td>
</tr>
<tr>
<td>Trumpet</td>
<td>0.31</td>
</tr>
<tr>
<td>Tuba</td>
<td>0.20</td>
</tr>
<tr>
<td>Double bass</td>
<td>0.16</td>
</tr>
<tr>
<td>Flute</td>
<td>0.055</td>
</tr>
<tr>
<td>French horn</td>
<td>0.053</td>
</tr>
<tr>
<td>Clarinet</td>
<td>0.050</td>
</tr>
</tbody>
</table>
You and I are standing next to each other, listening to the exact same steady sound. Our ears are identical. You listen for TWICE as long as I do.

How does the total energy received compare?

A) You receive twice what I do
B) You receive half what I do
C) We receive the same

How does the (average) power compare? (Please average ONLY over the time that the individual is listening!)

How does the (average) intensity received compare?
5.2.2

BANG! The sound wave from a firework carries 1 J of energy (total!). If the sound burst lasts .2 seconds, what is the power of this sound wave?

a) 1 W  
b) .2 W  
c) 5 W  
d) 2 W  
e) ??

A lawnmower runs for 10 minutes. Over that time, a total of 1 J of sound energy is released. How does the power of the lawnmower sound compare to that of the firework sound?

A) Greater than       B) Less than
C) Equal to       D) ??
The wave fronts are crests, separated by $\lambda$.

Troughs are halfway between wave fronts.

This graph shows the displacement of the medium.
We define the Sound Intensity $I$ as the Audio Power crossing a unit area, 
or $I = \frac{P}{A}$
Units- $W/m^2$
Area of a sphere is $4\pi \ r^2$
There is a source in the center emitting sound outward. How does intensity of the sound at $r$ compare to that at $R$?

a) $I_{(at \ r)} > I_R$
b) $I_{(at \ r)} < I_R$
c) $I_{(at \ r)} = I_R$
d) Not enough information
If $R=2r$, what is $I_R/I_r$?

a) 1  
b) 2  
c) 4  
d) .5  
e) .25
How does the total power (Energy/second) passing through the whole spherical surface at r compare to that at R?

A) $P_r > P_R$
B) $P_r < P_R$
C) $P_r = P_R$
D) ??

How does the power passing through a patch of 1 cm$^2$ at radius r compare to that at R?
12-2 Intensity of Sound: Decibels

An increase in sound level of 3 dB, which is a doubling in intensity, is a very small change in loudness.

In open areas, the intensity of sound diminishes with distance:

\[ I \propto \frac{1}{r^2} \]

However, in enclosed spaces this is complicated by reflections, and if sound travels through air the higher frequencies get preferentially absorbed.
Difference in Sound intensity level

- 10 times the power gives +10 dB
- Twice the power gives +3 dB
- Same power gives 0 dB difference
- One half the power gives -3 dB
- One tenth the power gives -10 dB

\[ \frac{P_2}{P_1} \]
Logarithms

If \( y = 10^x \), we define \( x \) as the log of \( y \), or

\[ x = \log y \]
Some useful facts:

\[ \log (ab) = \log a + \log b \]

\[ \log a/b = \log a - \log b \]
\[
\log 1000 = 3, \\
\log 100 = 2, \\
\log 10 = 1, \\
\log 1 = 0, \\
\log 0.1 = -1.
\]
### TABLE A-1 Short Table of Common Logarithms

<table>
<thead>
<tr>
<th>N</th>
<th>0.0</th>
<th>0.1</th>
<th>0.2</th>
<th>0.3</th>
<th>0.4</th>
<th>0.5</th>
<th>0.6</th>
<th>0.7</th>
<th>0.8</th>
<th>0.9</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>000</td>
<td>041</td>
<td>079</td>
<td>114</td>
<td>146</td>
<td>176</td>
<td>204</td>
<td>230</td>
<td>255</td>
<td>279</td>
</tr>
<tr>
<td>2</td>
<td>301</td>
<td>322</td>
<td>342</td>
<td>362</td>
<td>380</td>
<td>398</td>
<td>415</td>
<td>431</td>
<td>447</td>
<td>462</td>
</tr>
<tr>
<td>3</td>
<td>477</td>
<td>491</td>
<td>505</td>
<td>519</td>
<td>531</td>
<td>544</td>
<td>556</td>
<td>568</td>
<td>580</td>
<td>591</td>
</tr>
<tr>
<td>4</td>
<td>602</td>
<td>613</td>
<td>623</td>
<td>633</td>
<td>643</td>
<td>653</td>
<td>663</td>
<td>672</td>
<td>681</td>
<td>690</td>
</tr>
<tr>
<td>5</td>
<td>699</td>
<td>708</td>
<td>716</td>
<td>724</td>
<td>732</td>
<td>740</td>
<td>748</td>
<td>756</td>
<td>763</td>
<td>771</td>
</tr>
<tr>
<td>6</td>
<td>778</td>
<td>785</td>
<td>792</td>
<td>799</td>
<td>806</td>
<td>813</td>
<td>820</td>
<td>826</td>
<td>833</td>
<td>839</td>
</tr>
<tr>
<td>7</td>
<td>845</td>
<td>851</td>
<td>857</td>
<td>863</td>
<td>869</td>
<td>875</td>
<td>881</td>
<td>886</td>
<td>892</td>
<td>898</td>
</tr>
<tr>
<td>8</td>
<td>903</td>
<td>908</td>
<td>914</td>
<td>919</td>
<td>924</td>
<td>929</td>
<td>935</td>
<td>940</td>
<td>944</td>
<td>949</td>
</tr>
<tr>
<td>9</td>
<td>954</td>
<td>959</td>
<td>964</td>
<td>968</td>
<td>973</td>
<td>978</td>
<td>982</td>
<td>987</td>
<td>991</td>
<td>996</td>
</tr>
</tbody>
</table>

Since $10 = 10^1$, then $1 = \log (10)$ Thus
The loudness of a sound is much more closely related to the logarithm of the intensity. Sound level is measured in decibels (dB) and is defined:

\[ \beta \text{ (in dB)} = 10 \log \frac{I}{I_0} \]  

(12-1)

\( I_0 \) is taken to be the threshold of hearing:

\[ I_0 = 1.0 \times 10^{-12} \text{ W/m}^2 \]
Difference in Sound intensity level

10 times the power gives +10 dB

twice the power gives +3 dB

same power gives 0 dB difference

one half the power gives -3 dB

one tenth the power gives -10 dB
The intensity of a wave is the energy transported per unit time across a unit area.

The human ear can detect sounds with an intensity as low as $10^{-12}$ W/m$^2$ and as high as 1 W/m$^2$.

Perceived loudness, however, is not proportional to the intensity.

<table>
<thead>
<tr>
<th>Source of the Sound</th>
<th>Sound Level (dB)</th>
<th>Intensity (W/m$^2$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jet plane at 30 m</td>
<td>140</td>
<td>100</td>
</tr>
<tr>
<td>Threshold of pain</td>
<td>120</td>
<td>1</td>
</tr>
<tr>
<td>Loud rock concert</td>
<td>120</td>
<td>1</td>
</tr>
<tr>
<td>Siren at 30 m</td>
<td>100</td>
<td>$1 \times 10^{-2}$</td>
</tr>
<tr>
<td>Auto interior, at 90 km/h</td>
<td>75</td>
<td>$3 \times 10^{-5}$</td>
</tr>
<tr>
<td>Busy street traffic</td>
<td>70</td>
<td>$1 \times 10^{-5}$</td>
</tr>
<tr>
<td>Talk, at 50 cm</td>
<td>65</td>
<td>$3 \times 10^{-6}$</td>
</tr>
<tr>
<td>Quiet radio</td>
<td>40</td>
<td>$1 \times 10^{-8}$</td>
</tr>
<tr>
<td>Whisper</td>
<td>20</td>
<td>$1 \times 10^{-10}$</td>
</tr>
<tr>
<td>Rustle of leaves</td>
<td>10</td>
<td>$1 \times 10^{-11}$</td>
</tr>
<tr>
<td>Threshold of hearing</td>
<td>0</td>
<td>$1 \times 10^{-12}$</td>
</tr>
<tr>
<td>Sound</td>
<td>$\beta$ (dB)</td>
<td></td>
</tr>
<tr>
<td>--------------------------------------------</td>
<td>--------------</td>
<td></td>
</tr>
<tr>
<td>Threshold of hearing</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>Person breathing, at 3 m</td>
<td>10</td>
<td></td>
</tr>
<tr>
<td>A whisper, at 1 m</td>
<td>20</td>
<td></td>
</tr>
<tr>
<td>Quiet room</td>
<td>30</td>
<td></td>
</tr>
<tr>
<td>Outdoors, no traffic</td>
<td>40</td>
<td></td>
</tr>
<tr>
<td>Quiet restaurant</td>
<td>50</td>
<td></td>
</tr>
<tr>
<td>Normal conversation, at 1 m</td>
<td>60</td>
<td></td>
</tr>
<tr>
<td>Busy traffic</td>
<td>70</td>
<td></td>
</tr>
<tr>
<td>Vacuum cleaner, for user</td>
<td>80</td>
<td></td>
</tr>
<tr>
<td>Niagara Falls, at viewpoint</td>
<td>90</td>
<td></td>
</tr>
<tr>
<td>Jackhammer, at 2 m</td>
<td>100</td>
<td></td>
</tr>
<tr>
<td>Stereo, at maximum volume</td>
<td>110</td>
<td></td>
</tr>
<tr>
<td>Rock concert</td>
<td>120</td>
<td></td>
</tr>
<tr>
<td>Threshold of pain</td>
<td>130</td>
<td></td>
</tr>
</tbody>
</table>

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<table>
<thead>
<tr>
<th>SL</th>
<th>Intensity</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 dB</td>
<td>$I_0$</td>
</tr>
<tr>
<td></td>
<td>$(10^{-12} \text{ W/m}^2)$</td>
</tr>
<tr>
<td>10 dB</td>
<td>$10 I_0$</td>
</tr>
<tr>
<td></td>
<td>$(10^{-11} \text{ W/m}^2)$</td>
</tr>
<tr>
<td>20 dB</td>
<td>$100 I_0$</td>
</tr>
<tr>
<td></td>
<td>$(10^{-10} \text{ W/m}^2)$</td>
</tr>
<tr>
<td>30 dB</td>
<td>$1,000 I_0$</td>
</tr>
<tr>
<td></td>
<td>$(=10^3 I_0)$</td>
</tr>
<tr>
<td></td>
<td>$(10^{-9} \text{ W/m}^2)$</td>
</tr>
<tr>
<td>??</td>
<td>$100,000 I_0$</td>
</tr>
<tr>
<td></td>
<td>$(=10^5 I_0)$</td>
</tr>
<tr>
<td></td>
<td>$(10^{-7} \text{ W/m}^2)$</td>
</tr>
</tbody>
</table>
One can solve problems involving the sound level, $SL$ (in dB) using the defining equation above.
We will give simple problems in which one can solve problems using the following:

If $I/I_0 = 10$, $\log 10 = 1$ and $SL = 10$ dB.
If $I/I_0 = 100$, $\log 100 = 2$, and $SL = 20$ dB.
If $I/I_0 = 1000$, $\log 1000 = 3$, and $SL = 30$ dB,
Etc.

So we note that we ADD 10 dB to the SL for each 10–FOLD increase of intensity. This doubling in “loudness” is, to a good approximation, similar to the response of the ear to 10–fold increases in sound intensity at a fixed frequency.
Looking at the following two graphs what can you say about the loudness of the two sounds?

a) I is louder than II.
b) You can't tell which is louder.
c) II is louder than I.
Suppose $R, (I/I_0) = 10000$. How many decibels is this?

A) 0.5
B) 40
C) 50
D) 0.4
E) 400
Suppose sound A has an intensity of 7 W/m², and sound B has an intensity of 0.07 W/m². What is the ratio of A to B expressed in dB?

A)100
B)20
C)-10
D)-20
E)none of these
Suppose sound A has an intensity of $7 \text{ W/m}^2$, and sound B has an intensity of $0.07 \text{ W/m}^2$. Are these sounds loud or soft?

A) Loud
B) Soft
C) I don’t know
There are two instruments, a trumpet and a flute. The trumpet produces a sound with 10x more intensity than that of the flute. The decibel level for the trumpet is... compared to the flute.

a) 10 dB greater
b) 10 dB less
c) 1 dB greater
d) 1 dB less
e) Not enough information
HINT:

\[ SL_2 = 10 \log \frac{I_2}{I_0} \]
\[ SL_1 = 10 \log \frac{I_1}{I_0} \]

\[ SL_2 - SL_1 = 10(\log I_2 - \log I_0 - (\log I_1 - \log I_0)) \]

So

\[ SL_2 - SL_1 = 10 \log \frac{I_2}{I_1} \]
There are two instruments, a trumpet and a flute. The trumpet produces a sound with 100x more intensity than that of the flute. The sound intensity of the trumpet is...compared to the flute.

a) 2 dB greater  
b) 10 dB greater  
c) 20 dB greater  
d) 100 dB greater  
e) Other/Not enough information/???
If a sound is 0 dB, does that mean that no energy is transferred?

a) Yes
b) No
c) ??
At a concert, the trumpet section is playing 30 dB louder than the French horn section.
The trumpet section is playing with ... of the French horn section.
a) 3x the intensity
b) 10x the intensity
c) 30x the intensity
d) 1000x the intensity
e) $10^{30}$x the intensity
100 dB corresponds to what intensity, in W/m$^2$?

A) $10^{-12}$ W/m$^2$
B) $10^{-10}$ W/m$^2$
C) $10^{-2}$ W/m$^2$
D) $10^{+10}$ W/m$^2$
E) None of these/???
Fig. 1. Schematic diagram of the human ear, with the cochlea uncoiled.
12-3 The Ear and Its Response; Loudness

- Skull
- Stirrup
- Anvil
- Hammer
- Semicircular canals
- Auditory nerve (to the brain)
- Cochlea
- Eustachian tube
- Ear canal
- Tympanum (eardrum)
- Oval window
- Round window
- External ear
Structure of the ear
The ear’s sensitivity varies with frequency. These curves translate the intensity into sound level at different frequencies.
True or false: the auditory nerve carries information to the brain from the middle ear?

a) true  
b) false
The ear is more sensitive to sounds of 0 phons at:
   a) 100 Hz
   b) 1000 Hz
   c) 10,000 Hz
   d) sounds of 0 phons cannot be heard at any frequency