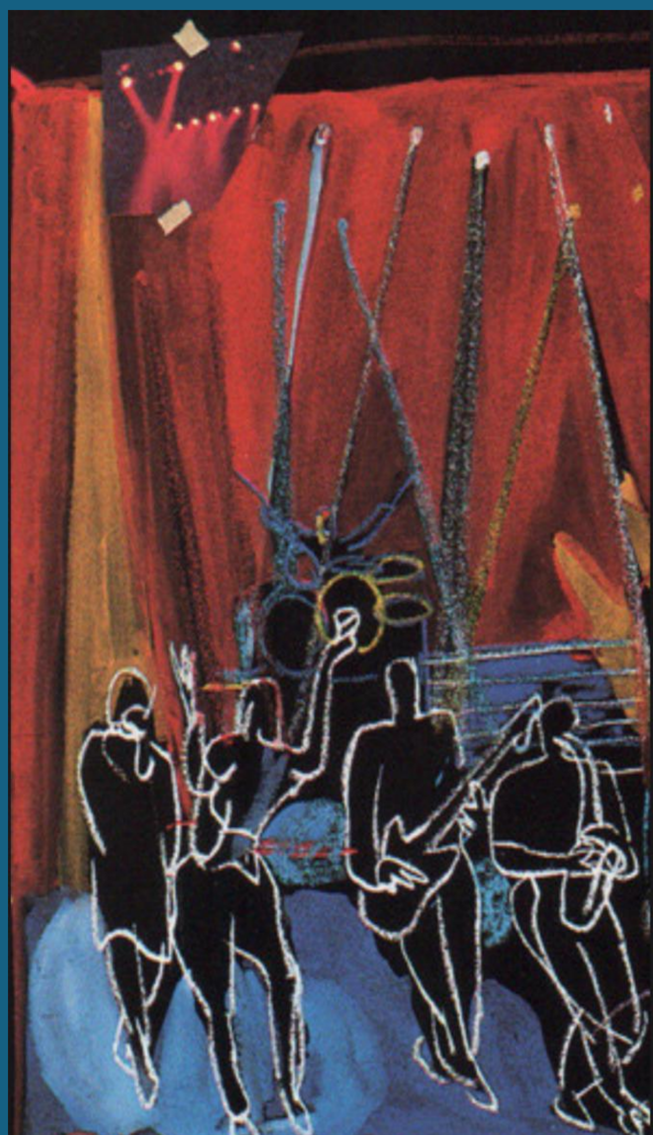
PHYSICS OF SOUND & MUSIC



Lab
Manual

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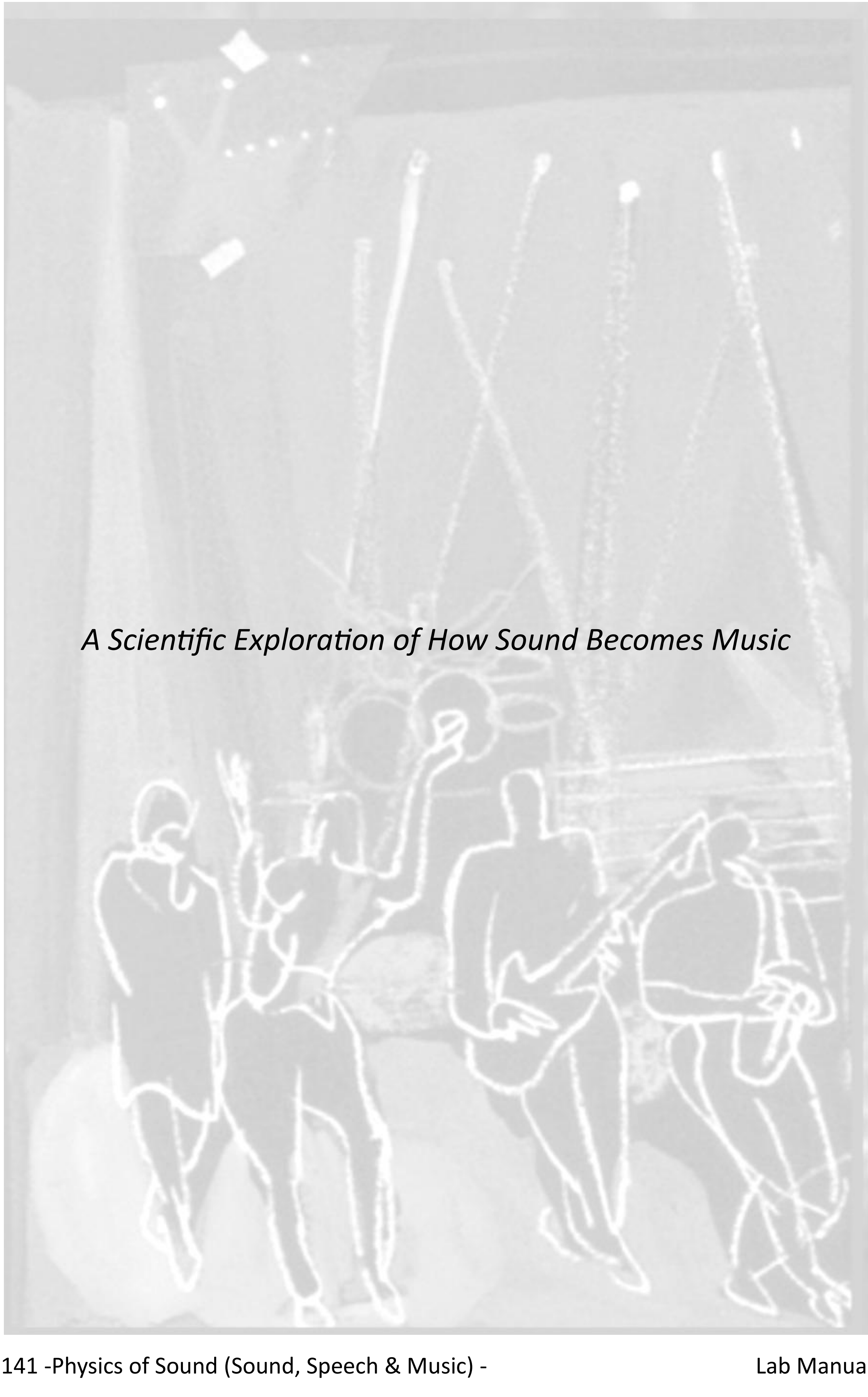
A Scientific Exploration of How Sound Becomes Music

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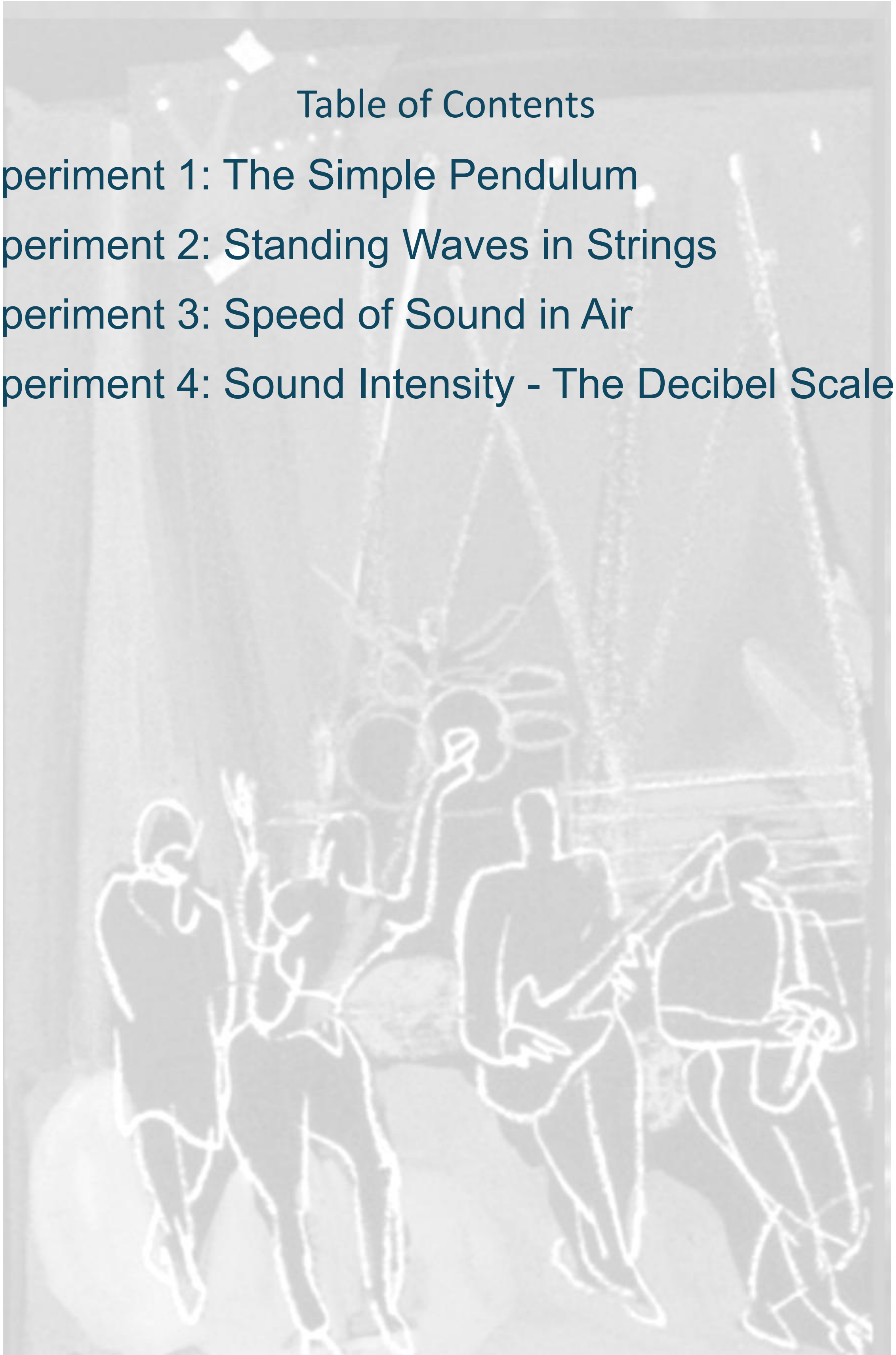


Experiment 1: The Simple Pendulum

INTRODUCTION

A simple pendulum is an idealized physics model of a mass (bob) suspended by a massless string from a fixed pivot, swinging back and forth in periodic motion, acting like a clock's pendulum or a child's swing. For small swings (small angles), its motion approximates simple harmonic motion, with a period (T) determined by its length (L) and the acceleration of gravity at the Earth surface (g) via

$$T = 2\pi\sqrt{(L/g)} \tag{1}$$

independent of mass or amplitude.

OBJECTIVE

To build a pendulum by taping a pencil horizontally over a table edge as a support, hanging a string with a weight (like a nut or key) from it, and then testing how different string lengths or weights affect swing time using a stopwatch, focusing on variables like length and mass to see how they change the period (time for one swing). You will need a ruler, tape, string, and a small heavy object for the bob, plus a phone timer.

MATERIALS

- Support: A table, chair, or tall stack of books.
- Pivot: A pencil or chopstick.
- String: A few feet of thread or string.
- Pendulum Bob: A metal nut, key, and washer.
- Tools: Tape, ruler/measuring tape, stopwatch (phone timer).

PROCEDURE

1. Set up the Pivot: Tape a pencil horizontally across the edge of a table so that about an inch hangs off, ensuring it is very secure; see figure.
2. Attach the String: Tie a small loop in one end of the string and slide it onto the pencil. Make sure it can swing freely.
3. Add the Bob: Tie your weight (nut/key/washer) to the other end of the string. You can make a small hook from wire to easily change bobs.
4. Measure Length: Measure the string from the pivot point (pencil) to the center of the bob.
5. Test and Record:
   (a) Pull the bob back (only a little, maybe 10 degrees) and release it gently.
   (b) Use your stopwatch to time 10 full swings (back and forth) and divide by 10 to get the average period.
   (c) Repeat for different lengths (e.g., 20 cm, 40 cm, 60 cm) and record your results in a table.
6. What to Experiment with (variables):
   (a) Length: Does a shorter string make it swing faster or slower? (Shorter: Faster!).
   (b) Mass: Does a heavier or lighter bob change the swing time? (It should not, significantly!).
   (c) Angle: Does swinging it farther (but still gently) change the period? (It should not!).

Note: The small angle approximation ($\sin\theta \approx \theta$, with θ in radians) for a simple pendulum is considered viable for initial angular displacements of about 15 degrees (or approximately 0.26 radians) or less, as this range typically results in an error of less than 1%. The “viability” of the approximation depends entirely on the required accuracy of the calculation. For this experiment, it will be reasonable for you to vary the angle between 5° and 20° degrees.

DATA ANALYSIS AND RESULTS

For your conclusions:

1. Based on your measurements, state how the period is affected by the following changes:

   a) Increasing mass b) Increasing length c) Increasing amplitude

2. Do your measurements support or refute your original

hypothesis?

3. What is the variable that had the most effect on the period?

4. What are the forms of energy involved in the motion of a simple pendulum? What happens to these forms of energy as the pendulum moves through half a cycle?

5. What would happen to the amplitude of your swinging pendulum if friction was present in the system? Try to explain why, thinking in terms of work and energy.

6. Confront your measurements with the predictions from Eq. (1), take $g \approx 9.8$ m/s^2.

Don’t forget to show a picture of your experimental set up.

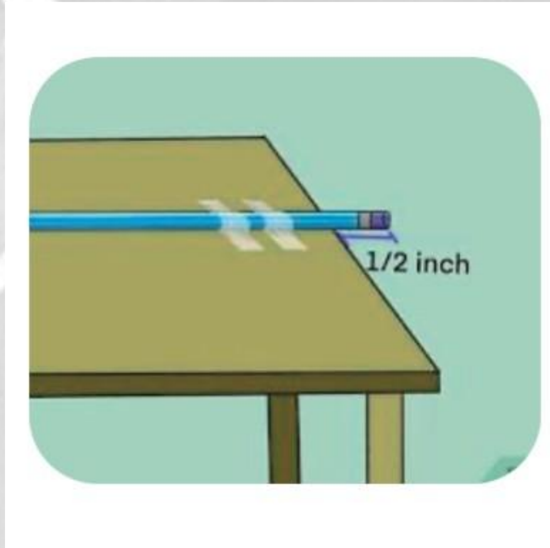


Table 1: Varying Mass

Fixed length, L = 20 cm

Mass	Period, T (s)
metal nut	
key	
washer	

Table 2: Varying Length

Fixed mass, metal nut

Length, L (cm)	Period, T (s)
20	
40	
60	

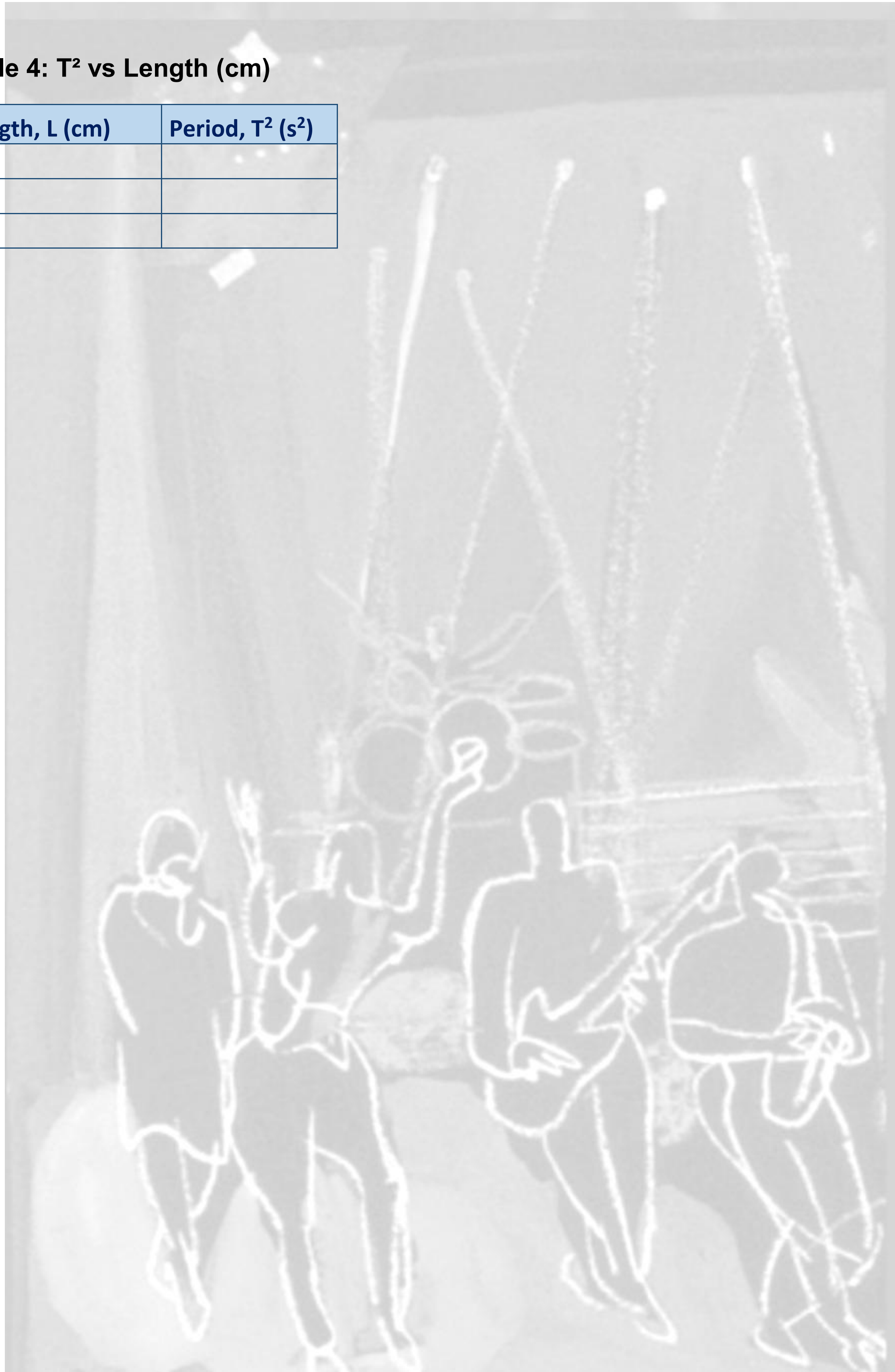
Table 3: Varying Amplitude

Fixed length, L = 20 cm. Fixed mass, metal nut

Amplitude, θ (º)	Period, T (s)
5º	
10º	
15º	
20º	

Table 4: T^2 vs Length (cm)

Length, L (cm)	Period, T^2 (s^2)



Experiment 2: Standing Waves in Strings

INTRODUCTION

Standing waves are produced by the interference of two waves that have equal wavelengths, equal velocities, and equal amplitudes, but traveling in opposite directions through the same medium. Basically, two identical waves need to occupy the same space at the same time.

If one end of a light, flexible, but non-extending string is attached to an oscillator, and the other end hung over a clamped pulley with a weight hanging from it, there are waves traveling away from the oscillator that reflect upon reaching the pulley and interfere with the waves coming from the oscillator. When the conditions (f, F, μ & L) are right, standing waves are formed.

In this experiment, the number of loops (one loop is half of a full wavelength) between the two ends of the string can be changed by varying the driving frequency (f) and/or the tension in the string (F). A value for the speed of the wave can be obtained using the standard wave equation:

$$v = f\lambda$$

A value for the speed of the wave can also be obtained using Mersenne's law:

$$v = \sqrt{\frac{F}{\mu}}$$

In general, the wavelength for any normal mode of a standing wave fixed at both ends can be expressed as:

$$\lambda = \frac{2L}{N}$$

where L is the length of the string and N is the number of the normal mode. For the first normal mode (also called the first harmonic), the wavelength can be found as:

$$\lambda = 2L$$

which means that only half of a wavelength (what will visually appear as one loop) will be present. For the second normal mode (also called the 2nd harmonic), the wavelength is:

$$\lambda = \frac{2L}{2} = L$$

which means that a whole wavelength (two loops) is present and so on.

OBJECTIVE

This experiment studies traveling waves and their reflections in stretched strings to determine the possible normal modes of standing waves when the string is fixed at both ends. The formation of the normal modes is achieved by adjusting the parameters available in the applet, while the wavelengths are obtained by observation of the number of complete wave cycles present in the length of string that is being used for the experiment. The wave speed is calculated using the wavelength and frequency, as well as by using Mersenne's law.

MATERIALS

This is an online experiment, which you will be conducting on your own. The link to the simulation (or sim, for short) is: https://ophysics.com/w8.html

PROCEDURE

Adjust the sliders at the bottom of the applet to form the first four possible normal modes (shown below) in a string fixed at both ends.
Record the frequency (f), tension (F), and the linear density of the string (μ) used for each mode.

1. For this experiment, take L = 4 m. Keep the tension as 52 N. Change the linear mass density to $\mu = 0.4 \times 10^{-3}$ kg/m. For the values of the experiment, $v \approx 360.5$ m/s (calculated).
2. Start by adjusting the frequency. This can be done by carefully moving the bar under "Adjusting Frequency". Remember that the first normal mode looks like one "loop" – it has one antinode. When you are at the correct frequency, you will see a single loop oscillating up and down, with the amplitude being as large as it can possibly be. Write the frequency down in the appropriate column for the first normal mode. It gives you the exact value next to the slider. Remember that L = 4 m and does not change.
3. Repeat for the second normal mode, which will look like two loops – or two antinodes. Make sure that it also has a maximum amplitude. Write the frequency in the column for the second normal mode. Remember that L = 4 m and does not change.
4. Repeat for the third normal mode, which will look like three loops – or three antinodes. Make sure that it also has a maximum amplitude. Write the frequency in the column for the third normal mode. Remember that L = 4 m and does not change.

5. Repeat for the fourth normal mode, which will look like four loops – or four antinodes. Make sure that it also has a maximum amplitude. Write the frequency in the column for the fourth normal mode. Remember that L = 4 m and does not change.

DATA ANALYSIS AND RESULTS

Normal Mode	Wavelength (m)	Frequency (Hz)	Velocity (m/s)
First Normal Mode (one loop)	($\lambda = 2L$)		
Second Normal Mode (two loops)	($\lambda = 2L / 2$)		
Third Normal Mode (three loops)	($\lambda = 2L / 3$)		
Fourth Normal Mode (four loops)	($\lambda = 2L / 4$)		

1. Determine the wavelength of each mode, using the general formula $\lambda_n = 2L / n$.
2. Calculate wave speed v_0 for each mode using equation $v = f \lambda$.
3. Calculate wave speed v using Mersenne's law ($v = \sqrt{F / \mu}$).
4. Determine the error (as a percentage) in using Mersenne's law for the speed of waves for each mode, given by the following formula:

$$\% \, error = \left| \frac{v_0 - v}{v_0} \right| \times 100$$

Don't forget to show sample calculations in your Analysis section!

Experiment 3: Speed of Sound in Air

INTRODUCTION

The speed of sound could be measured using a variety of methods. Pherhaps one of the simplest approaches employs the property of wave interference.
To measure the speed of sound using wave interference, you create overlaping sound waves (from two speakers or a speaker and a reflexion) and find points of constructive (loud) or destructive (quiet) interference, which helps determine the wavelength. Then, using the known frequency of the source, you can calculate the speed of sound in air. In class we have demonstrated how to measure the wavelength by finding the distance between loud spots (maxima). Now, you will apply a different method to measure the wavelength.

Risks

- For hygiene reasons use unused toilet rolls (need them to be full size anyway)
- The sounds you play are quite pure and loud if listened to directly, it is best not to put earphones in ear when playing them.

SI measurement units

- metre (m) for length.
- second (s) for frequency, actually 1/s which is written as hertz (Hz).

OBJECTIVE

In this experiment you will measure the speed of sound using a pair of wired or wireless earbuds, a string (if wireless earbuds are used), a smartphone signal generator application, three roles of toillet paper, and a ruler. If the experiment is correctly performed, it is possible to determine the speed of sound to within 5% error.

MATERIALS

- 3 un-used toilet rolls
- Blu Tack (or equivalent)
- in-ear headphones
- smartphone or tablet for YouTube
- ruler or tape measure
- optional pen (non-permanent)

PROCEDURE

1. Place toilet roll on a flat surface with one headphone at the bottom of the tube.

2. Stack two more rolls on top to make a tunnel for the sound and help isolate experimental sound from other noise.

3. Stick some Blu Tack on the cable near the other headphone to make it heavier and keep the cable taut.

4. Search YouTube for ‘3 kHz test tone’ or find similar elsewhere.

5. Whilst playing the sound, carefully lower the second headphone into the tube as far as it will go. Slowly raise the headphone. Listen carefully. At one point the sound should almost disappear. Make tiny adjustments to find the quietest point.

6. Mark the cable at the top of the tube with the pen (or Blu Tack).

7. Move the cable up higher to find the next quietest point, and mark that too.

8. Remove the headphone and measure the distance between the marks in millimetres. This distance is the sound’s wavelength.

9. Multiply the frequency by the distance (in mm) divide by 1000 (to convert mm to metres). This is your answer: speed of sound in metres per second.

10. You can check the value by duplicating the procedure. You could also try other frequencies which will give different wavelengths, but the calculation should give the same speed. (Try 2 kHz and 4 kHz.)

DATA ANALYSIS AND RESULTS

Frequency (Hz)	Wavelength (mm)	Speed of sound = frequency x wavelength divide by 1000 (m/s)

The speed of sound in air varies with temperature, but is approximately 343 meters per second (m/s) at sea level and room temperature (20°C/68°F), and slower in colder air, around 331 m/s at 0°C (32°F). For the conclusion, compare your results with the value given above and the one obtained in class using a different determination of the wavelength.

Don't forget to show a picture of your experimental set up.

Experiment 4: Sound Intensity - The Decibel Scale

INTRODUCTION

A bel (B) is a logarithmic unit measuring the ratio of two power levels named for Alexander Graham Bell, but it is rarely used alone; instead, its tenth part, the decibel (dB), is the standard for expressing sound intensity, or signal levels, offering a practical scale for vast differences in magnitude (like human hearing).

Key Aspects

- **Logarithmic Scale**: Bels (and decibels) use base-10 logarithms to compress large numerical ranges into smaller, more manageable numbers, useful for wide dynamic ranges like sound.
- **Power Ratio:** A bel represents a 10:1 power ratio.
- **Decibel (dB):** The common unit, where 1 dB is 1/10th of a bel, making calculations more intuitive for everyday use (e.g., smallest change in sound humans hear).
- **Applications:** Used extensively in acoustics (sound levels), electronics (amplifier gain/loss), and telecommunications to compare signal strengths. n
- To relate the bel to intensity, you use a logarithmic scale that compares a measured intensity I (e.g., in Watts per square meter, W/m^2) to a reference intensity I_0. The bel is the base-10 logarithm of the ratio of these two power levels. The intensity level in bells is defined as

$$L_{\mathrm{B}} = \log_{10}\left(\frac{I}{I_0}\right) \tag{1}$$

For sound in air, the standard reference intensity is the threshold of human hearing,

$$I_0 = 10^{-12}\ \mathrm{W/m^2} \tag{2}$$

- **Tenfold Increase:** An increase of 1 bel signifies a 10-fold increase in physical intensity (I).

- **Exponential Scale:** Because the scale is logarithmic, an increase of 2 bels corresponds to a 100-fold increase (10^2) in intensity, and 3 bels is a 1,000-fold increase (10^3).
- **Perception (Loudness):** Human hearing is also approximately logarithmic, but its response to intensity is non-linear. Psychoacoustic experiments have consistently shown that a sound must increase in intensity by roughly 10 times (an increase of 10 dB) for an average person to perceive it as twice as loud.
- **In Simple Terms:** Think of it like if one sound is 10 times more powerful than another, it is a difference of 1 bel, or 10 decibels. Because humans hear over an enormous range, using decibels (which are smaller steps) makes measuring loud thunder versus quiet whispers much easier than using bels.

OBJECTIVE

Since decibels are on a logarithmic scale, it is trickier to compare the intensity levels of two different sounds if you are given their intensity in decibels. In this lab you will get familar making these comparisons.

To this end, you must first understand how to do the calculations. Here are some typical examples.

Example 1: If a sound intensity is 10 times higher than another sound, then it is 10 dB higher. As noted above, the relationship between sound intensity ratio and the decibel difference is logarithmic.

The difference in sound level (ΔL) in decibels (dB) between two intensities (I_1 and I_2) is calculated using the formula

$$\Delta L = 10 \times \log_{10}(I_2/I_1). \tag{3}$$

If the second sound intensity is 10 times higher than the first ($I_2/I_1 = 10$), the increase in decibels is

$$\Delta L = 10 \times \log_{10}(10) = 10 \times 1 = 10 \text{ dB}. \tag{4}$$

Example 2: It is now straightforward to convince yourself that if the sound intensity of one sound is 10^4 (10,000) times higher than another sound, it is $4 \times 10 = 40$ dB higher than that sound.

Example 3: The intensity of one sound is $I_1 = 5 \times 10^{-6}$ W/m^2. The intensity of a second sound is $I_2 = 4\times10^{-6}$ W/m^2. The combined intensity is 5×10^{-6} W/m^2+4×10^{-6} W/m^2 = 9×10^{-6} W/m^2.

The, the decibel level is

$$\text{Sound level in dB} \equiv \Delta L = 10 \times \log_{10}\left(\frac{9\times10^{-6}\ \text{W/m}^2}{1\times10^{-12}\ \text{W/m}^2}\right) = 10\log_{10}(9\times10^6) \tag{5}$$

Then, using the properties of logs, this can be expressed as:

$$10\log_{10}(9 \times 10^6) = 10 \times [\log_{10}(9) + \log_{10}(10^6)] = 10 \times (0.954 + 6) = 10 \times 6.954 = 69.54 \text{ dB}, \tag{6}$$

which is the decibel level of the combined sound waves.

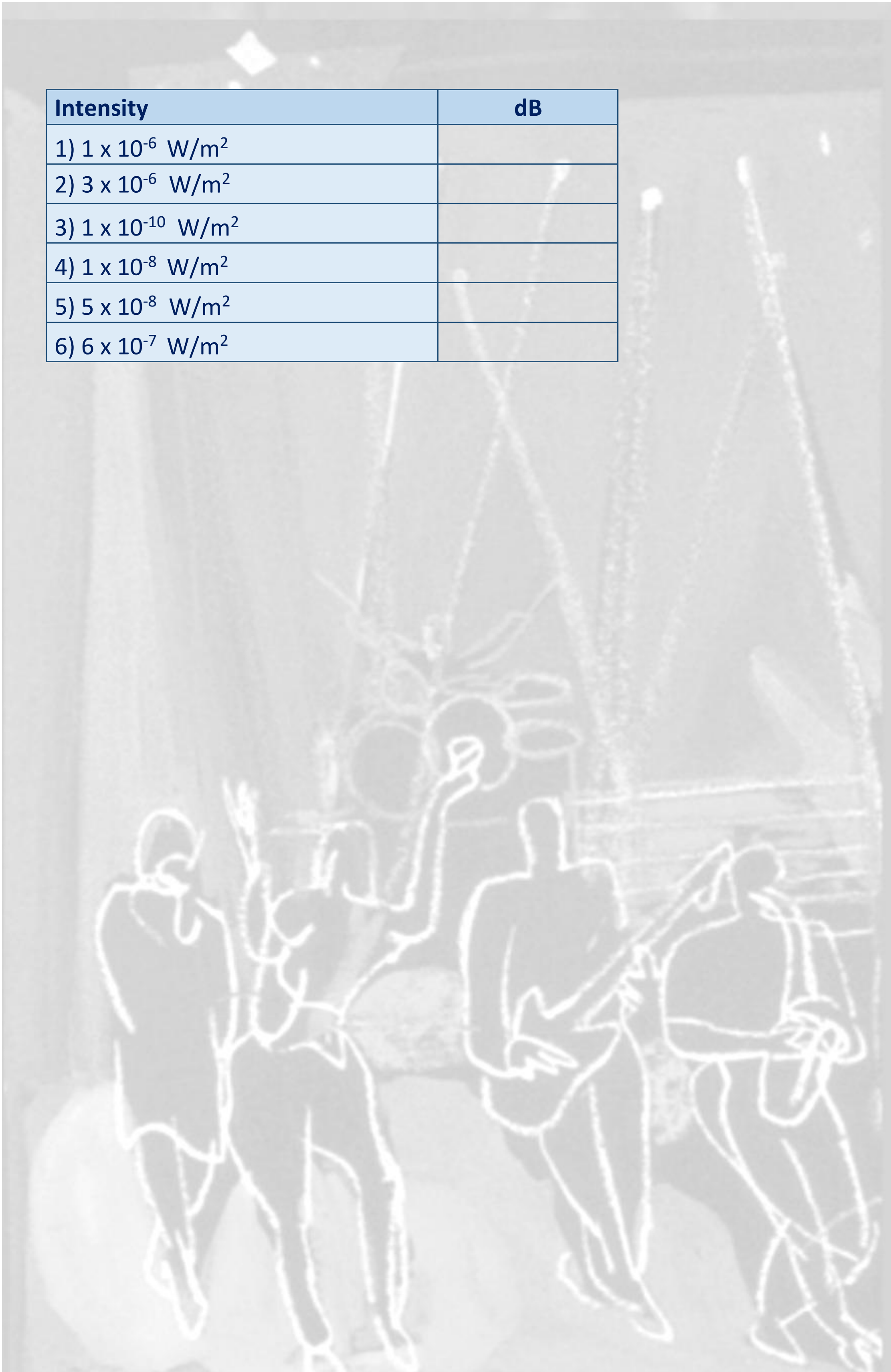
Example 4. How many decibels represent a doubling or halving of the sound volume?

An increase in intensity by 10 times will double the perceived 'volume' – this equals an addition of 10 dB – and vice versa for halving. Note that an increase in sound intensity by a factor of 10 corresponds to an addition of 10 dB, and this change is generally perceived by human hearing as a doubling of the perceived loudness or 'volume.' Similarly, decreasing the intensity by a factor of 10 (a decrease of 10 dB) is perceived as halving the loudness. This is a widely used rule of thumb in audio engineering and acoustics.

ANALYSIS AND RESULTS

1. Compute the intensity in decibels foreach of the intensities in the table.
2. Compute the decibel level of the combined sounds 1) and 2).
3. Compute the decibel level of the combined sounds 4) and 5).
4. Compute the decibel level of the combined sounds 3) and 6).

For the conclusion, comment on which of the sounds would be tolerable to your ear. What is the difference in the intensity levels between 1) and 3) (as a power of 10)? What is the difference in their decibel level? If you doubled the decibel level of sound 1), would its new intensity hurt your ear?



Intensity	dB
1) 1×10^{-6} W/m^2	
2) 3×10^{-6} W/m^2	
3) 1×10^{-10} W/m^2	
4) 1×10^{-8} W/m^2	
5) 5×10^{-8} W/m^2	
6) 6×10^{-7} W/m^2	