

The Science of Acoustics

Course Notes

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Preface

This is a set of course notes designed to be used in the Science of Acoustics course at Columbia College Chicago. It has been written so students can have a free source of information that goes deeper than anything like a set of blackboard notes or PowerPoint slides can. It is also a multimedia document that includes links to useful websites and videos (some produced here at the college). No previous physics experience is required or assumed, but to fully understand everything, you should be comfortable with algebra, including logarithms and exponents. A mathematical supplement is included for some details, and in many cases the worked examples also touch on the math.

Previous iterations of this course used a coursepack featuring selections from *Physics and Music: The Science of Musical Sound* by White and White. This text has a lot of good information in it, but it's now over thirty years old and out of print. As time goes by, using selections from this text as a coursepack made less and less sense. Other good books on the subject exist as well, for example, *The Physics of Sound* by Berg and Stork. I recommend this book as a supplemental text if you feel you need one – its material overlaps with the course a good bit and it is more up-to-date. However, it is probably more expensive than you want to pay for a course textbook outside your major, and it covers a lot of material about specific musical instruments that we will not be covering in Science of Acoustics.

I do not intend for this set of notes to serve as an exhaustive reference or even a complete textbook. I do hope that the notes supplied here will help you as you study the material covered in the Science of Acoustics course.

I would like to acknowledge my colleague Luis Nasser for feedback on these notes as well as some additional homework problems. He helped clear up some inaccuracies and imperfections, but of course, I am responsible for those that remain.

If you spot errors, I am happy to receive any feedback at tmccaskey@colum.edu.

Chapter 1: Introduction to acoustics and scientific measurements

What is acoustics?

Art and science need not be separate entities in the world. You might be taking an acoustics class to help better understand the connection between the art form of music and the science behind it. Knowledge of scientific principles can be used to hone one's artistic craft; [for example, Brian May](#) famously thought of a way to use scientific principles to create echo effects in "We Will Rock You."

Albert Einstein once noted that "the whole of science is nothing more than the refinement of everyday thinking," and we will be doing a variety of quantitative and scientific refinements in this course. Though the topic of *acoustics* technically can refer to the study of any kind of mechanical wave traveling through a medium, we will focus on sound waves traveling through air for the most part.

We will discuss many facets of the listening experience. Later in the course, we will use the principles of physics to discuss how loudspeakers work. We will also discuss how sound travels in air and how to measure its speed. We will study how sound travels and reverberates in rooms, and figure out how to determine what kind of environment a room with given dimensions and walls will be like. A branch of acoustics called *psychoacoustics* deals with how sounds are perceived by the human ear, and we will discuss that briefly as well.

Future chapters of these notes will go into more detail, but you should know now what I mean by quantitative refinements. Though individual students will have different levels of experience dealing with acoustical quantities, just about all of you know what it's like to call a sound loud, quiet, high-pitched, low-pitched (or sharp/flat if you prefer), harsh, or mellow. To get specific about these details, we will discuss the relationship of musical *pitch* to the *frequency* of a sound wave, the connection of *loudness* to *intensity*, and how different *waveforms* produce different musical *timbres*.

The scientific method

I'm sure that like me, you were all exposed to the scientific method as early as elementary school. There is no one correct way to outline the steps, but I will give one version here. A scientific investigation typically involves a cycle of the following:

- Observations (that is, a phenomenon or phenomena people notice in the world)
- Hypotheses (devising possible explanations for a phenomenon)
- Experiments (carefully-done tests of all these things)
- Analysis (interpretation of data from the experiments)

I prefer sometimes to use the idea of “coming up with a research question” instead of “inventing a hypothesis” because the phenomenon of [confirmation bias](#) can taint an otherwise good experiment. However, the idea of a hypothesis is important for many historical reasons, such as to illustrate the contributions of Galileo Galilei (1564-1642) to the scientific method. Galileo stressed the importance of using experiments not only to confirm hypotheses, but to disprove them explicitly. In science, experiments that disprove previous ideas are often the most interesting; they force us to rethink things and come up with new and more exciting ideas.

This course will give you experience both in thinking about questions to research and performing measurements. The next section will go into how measurements are commonly performed and discussed.

Measurement and the International System of units

Base units

Most of the world and all of the scientific community uses the International System of units (also known as the SI system, abbreviated from the French *Système international d'unités*). This system uses the convenience of our base ten number system to convert between units. A set of standard prefixes is applied to any base unit, and then the appropriate power of ten is understood. Though there are good reasons, for example, we have 16 ounces in a pound or 12 inches in a foot, conversions become cumbersome quickly.

The three most basic units (with their abbreviations) in the SI system are the following:

Quantity	Unit	Symbol
mass	kilogram	kg
length	meter (or metre)	m
time	second	s

In physics, we often think of mass as a measure of *inertia*, that is, the resistance of an object to a given force. For example, an object with a large mass experiencing a push will undergo a smaller acceleration than a smaller mass experiencing the same push. Many people confuse *mass* with *weight*. *Weight* is defined as the gravitational force acting on an object. If you consider only people and things on Earth, weight and mass are proportional: the more mass you have, the more you will weigh. Your mass does not change if you were to go to the moon or out into deep space, however, your weight will. On the moon, your weight is lower than your Earth weight by a factor of about six.

The unit of mass is the *kilogram*, which is the only base SI unit that has a prefix in it already. It is also the only unit that until 2018 was defined by the properties of a specific artifact – in this case, a platinum-

iridium cylinder about the size of a golf ball. The original (pictured at right) is located in France, but dozens of replicas have been distributed to labs around the world. A major problem with this system was that the kilogram prototypes gain and lose small amounts of matter over time due to wear, contamination, and absorption of matter from the atmosphere.

Currently, the kilogram is defined in terms of Planck's constant, a very small constant of nature important in quantum physics. Without well-defined definitions of the meter and second, the new definition is not useful, so I'll discuss those units next. A better picture of a kilogram replica as well as an article giving more information is [here](#).



The *meter* has been defined a number of ways over the years. The original SI system featured a prototype meter bar with notches on it that represented the appropriate distance (originally based on 1/40,000 the distance around the Earth along a longitude through Paris). A later definition (1960) expressed a meter in terms of wavelengths of orange-red light from a krypton atom. Finally, in 1983, the meter was defined in terms of the speed of light: one meter is the distance light travels through vacuum in 1/299,792,458 of a second. This means we'll need to define the second precisely as well; that's coming next. For practical purposes to Americans, a meter is a little longer than a yard (3 feet), and it is about 39.37 inches. A mile is about 1600 meters – closer to 1609, actually, but anyone who has run track knows that a quarter-mile lap around a standard track is 400 meters.



A *second* was once defined as 1/86,400 of a day (multiply 24 by 60 by 60 and you get 86,400), but the problem with that system is that the Earth's rotation speed is slowly increasing over time. Since scientists wanted the second to remain the same value throughout time, another standard was chosen: the transition between two states of a particular cesium isotope occurs very regularly. A fixed number of these (over nine billion) are counted with an [atomic clock](#) to measure one second of time.

Thanks to the influence of the ancient Sumerians and Babylonians, who used a base-60 number system, the convention of 60 seconds to a minute and 60 minutes to an hour have not changed. The counting system you are most familiar with is base-10; our number system has a ones place, tens place, hundreds

place, and so on. Base-2 (binary) and base-16 (hexadecimal) number systems are used frequently in computing. Number bases will prove important later when we discuss logarithms.

SI prefixes and conversions

The following table gives the meaning of some common SI prefixes:

SI prefix	Abbreviation	Multiplying factor
tera-	T	10^{12} (1,000,000,000,000)
giga-	G	10^9 (1,000,000,000)
mega-	M	10^6 (1,000,000)
kilo-	k	10^3 (1,000)
centi-	c	10^{-2} (0.01)
milli-	m	10^{-3} (0.001)
micro-	μ	10^{-6} (0.000001)
nano-	n	10^{-9} (0.000000001)
pico-	p	10^{-12} (0.000000000001)

Suppose you want to convert units from one metric prefix to another. The method (using what are called *conversion factors*) involves multiplying your starting quantity by one in a strategic way. One is the only number you can multiply any quantity by without changing it, but you *can* shift the units. For example, suppose you want to convert 15 millimeters to meters. You'd do it as shown here.

$$15 \text{ mm} = 15 \text{ mm} \times \left(\frac{10^{-3} \text{ m}}{1 \text{ mm}} \right) = 0.015 \text{ m}$$

Note that in the fraction in parenthesis, the numerator and denominator are equal ($1 \text{ mm} = 10^{-3} \text{ m}$). I put the mm on the bottom and the m on the top so the unwanted mm units cancel and we are left with meters.

I've often seen confusion with a table like this because conversions can be done in multiple ways. For example, the prefix "milli" means 0.001, therefore $1 \text{ mm} = 0.001 \text{ m}$. However, multiplying both sides of that equation by 1000, you can also see there are 1000 millimeters in one meter. Therefore, one can correctly do the above conversion as below. Just be careful the top and bottom of your conversion factors are equal!

$$15 \text{ mm} = 15 \text{ mm} \times \left(\frac{1 \text{ m}}{1000 \text{ mm}} \right) = 0.015 \text{ m}$$

The conversion factors in a problem don't have to involve powers of ten, and this happens often when converting Imperial (U.S./English) units to metric. For example, the SI unit of speed is meters per second (written m/s) as opposed to the typically-American miles per hour (mi/hr or mph). Suppose you want to

convert 55 miles per hour to meters per second. Knowing that 1 mi = 1609 m, 1 hour = 60 minutes, and 1 minute = 60 seconds, we can proceed as follows:

$$55 \frac{mi}{hr} = \frac{55 miles}{1 hour} \times \frac{1609 m}{1 mile} \times \frac{1 hour}{60 min} \times \frac{1 min}{60 s} = 24.6 m/s$$

The order of the conversion factors is not important – I could have done the time conversions first and gotten the same result.

As you continue your work in this course, you should get a feel for how large or small certain quantities are. A good problem solving tip is to *check your answer and units* to see if they are reasonable. If your answer is not reasonable, you may have made a mistake setting up the problem or converting units.

For example, on a math diagnostic I give, I ask students to convert 11 meters to millimeters. One student remembered that to convert to the milli- prefix, one must move the decimal point three places. He moved the decimal point three places to the LEFT and got 0.011 mm. This can be checked for reasonableness. If you know a millimeter is the smallest marking size on most metersticks, you should know that converting the length of multiple such sticks to millimeters would yield a large number, not a small one.

Dimensional analysis – another tool for checking oneself

In physics, especially courses dealing with motion, energy, and the like, we use the technique of *dimensional analysis* to look at the relationships between important quantities. Examples of such quantities include speed, acceleration, force, momentum, and energy. All of these can be broken down into fundamental dimensions of length (denoted [L]), mass ([M]), and time ([T]). Note that these correspond to the basic SI units discussed above. Speed, for example, is broken down as [L]/[T], which can be confirmed by noting common units used (miles per hour, meters per second, etc.)

Breaking quantities into fundamental dimensions is useful for testing a formula. If you are unsure whether your memory of a formula is right, check the dimensions! I have had students use the following incorrect formula on homework:

$$time = \frac{speed}{distance} \quad (WRONG!)$$

How can we see this is wrong? Substitute the dimensions for all these quantities and check that the left and right sides are the same:

$$[T] = \frac{[L]/[T]}{[L]}$$

$$[T] = \frac{1}{[T]} \quad (WRONG!)$$

Since the left and right sides are NOT the same, I know my initial equation is wrong. I know I gave that away as soon as I typed it, but I don't want casual glancers to think I was claiming it as true!

It is possible to use standard SI units of meters, kilograms, and seconds as proxies for L, M, and T when doing dimensional analysis. An equation is dimensionally correct if the left and right sides work out to be the same units. Note that equations will often have constants such as $\frac{1}{2}$ or 2 that have no units at all.

Homework problems

I often ask questions about period and frequency in the first week – if that is not done in your section, you can check the next chapter for some simple material on how those concepts are related.

1. Find the number of inches in one mile. Show your steps.
2. Find the number of seconds in a century, expressing your answer in scientific notation.
3. A pendulum is a system where a mass on a string swings back and forth. Old clocks and metronomes use these to keep time. A simple pendulum performs 9 complete oscillations in 12 seconds. Calculate the period T and the frequency f of oscillation.
4. A mass-spring system performs 8 complete oscillations in 32 seconds. Calculate the period T and frequency f of oscillation.
5. The G string on my guitar vibrates with a fundamental frequency (we'll learn exactly what "fundamental" means later) of 196 Hz. How long does it take the string to undergo 4 complete oscillations once I pluck it?
6. Complete the following table. The left column is the period of oscillation for a vibrating system, and the right represents frequency.

Period T (s)	Frequency f (Hz)
1.40	
	4.40×10^2 (A-natural)
	9.15×10^7 (carrier for NPR in Chicago)
4.50×10^{-3}	
	0.0238

7. That 4.40×10^2 Hz frequency in the previous problem matches the A-string of a violin. Compute how long it takes this string to perform three complete oscillations.
8. A spring with a mass attached at the end oscillates with maximum amplitude of 8 cm (over 3 inches). Its decay half-time is 12 seconds. (a) How long will it take the spring's

vibration to decay to the point where its amplitude is 2 cm? (b) What will the amplitude of the oscillation be after one minute?

9. Consider the equation $mgh = \frac{1}{2}mv^2$. Here, m represents mass in kg, h represents distance in m, v represents speed in m/s, and g represents acceleration due to gravity. (a) What must the units of g be to make this equation dimensionally correct? Show your work and explain your reasoning. (b) Is the equation $v^2/h = g$ dimensionally correct? (c) What are the units of the combination g/v ?

10. The formula for the period of a mass/spring system is $T = 2\pi\sqrt{\frac{m}{k}}$. T is the period in s, m is the mass in kg, and k is what's called the spring constant. (a) Before plugging in any numbers, solve for k (that is, rearrange this and get k by itself.) (b) If a 300 g mass causes a period of 1.8 s, find the numerical value of k . (c) What units should k have?