Notes from and comments upon "The Acoustical Foundations of Music" by John Backus
Second Edition, W.W. Norton and Company, New York, 1977.
Prepared for MUC 4313/5315, The University of Florida, Fall 2003 by Sam Hamm

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Introduction
Chapter One: The Fundamental Physical Quantities (pp. 3-21)

Notes derived from the text will be in plain type
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Introduction (pp. xi-xiv)

Exploration of the relationship between science/mathematics and music has occupied many of the great minds of history: Pythagoras, Aristotle, Ptolemy, Huyghens, Euler, Ohm, Young, Helmholtz, and many others.

Since it is possible to examine music from a scientific perspective, it is valid to apply the process known as the scientific method in the quantitative study of music and acoustics.

Experimentation, and the subsequent interpretation of the results, can provide a set of laws and principles that can explain physical behaviors. We must keep in mind, however, that any conclusions are open for skepticism and scrutiny, for history has shown that the scientific truths of one generation may be refuted by the research of the next generation.

"A more practical reason for the study of acoustics of music is to acquaint the musician with the basis of his craft, and enable him to understand which physical things are important to it and which are not. He should know, for example, that a rise in air temperature affects the intonation of the winds, and not of the strings." (p. xiv)

Simply put, the more you know about acoustics and the more you understand the physics of sound, the better equipped you are to deal with any number of questions or situations that occur in the practice of musicmaking. The practical value of this knowledge cannot be overstated, so long as the individual actively seeks to integrate the information into action.

Chapter One: The Fundamental Physical Quantities (pp. 3-21)

The primary aim of this chapter is to develop a vocabulary and to introduce the student to the basic physical characteristics of sound. This vocabulary serves as a basis for more in-depth discussions that will occur later, so it is important to gain command of the language as early as possible. Some of the definitions may seem simplistic and tedious, but are very important nonetheless.

"Acoustics is the study of systems that produce and propagate what we recognize as sound, and is based on the larger area of science called physics." (p. 3)

The value of developing a practice of quantitative definitions is in the enhanced descriptive precision that results.

There are three fundamental physical quantities: **length**, **time**, and **mass**.

Length, or **distance**, is the spatial separation of two points.

The method of determining length is called **measurement**, and requires a **standard of length**. By subdividing a distance into portions of a standard of length, and then counting these subdivisions (plus any remainder), a numerical representation of length can be generated.

Our standard of length is the **meter**; hence, our system is known as the **metric system**. Even the standards of the English system are defined in terms of the meter: 1 foot = 0.3048 meter.

The metric system allows for the measurement of lengths larger and smaller than those that can be conveniently expressed in meters alone. To accommodate the varying lengths, prefixes are placed before "meter" that indicate a subdivision or a multiplication of length based upon powers of 10:

mega = 10^6 = 1,000,000, so a megameter = 1,000,000 meters (Mm)

kilo = 10^3 = 1000, so a kilometer = 1000 meters (km)

centi = 10^{-2} = 0.01, so a centimeter = 0.01 meter (cm)

milli = 10^{-3} = 0.001, so a millimeter = 0.001 meter (mm)

micro = 10^{-6} = 0.000001, so a micrometer = 0.000001 meter (μm)

The Greek letter used for "micro" above is the lowercase mu. Becoming comfortable with the abbreviations shown above and the Greek letters used in them is an important aspect of learning the proper terminology.

When an object moves from one point to another, a **displacement** occurs. A displacement has both **magnitude** (essentially, length or distance) and **direction**. This movement can be represented by an arrow of a certain direction and length (as shown in the diagram on p. 6), and as such we consider displacement to be a **vector quantity**.

By combining our fundamental units of measurement we may obtain new units called **derived units**. Area, for instance, is obtained by multiplying the length and width of a two-dimensional space, and we thusly express area in terms of m^2, a derived unit. *Another familiar derived unit is mph (miles per hour).*

Time is the second fundamental physical quantity. Despite all of the simple precision provided by our standard of length and the metric system, our system of measuring time is more complicated: 60 seconds = 1 minute, 60 minutes = 1 hour, 24 hours = 1 day, a month can be between 28 and 31 days, and so on.

*In general, we will deal with seconds expressed as a decimal quantity, such as 2.67 seconds; in addition, we will often describe time in units of **milliseconds** (0.001 seconds, or a thousandth of a second). You should be comfortable thinking of 100 milliseconds as a tenth of a second, for instance, or as 500 milliseconds as a half of a second. When dealing with electroacoustic music, it is important to be fluent in expressing and conceptualizing milliseconds, as many time-based effects devices will display their settings in milliseconds.*

When dealing with derived units, we must be careful to know exactly what is being described since there is more than one fundamental quantity in action. Not only do we measure the change of the measurement of an object, in many cases we are equally concerned with the instantaneous rate of change. Consider a body in motion. We can measure the net change in spatial location of an object as displacement, which we have already discussed. We can also measure the instantaneous rate of change of displacement while the body is in motion, and we call this quantity **velocity**. We can also consider only the magnitude of the velocity, which we call **speed**. Or, we can examine the rate of change of velocity, which we call **acceleration**.

There is a mathematical relationship that exists between the rate of change of a quantity and its instantaneous value, and that relationship can be expressed through elementary calculus, specifically, the process of taking the first derivative. Calculus is crucial to an understanding of the interrelationships of the physical quantities, but is beyond the scope of this course. Simply trust for now that there exists a tremendous amount of mathematical interrelationships underneath the surface.

Mass, the third fundamental physical quantity, is also measured by the metric system with the fundamental unit being the **gram**. The process of **weighing** compares the mass of an object to a standard gram, and the resulting weight is expressed in some number of grams, with or without prefixes as appropriate.

Force is an important derived quantity, and can be simply described as either a push or a pull. Force acts upon mass. For example, a force applied to a mass can create a **distortion** (a changing of the physical shape of a mass) or an acceleration (change in velocity of a mass).

"A famous physical law, the law of **gravity**, states (in part) that every piece of matter in the universe exerts an attractive force on every other piece of matter. Hence the large mass of the earth exerts this force on all objects near it; the force is directed toward the geometrical center of the earth, which means that for us on the surface of the earth the force is directed vertically downward. The force of gravity acting on a mass is given a special name; it is called its **weight**." (p. 11)

Equilibrium occurs when all forces acting upon a mass are equal, and have canceled one another so that there is no change in the mass. An object resting on a table is at equilibrium is at rest because the upwards force of the table directly and equally counteracts the force of gravity.

This prior definition and example may seem trivial, but it is actually quite important: we should always keep in mind that the effects of force, or any other physical quantity, are not immediately apparent. This is why predictions as to physical behavior can be inaccurate: perhaps not all quantities were taken under consideration. The importance of this concept will become clearer when discussing complex systems such as reverberations.

Friction is a force that is complex to describe, but important to consider in examination of physical systems. For sake of a definition, the following is taken from m-w.com, the online Merriam-Webster dictionary: "the force that resists relative motion between two bodies in contact". Again, note that friction will become an important factor in future discussions.

Formal definition of force: **F=M • a** (force equals mass times acceleration). The unit of force is known as a **newton**.

"If a mass is accelerated by a force and the force removed when a given speed is reached, the mass will continue to move in a straight line with that speed. Only the application of another force can change the speed; in particular, the mass can only be stopped by applying a force in the direction opposite to its motion. This property of a mass in motion to remain in motion is called **momentum**." (p. 15)

Pressure is defined as Newtons per square meter (N/m^2), or as **p = F / A** (pressure equals force divided by area). Thus, it is apparent that the derived unit of pressure serves to unify the other derived units of force and area. The concept of pressure will be EXTREMELY important in discussion of sound to follow in subsequent chapters.

"We spend our lives surrounded by the earth's atmosphere, which exerts a pressure on everything in it, like any other fluid. At sea level, this pressure amounts to nearly 10^5 newtons per square meter, or (in English units) about 15 pounds force per square inch. It decreases with altitude; at an elevation of 15,000 feet it is about half that at sea level. We are unaware of this pressure, but we notice changes in it if they are large enough, as when we go up in an airplane or under water; generally, the change in pressure manifests itself in our ears as curious noises or perhaps pain. The actual value of the atmospheric pressure changes a little from time to time; its value at any given time is called the **ambient pressure**. Small changes in ambient pressure are of pressure to meteorologists, furnishing information on changes in the weather. Small but rapid changes in the ambient pressure produce sensations in the ear which we call **sound**, and which we will subsequently study in greater detail." (pp. 18-19)

A **joule** is the unit of **work**, and is the force of one Newton acting through the distance of one meter.

The **law of conservation of energy** states that energy cannot be created or destroyed, but can only be transformed from one form into another.

A **watt** is the unit to describe the rate at which work is done, unifying all three fundamental physical quantities, and is defined as the expenditure of energy at the rate of one joule per second. When using watts to describe the power behind sound, we are describing the energy needed to move air over the distance that the sound is propagated.

Chapter Two: Simple Vibrating Systems (pp.22-31)

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Backus uses a description of a mass connected to a spring and resting on a table as an introductory analogy into simple vibrating systems. It may seem an odd choice, initially, but he uses this particular example as a means of clearly and simply introducing the concepts and terminology that apply to all vibrating systems.

Equilibrium: when all of the forces acting upon an object are equal, causing the object to be at rest. In the example with the mass and the string, equilibrium exists at the place (or time) at which the spring exerts no pushing or pulling forces on the mass. In other words, the spring is neither compressed nor stretched.

Restoring force: a force that causes an object to return to its equilibrium position after the object has been displaced from that position. Note that this force is always directed toward the equilibrium position.

Oscillation, or **vibration**: the repetitive motion of a mass back and forth about the equilibrium position, yielding maximum and minimum values of displacement

Amplitude: the maximum displacement of an oscillation from the equilibrium position. In sound, we think of this as pressure, or as expressing how loud a sound is.

Cycle: one complete excursion of an oscillation or vibration from a given point, through the maximum and minimum, and back to the starting point

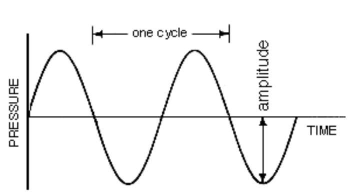
Period: the length of time it takes to complete a single cycle

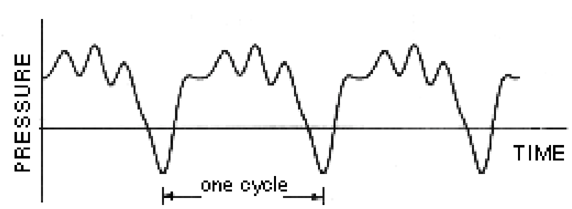
Periodic motion: a motion such as an oscillation that repeats over a given space and time

Frequency: the number of oscillations that occur within an interval of time. When dealing with sound, we typically measure the number of oscillations that occur within a second, and this expresses **pitch**, or how high or low a sound is.

Frequency can be expressed as the following formula: **f = 1 / T** (f=frequency and T=time of a complete oscillation)

Hertz: the unit of measurement of frequency, also referred to as **cps** (cycles per second)



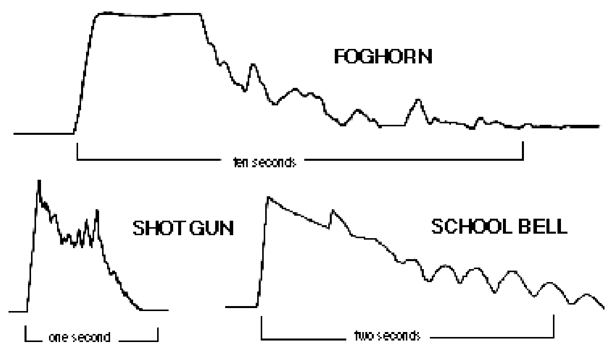


For the types of systems we will study, amplitude and frequency operate independently; in other words one does not affect the other. As you come to understand these concepts further, and apply them to your own musicmaking, you will discover that the physical design of many instruments often creates a subtle link between amplitude and frequency.

"The type of oscillatory motion we obtain when the restoring force is proportional to the displacement is given a special name; it is called **simple harmonic motion**. The reason for using the word *simple* is that any other kind of vibrating motion is more complicated to describe, and will usually be expressed in terms of a number of simple harmonic motions." (pp.24-25)

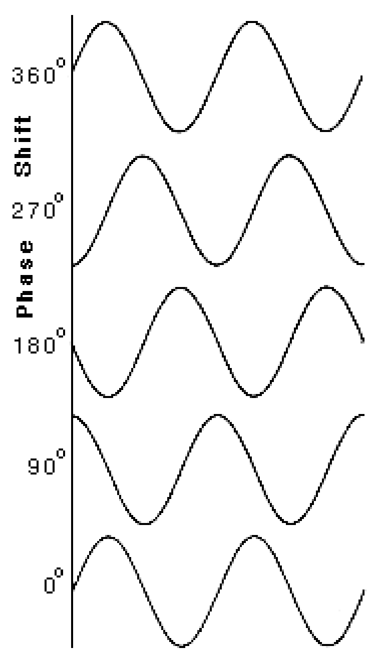
Think of simple harmonic motion as sinusoidal motion, which generates sine waves.

Graphs are often useful in describing acoustics. It is common to graph sound in terms of the amplitude being measured on the vertical (Y) axis and time being measured on the horizontal (X) axis. When looking at a small number of cycles (less than 3, usually), the graph covers a very small amount of time and will indicate a waveform. When looking at a larger interval of time, graph will often indicate the shape of the **amplitude envelope** of the sound.



Remember that envelopes are made up of multiple cycles, but that she shape of a single waveform can be used to model an envelope.

Phase: simply put, a part of a cycle. The term can be used in a variety of ways, but most often is used to describe the offset of the starting point of a waveform.



Effect of mass, tension, and distance on an oscillation:

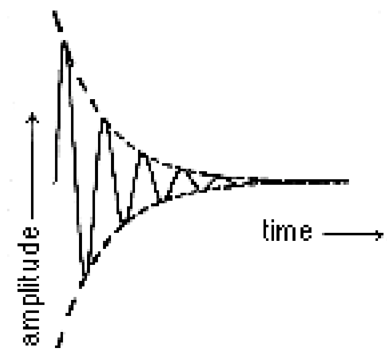
Greater mass, slower oscillation   Lesser mass, faster oscillation
Grater tension, faster oscillation   Lesser tension, slower oscillation

Distance: if a string of constant mass is stretched to a greater length, faster oscillation results
if a string of constant mass is relaxed to a shorter length, slower oscillation results

Decay: in the physical world, vibrating systems tend to lose energy over time due to friction. As a result, the maximum and minimum values of the oscillation get closer and closer to zero, a process known as decay. The overall shape created by the successively smaller amplitudes over time can be graphed into a **decay envelope**.

Friction, or any other outside force that causes decay through **resistance**, results in a process known as **damping**.

An amplitude envelope is made up of three main parts: the ramp up from zero to maximum, which is called the **transient**, the period over which the maximum values of an envelop remain constant for a given interval of time, known as the **steady-state**, and the return to zero, known as the **decay**.



In many old analog synthesizers, an envelope could be created with an **ADSR generator**, with the letters standing for Attack, Decay, Sustain, Release. Attack and Decay allow for shaping of the transient, Sustain controls the steady-state, and Release controls the decay.

Chapter Three: Waves and Wave Propagation (pp.32-54)

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We start off with a bunch of definitions to establish a terminology…

Medium: the matter through which vibrations are transmitted

Density: mass of a unit amount of a medium

Impulse: a sharp and sudden disturbance in a medium

Propagation: the movement of the energy of an impulse through the medium

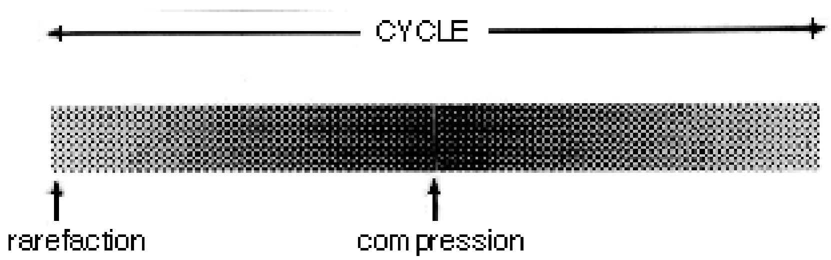
Longitudinal disturbance/waves: the displacements/waves of matter occur in the same direction as the disturbance is traveling, creating areas of **compression** and **expansion**.

Transverse disturbance/waves: the displacements/waves of matter occur perpendicular to the direction the disturbance is traveling, creating a succession of **crests** and **troughs** in a succession known as a **wave train**.

Wave: periodic (repeated in time) disturbances traveling through a medium.

Now we're getting to the good part…

Many musical instruments are based upon a system known as an **air column**, which consists of air contained in a rigid tube. As periodic disturbances are introduced to this tube (perhaps by a reed or mouthpiece), areas of **compression** and **rarefaction** result. Because of the limitations of the tube, these disturbances are longitudinal rather than transverse, creating a **sound wave**.



"**Sound pressure** is the amplitude of the pressure variation in a sound wave, above and below the ambient pressure." (p.40)

Concepts we have already discussed, such as amplitude, wavelength, period, and phase all apply to this new method of discussing sound waves. As we will soon see, the characteristics of the matter itself have a direct impact upon the type and frequency of waves that are produced.

"Note that the individual particles in the medium through which the wave is traveling oscillate back and forth about their equilibrium as the wave passes by; they do not undergo any permanent displacement." (pp.40-41)

Speed of sound: at "standard conditions", which is a temperature of 0º C and a typical atmospheric pressure of $1.013 \cdot 10^5$ newtons per square meter, the speed of sound is 331.5 meters per second (1087 feet per second). For each additional degree of increased temperature, the speed of sound increases by 0.6 meters per second (1.1 feet per second).

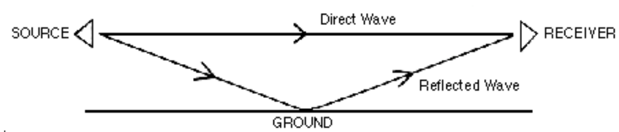
Thus, we can compute that on a steamy and stormy Florida afternoon, with a temperature of 86º F or 30º C, the speed of *sound is 331.5 m/s + (30 • 0.6 m/s), giving a new speed of sound as 349.5 m/s, or 1146.65 ft/s. This means that the sound of thunder travels a mile (5280 ft) in 4.60 seconds. Considering that the increased density of the humid air will slow down the sound waves slightly, the old rule of thumb that "for every five seconds between a flash of lightning and the sound of the thunder, the lightning strike is a mile away" holds as being quite accurate.*

Doppler Effect: a moving sound source will create areas of compressed waves in front of it and expanded waves behind it. To a listener who remains in a single position, compression of the waves creates the impression of an increase in frequency. Once the sound source passes, the expansion of the waves creates the impression of a decrease in frequency.

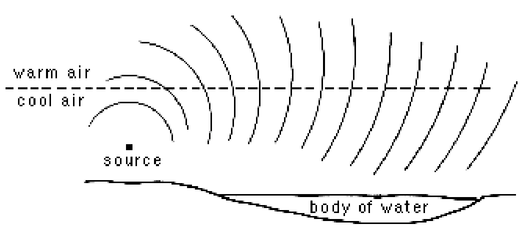
The Doppler effect, though an easily observed phenomenon in the range of human hearing, has little practical application in terms of sound. However, the same concept is extremely useful in other fields when applied to waves of much higher frequencies. For instance, we could have been warned of the thunderstorm in the prior example by Channel 2's Super Doppler Radar; another field that makes tremendous use of Doppler shifts is astronomy.

Properties of waves:

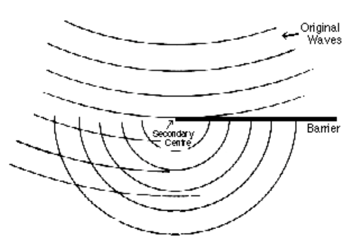
1. **Reflection**: when waves traveling through a medium reach a boundary surface where the properties of the medium suddenly change, the waves may be reflected of bounced off of the medium. Note that the medium may absorb some of the energy as well.



2. **Refraction**: when waves travel through a medium whose properties change slowly with distance, the wave may ultimately be moving in a direction different from that in which it started.

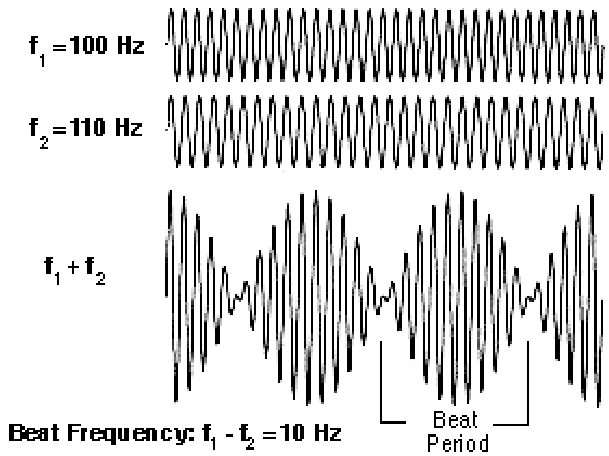


3. **Diffraction**: the ability of waves to go around corners



4. **Interference**: when waves from two different sources exist simultaneously in a medium and interact with one another, reinforcement or cancellation can occur.

Beats: when two sound sources of slightly different frequencies are sounded together, the resulting sound has a periodic rise and fall in amplitude that is heard as a periodic change in loudness and called a beat. The beat frequency is simply the difference in Hertz between the frequencies of the two sound sources.



Radiation: the process by which energy is carried away from a vibrating source

Since we are dealing with energy and time, we could use watts (joules per second) to describe the amount of output from a sound source. However, in later chapters we will establish more useful means for measuring sound.

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Chapter Four: Complex Vibrations and Resonance (pp.55-86)

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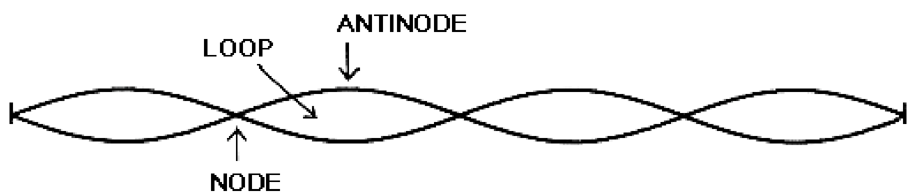
- *The simple systems we have described to this point serve as foundations for the more complex systems that make up the practical world of acoustics and sound. This where familiarity and understanding of the material previously discussed will pay off.*

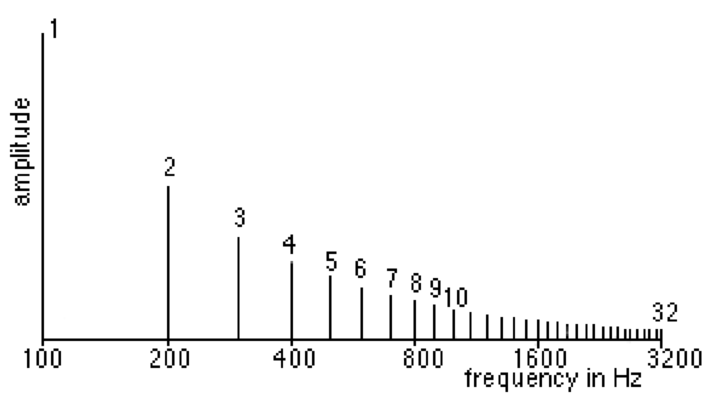
- Combining waves is most easily understood as a sum: when multiple waves are present within a medium, the resulting disturbance is simply the sum of the instantaneous values of the existing waves.

- *Note that in this chapter, the lowercase Greek letter lambda (λ) is used to represent string length. Mathematics always looks more fancy when you can throw a few Greek letters in there.*

- **Standing wave**: in a medium of fixed size or length, some waves of certain frequencies simply oscillate in place rather than travel through the medium. For example, on a vibrating string, there will be locations on the string that do not move, which are called **nodes**. Between the nodes, in the portion of the string known as the **loop**, there will be points of greatest displacement called **antinodes**. The antinodes correspond to the amplitude of the wave, and the distance between antinodes to the period of the wave.



- A string that is stretched between two points can vibrate on a number of different **modes**. Modes correspond to subdivided string lengths that are integral divisions of the total length of the string, 1, 1/2, 1/3, 1/4, etc., and produce frequencies that are integral multiples of the vibration frequency of the entire string. The vibration of the entire length of the string is known as the **fundamental mode**, or simply the fundamental. The vibrations of the string on frequencies of integral multiples are known as **harmonics**. We will discuss this topic in much greater depth in the future.



- "A medium can carry many waves simultaneously, as we stated earlier, so the stretched string can vibrate in many modes simultaneously. If we set the string into motion by plucking it – that is, by drawing it to one side and suddenly releasing it – all the modes will be present, with amplitudes that depend upon the point along the string at which it was plucked." (p.62)

- *As will be seen in a later chapter, Pythagoras, using an instrument called a monochord, conducted many of the first studies into the properties of vibrating strings.*

- "The complex string motions discussed here are examples of a famous theorem [due to the mathematician **Fourier**] which states that any curve of arbitrary shape [within certain liberal limits] which repeats periodically [and hence has wavelength λ] can be reproduced by adding sinusoidal curves of wavelengths λ, λ /2, λ /3, λ /4, and so on, with properly adjusted amplitudes and phases." (p.62)

- This is the concept behind **additive synthesis**, a way of creating a wide variety of sounds by just adding sine waves together. Theoretically, any complex periodic waveform (=sound) can be produced via additive means.

- In the same way that vibrating strings can conduct multiple transverse waves, an air column can conduct multiple longitudinal waves. Amplitude is analogous to pressure, rather than displacement. When discussing air columns and the waves within them, all of the same concepts apply that we used with vibrating strings: standing waves, nodes, antinodes, modes.

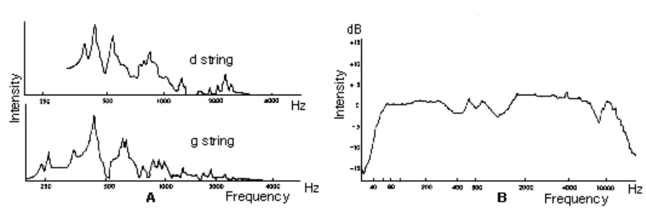
- *In the practical world, we interact with a variety of air columns, often thought of as being enclosed in tubes: some are closed on both ends (such as being in a room), some are open on both ends (as in a hallway or tunnel), and some are open on one end (wind instruments). Each of these types of air columns exhibits particular behaviors regarding frequency and amplitude. The book explains this in detail, but for the purpose of these notes we will simply acknowledge that different systems behave differently.*

- One type of variation of particular musical interest arises in dealing with tubes containing air columns. The shape of the tube itself can have a significant impact upon sound. In our musical instruments there are two primary types: **cylindrical** (the diameter or **bore** of the tube remains constant throughout nearly its entire length) and **conical** (the diameter of the tube expands with distance from the source of excitation). For instance, in the brass family of musical instruments, the trumpet and cornet are very similar, except that the trumpet has a cylindrical bore and the cornet has a conical bore. The large-scale lesson to learn from this example is that seemingly small and subtle variations in the design of a musical instrument can have a significant impact upon the sound that is created. Our notions of acoustics thus operate on scales both large and small.

- In addition to strings and air columns, we also deal with membranes and solid vibrating materials as sources of musical sounds. Again, all the same concepts apply: a drumhead will exhibit varying modes of vibration depending upon where it is struck by a stick, or, a vibrating cymbal also has nodes and antinodes.

- Some musical instruments are designed in such a manner that the actual source of vibrations will transmit these vibrations immediately to another surface as a means of generating a larger amount of excitation of the surrounding air. Such an assisting surface is known as a **soundboard**, and is common in stringed instruments.

- **Resonance**: "Whenever a system that can vibrate with a certain frequency is acted upon from the outside by a periodic disturbance that has the same frequency, vibrations of large amplitude can be produced in the system. This situation is called resonance." (p.76)



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Chapter Five: The Ear: Intensity and Loudness Levels (pp.87-106)

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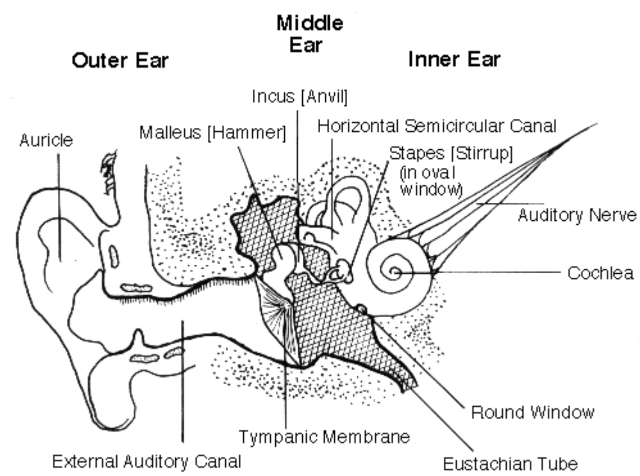
- *In the same way that we have examined the physicality of sound as a means of understanding acoustic phenomena, we will now turn our attention to our physiological sound receptors – our ears – and how our ears receive and process sound.*



- Structure of the ear:
  - Outer Ear
    - *pinna* – exterior visible structure of ear that gathers and focuses sound
    - *auditory canal (meatus)* – pathway for sound into the ear
    - *eardrum* – membrane at the end of the auditory canal that separates the outer and middle ear
  - Middle Ear
    - *Eustachian tube* – connects to throat, allows for equalization to changes to ambient air pressure
    - *ossicular chain (hammer, anvil, stirrup)* – transmit vibrations from eardrum to cochlea
    - *oval window* – where the stirrup connects to the cochlea
  - Inner Ear
    - *cochlea* – primary structure of the inner ear
    - *perilymph* – fluid that fills the cochlea
    - *basilar membrane* – partition that bisects the cochlea and is imbedded with nerve endings
    - *round window* – with oval window, constitutes barrier between middle and inner ears
    - *helicotrema* – opening between the two halves of the cochlea

- The *semicircular canals*, which assist us in balance, are also connected to the cochlea.

- We discern pitch by which end of the basilar membrane responds to incoming vibrations. High frequencies excite the end of the basilar membrane closer to the oval window, and low frequencies at the end closer to the helicotrema.

- The response of the basilar membrane is similar to the graph of a sonic spectrum in the frequency-domain.

- The manner in which the brain processes input from the ear is not entirely understood. For instance, speech signals are routed to the left side of the brain, whereas musical information is processed by the right side of the brain.

- **Binaural listening**: the way humans hear sound, with two ears, that allows us to identify the spatial origin of a sound. Differences in phase, intensity, and the time of arrival of sound provide our brains with the necessary information.

- **Sound intensity**: The sound energy transmitted per unit time through a unit area, thereby being a measure of the magnitude of a sound. The unit of measurement is the erg per second per square centimeter, or the watt per square meter. The threshold of hearing lies at 10^{-12} watts/m^2, whereas the threshold of pain is about 1 watt/m^2. The measurement of sound intensity is its intensity level and is measured logarithmically in decibels because of the wide range of intensities involved. Sound intensity is proportional to the square of the sound pressure, which, being easier to measure, is more commonly used as a basis of sound measurement. The term most often used in measuring the magnitude of sound. It is a relative quantity in that it is the ratio between the actual sound pressure and a fixed reference pressure. This reference pressure is usually that of the threshold of hearing which has been internationally agreed upon as having the value .0002 dynes/cm2. [Definition from the *Handbook for Acoustic Ecology*]

- **Decibel (dB)**: Unit of level of the intensity level of sound, such that L = 10 log (sound intensity / threshold intensity). Doubling the intensity of a sound increases its intensity level by 3 dB, since 10 log 2 = 3.0, approximately, and increasing intensity of sound by a factor of 10 increases its intensity level by 10dB, a factor of increase of 200 → 20dB.

- Table of sound intensities measured in decibels:

dB	**Sound**
0	Threshold of hearing
40	"Very soft sound", or the ambient sound of a quiet room
60	Normal conversation
80	"Loud sound"
107	Lawnmower
120	Threshold of pain

- The **just noticeable difference** of sound intensity roughly corresponds to a decibel.

- **Loudness**: the subjective impression of the intensity or magnitude of a sound. It is dependent on frequency, waveform, and duration, as well as sound intensity or sound pressure. It is expressed quantitatively in units of sones and phons for sine tones or narrow band noise, and in terms of perceived noise level (PNdB) for broad band environmental sounds. [Definition from the *Handbook for Acoustic Ecology*]

- **Phons** are used in instances of single frequencies, and **sones** in instances of multiple frequencies.

- "As explained earlier, a sound of a particular frequency produces a wave traveling upon the basilar membrane, and this wave has a maximum amplitude at some point whose position depends on the frequency of the sound. The disturbance produced by the wave at this point is spread over a certain length of the basilar membrane; that is, the nerve endings of the basilar membrane are excited over a narrow region extending on either side of the point of maximum motion of the membrane. This region corresponds to a range of frequencies above and below the frequency of the incoming sound itself. This region is known as the **critical band**. […] Once the critical band is excited by the sound of a particular frequency, a considerable increase in sound intensity is required to produce a subjective increase in loudness; twice the intensity raises the loudness level only three phons. However, exciting the basilar membrane at one point does not decreases its sensitivity at other points outside the critical band. Hence sounds of the same loudness level – but of two different frequencies far enough apart so as to excite the basilar membrane at two different locations – will give a subjective impression of greater loudness than if their frequencies are the same." (pp.100-01)

- **Masking**: when a sound that is quite audible by itself can become completely inaudible if another louder sound is present.

Notes from and comments upon "The Acoustical Foundations of Music" by John Backus
Second Edition, W.W. Norton and Company, New York, 1977.
Prepared for MUC 4313/5315, The University of Florida, Fall 2003 by Sam Hamm

Chapter Six: Tone quality (pp.107-125)

Notes derived from the text will be in plain type
"Excerpts from the text will appear in quotes"
Comments upon the material will be in italic type

- **Tone**: A sound that lasts long enough and is steady enough for the ear to ascribe to it the characteristics of loudness, quality, and pitch.

- **Timbre**: Another name for "tone quality", it is the characteristic of a tone that can distinguish it from others of the same frequency and loudness.

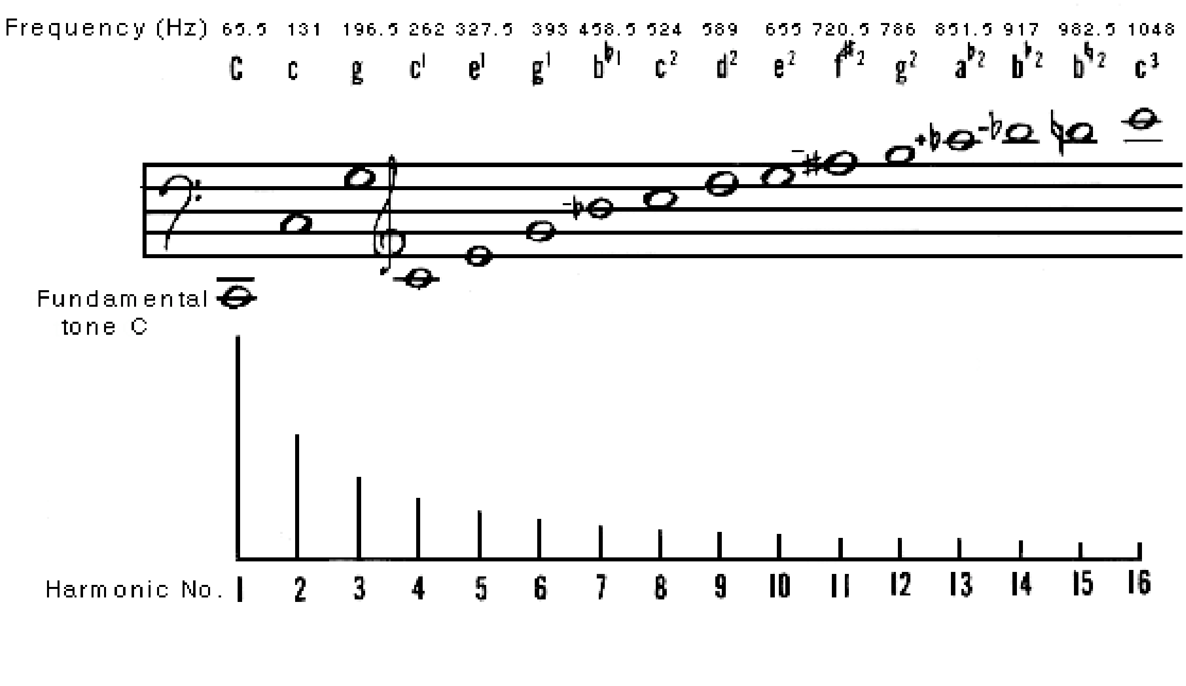
- *To this point we have primarily discussed sounds of a single frequency, but in the real world such sounds are uncommon. Most sounds we hear are made up of a combination of many frequencies.*

- **Complex tones**: Mixtures of sine tones of various amplitudes and frequencies. The individual tones that make up a complex tone are known as partials.

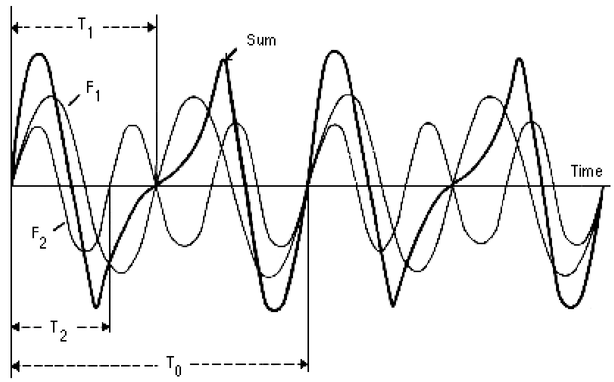
- "Individual tones produced by the steady-tone instruments have a very important characteristic: they are *periodic*. Investigation of these complex tones shows that whatever is the complicated vibration pattern of the sound wave, it consists of a single pattern repeated identically for a considerable number of cycles. The number of cycles produced per second is obviously the frequency of the complex tone; we will call this the **fundamental** frequency. For such a tone, the constituent partials must be related in a very simple way; their frequencies must be integral multiples 1,2,3,4, and so on times the fundamental frequency of the vibration." (p.108)

- Partials related in this simple way are called **harmonics**. The partial having the fundamental frequency is called either the *fundamental* or *first harmonic*. The partial having a frequency twice that of the fundamental is known as the *second harmonic* or the *first overtone*. It should be obvious that use of the term "overtone" can be confusing, and has generally fallen out of favor.

- The harmonic series, starting on C:

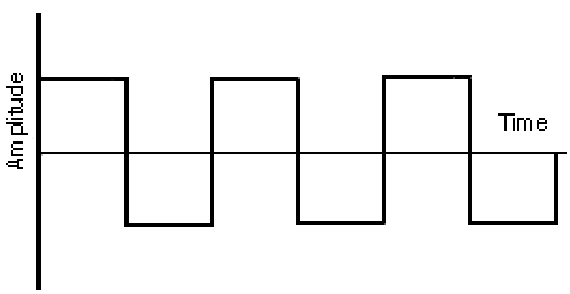


- Waveform diagram of the sum of the second and third harmonics:

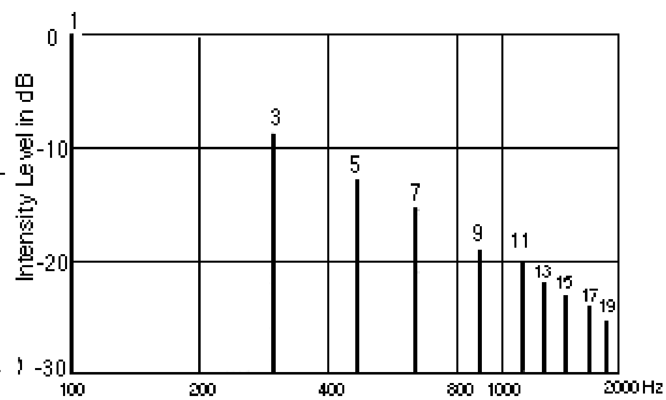


- The process of adding harmonics to produce an arbitrarily complex waveform is termed **additive synthesis**.

- "One important complex wave of interest to physicists and engineers is that made up of harmonics 1,2,3,4, and so on with relative amplitudes 1, 1/2, 1/3, 1/4, and so on all in the same phase. It is called a **sawtooth wave**. Another is obtained by using the odd harmonics 1,3,5,7 and so on with relative amplitudes 1, 1/3, 1/5, 1/7 and so on, again all in the same phase; it is called a **square wave**." (p.113)



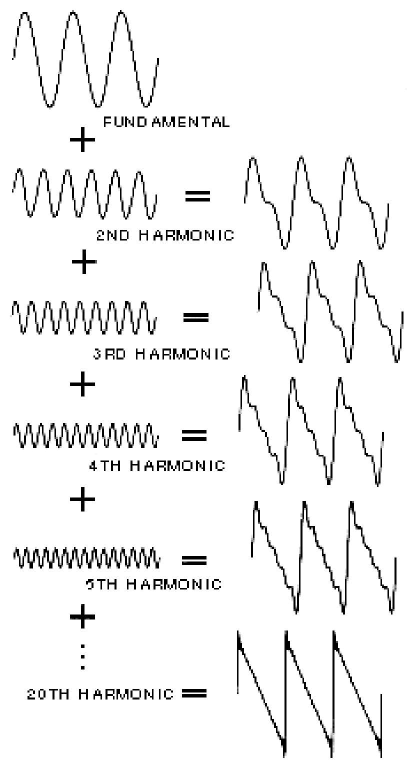
$$\frac{4}{\pi}\left(\sin \omega t + \frac{1}{3}\sin 3\omega t + \frac{1}{5}\sin 5\omega t + \frac{1}{7}\sin 7\omega t + \ldots\right)$$



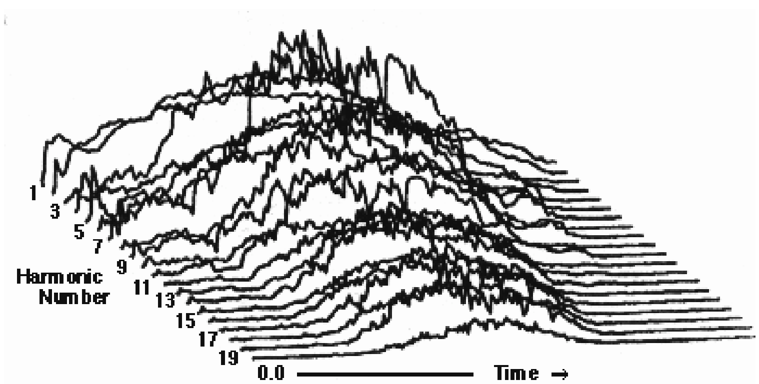
- Another way of expressing these waveforms, as well as another common one:

Sawtooth:	A = 1/n, all harmonics
Square	A = 1/n, odd harmonics
Triangle	A = $1/n^2$, odd harmonics

- Summation of sinusoidal harmonics is also known as the **law of superposition**.



- **Spectrum**: the representation of the analysis of a tone into its constituent harmonics



- "The analysis of a large number of tones from many musical instruments made over a considerable period of time, has demonstrated that there is no characteristic spectrum, somewhat the same from note to note, associated with a given musical instrument."

- Many instruments display inconsistency in timbre over their ranges, and for most instruments, harmonics above the seventh are unimportant, at least in terms of pitch.

- Instruments have a fixed region or regions in which harmonics of a tone are emphasized, regardless of the frequency of the fundamental. These fixed frequency regions are known as **formants**.

- **Vibrato**: periodic variation of the frequency of a tone about its average value.

- **Tremolo**, or **amplitude modulation**: periodic variation of the amplitude of a tone about its given value.

- Most instruments also contain an **inharmonic** component to their sounds that contribute to the timbre.

- **White noise**: a mixture of sounds of all frequencies that contains equal amounts of sound power in equal frequency bands of the spectrum.

- **Pink noise**: a mixture of sounds of all frequencies that contains equal amounts of sound power in octave-width bands of the spectrum, and therefore contains a lower component of higher frequencies and does not sound as bright.

- **Chorus effect**: results from the combination of multiple like instruments playing the same pitch simultaneously, and the minute discrepancies among the fundamentals and harmonics of the tones as they change in time.

- **Subjective tones** are not actually present in the sound, but are heard by the ear nonetheless, such as **summation tones** and **difference tones**. When two loud tones are sounded together, summation tones and difference tones are produced at frequency values equal to the sum and difference of the original tones.

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