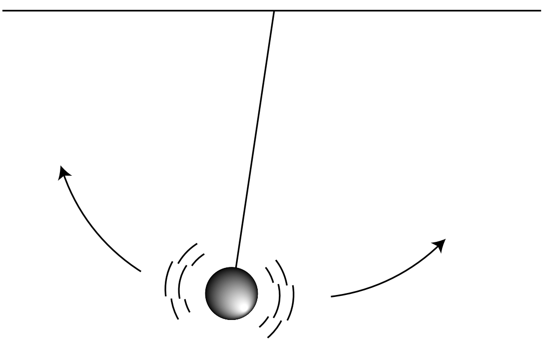
CHAPTER 2: THE BEHAVIOR OF WAVES

Things move. They sometimes move in random fashion, sometimes along a path of some sort, sometimes in a repeating motion. Let's first explore the latter, and narrow that further to things moving back and forth. Indeed, if you look at something going around and around from the side, it appears to be going back and forth anyway. The simplest back and forth, or vibrating motion is called **simple harmonic motion.**

In your imagination if not actually, take a string about 3 feet long and tie a reasonably large weight (two or three pounds) to one end, the other to a hook at the top center of your doorway or some other place where it can swing freely. You have made a pendulum, which is one example of something moving in Simple Harmonic Motion (See fig. 2-1).

Figure 2-1



Simple Harmonic Motion

Lift the weight back, let it swing and watch it—at least in your imagination. It's a simple but special motion. At the top of its swing, for an instant, it's dead still, then it gains speed as (in this case) gravity pulls it down. The string makes it fall in a curve and it is going fastest as it is at the bottom of the arc, but the weight has inertia and wants to keep going. By now, however, gravity is working against it: constantly slowing the weight until everything is balanced for a moment on the other side and it stops for an instant… before falling back the other way, constantly gaining speed through the bottom of the arc, then moving back up the other side, and so on… If it weren't for the friction of the air and the string, this would repeat forever, once started. It's a vibrating motion, repeating itself periodically in cycles, over and over. Simple harmonic motion can happen in a straight line, but it is easier to visualize it as the arc of a pendulum: our weight, a playground swing, a skateboarder on a half-pipe. And, as we shall see, simple harmonic motion is also the most basic component of sound.

Note that the actual speed of the weight through the air is constantly changing, from stopped and ready to fall, to faster, faster, *fastest*, slower, s l o w e r … stopped on the other side, then back the other way… The speed is always smoothly changing but there is a constant to the entire movement: it always takes the same amount of time to complete a cycle before it repeats. This **frequency** with which the weight (or anything moving in simple harmonic motion) begins a new cycle is one of the two most basic ways of measuring or describing that motion—and one of the two most basic measurements in our field of sound. Simple harmonic motion can be described by its frequency.

Take (or imagine) another, smaller weight and tie it to a string about a foot long. Hold the other string end steadily and start this pendulum with your other hand. Note that the frequency of this pendulum is higher (i.e., it starts each cycle more frequently). In this case the length of the string is the difference—as in all pendulums (pendula if you took Latin). We measure frequency in cycles-per-something. Cycles per minute or hour or millennium might be appropriate for some very low frequencies, but for our use, **cycles per second**, or **CPS,** is the most useful. Your short pendulum with the 1 foot string is probably vibrating in simple harmonic motion at a frequency of about 1 (complete—back and forth) cycle per second, or 1 CPS.

In general, frequency can be determined by other factors. Go back to your large pendulum, and grasp the string about 4 inches above the weight, holding it steady. Lift the weight with the other hand, and start it swinging. Was the movement as smooth and long-lasting as before? Probably not. The heavier weight was much happier moving at the lower frequency. This is an important concept that haunts us throughout our work in the Acoustic World of sound: big stuff likes to move at lower frequencies, little stuff at higher frequencies. Moreover, if you start both of your weights swinging at an appropriate frequency, the heavier one will continue to swing longer.

In the physical world, larger masses tend to require more energy to start motion, to vibrate at a lower frequency, and to vibrate longer. Smaller masses tend to vibrate more easily, at higher frequencies, but they also tend to be more delicate; their motion is easier to interrupt. We'll encounter this again and again.

Now for the second basic, critical way to describe or measure our simple harmonic motion. Get one of your pendulums swinging again. How high from the bottom does it go? How wide is the arc? How far does it swing from the lowest point? How much energy did you use to lift the weight, and to what height? What is the *size* of the motion? These questions all revolve around a vague, slippery, but critical characteristic. The term we use to talk about this is **amplitude**. The amplitude of a motion that repeats periodically (such as our simple harmonic motion) is directly related to the distance it travels from the bottom (zero) point in each arc. The wider the swing, the higher the amplitude; and in some sense, the more energy involved.

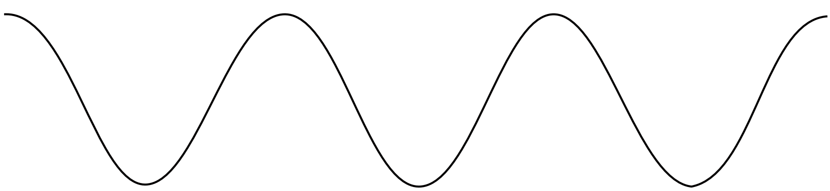
Try starting your pendulums from different heights. Notice that either pendulum is happy to vibrate at a variety of amplitudes. As you lift the weight out further (transferring more of your energy to it) it swings in a wider arc (higher amplitude). Barely move it and the amplitude is very low. Notice something else: no matter what amplitude you give the motion, the frequency remains the same; about 1 cycle per second for the short one. Later on you may discover that amplitude can impact our perception of frequency in hearing, but for now it's useful to understand that they are inherently separate things. We know we can quantify or measure frequency in CPS (cycles per second). But amplitude is a slippery concept, so for now let's just think of it as higher or lower.

Before we connect all this directly to sound, let's try one more thing: You now have some idea of the nature of simple harmonic motion, so try to emulate it with your arm. Hang it loosely from your raised elbow and let your forearm swing in quasi-simple harmonic motion. Now pick up a piece of (imaginary?) chalk and go to a handy blackboard. Move your arm up so that the motion becomes sideways, as though you were the homecoming queen doing that slow hackneyed wave from a parade float. If you wave with the chalk up against the blackboard, you'll make a nice arc, over and over in the same place. Notice that the width of the chalk arc is a tangible, concrete representation of the *amplitude* of your arm's simple harmonic motion. In order to chart the *frequency* of your arm's vibration, you'll have to move across the blackboard surface. If you walk at a constant speed you'll make a repeating, squiggly line. As a matter of fact, if you could move *precisely* at say, one foot per second, you would have made a tangible representation of your simple harmonic motion, and could measure the amplitude by the size of the arc, and the frequency (in cycles per second) by the number of repetitions of the squiggle in each foot of blackboard surface. Notice how smooth the change in curvature is… just like the smooth change in motion of the pendulum.

Simple Waves

Did you take trigonometry in high school or college? I didn't, but I understand that a part of trigonometry involves special equations called trigonometric functions. If you enter a series of numbers into one of these equations and plot the answers on a graph, they make designs. As it turns out, if you plot out numbers with what's termed the "sine" function they will make a squiggly design just like the idealized one you made on the blackboard when you made a tangible representation of simple harmonic motion (See fig. 2-2). This isn't a coincidence; trigonometry is a mathematical way of describing the universe, and the sine function happens to relate to simple harmonic motion, the most basic vibration in physics. Thus, a wave that vibrates in simple harmonic motion is called a **sine wave**, a term you may have encountered already in your exploration of sound. From now on, the term "sine wave" will begin to replace "simple harmonic motion" in this book, just as it has in the most of the sound art world.

Figure 2-2



A Sine Wave

We'll discuss the nature of *sound* waves themselves in the next chapter, but for now, let's accept on faith the notion that air can move in waves, including sine waves (simple harmonic motion). It turns out that when airborne sine waves fall in certain ranges of frequency and amplitude, our ears sense them as sound. Because sine waves periodically repeat themselves cycle after cycle (at, say 300 cycles per second) we hear sine waves as sound at a constant musical pitch. The higher the frequency, the higher the pitch, the higher the amplitude, the louder the pitch sounds. There isn't a perfect correlation between frequency (the measurement of a sine wave) and pitch (what pitch we hear) or between amplitude (the measurement of the energy in the wave) and loudness (how loud it sounds to us), but it's close enough for us to connect them now. There's plenty of time later to allow things to get complicated…

The frequency range of the average human is usually given as 20 CPS for the lowest sound we can sense, to 20,000 CPS for the very highest sound. In reality, almost from the month we are born, the top range of our pitch (frequency) sensitivity begins to drop, just by the act of living. If we are subjected to loud sounds, it may drop further. The average young adult may be able to hear pitches up to around 16-17,000 CPS. As for amplitude, for now let's just say it has to fall in the range of loud enough to hear, but not so loud it hurts your ears.

Before we go on, a couple new terms are in order:

1. If you are rich and give people money, they might name a building after you. If you are a famous scientist, they tend to name scientific stuff after you. Heinrich Hertz lived in the latter part of the 19th century and was first to detect electromagnetic waves. They were also measured in cycles per second, so they named cycles per second **hertz**, after Heinrich. Hertz is abbreviated as **Hz**. This is the more common term and the one we'll use from now on to measure frequency.

2. You are probably familiar with the metric term *kilo*, meaning thousand. It is often abbreviated K or k.

So if you see a readout on your cousin Oprah's digital keyboard that says "Sine Wave: 3 kHz", you now know it refers to a wave exhibiting simple harmonic motion at 3000 cycles per second, and you're confident that it would fall in the midrange of your hearing.

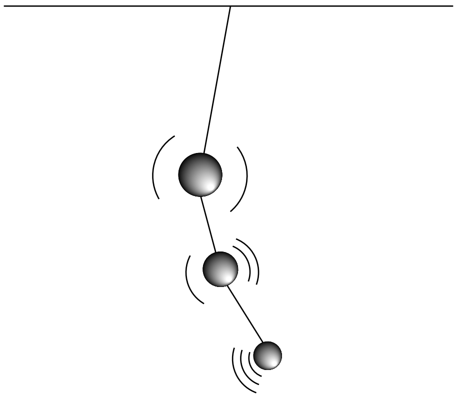
A sine wave makes a very smooth, mellow, simple sound, because of its smooth changes in motion. It has a precise, definite pitch. It can be characterized and measured by its frequency, which relates to our sense of pitch, and its amplitude, relating to our perception of its loudness.

If you have access to a digital keyboard, sound software, or a test CD, listen to some sine waves. Listen at all the frequencies your equipment will allow. Otherwise, simply imagine a quiet flute sound, or better yet a recorder, or pan pipes. These are approximations of sine waves, although even they are a bit more complex. The main pitch measurement in the sound technology arena is hertz (cycles per second) not musical letter names, so it's greatly to your advantage to form a mental 'hearing image' of what various frequencies sound like. You don't need perfect pitch memory. You'll be surprised how quickly you learn to hear in your mental ear approximately what 1 kHz (a sine wave vibrating at 1000 cycles per second), or 200 Hz, or 3.7 kHz, or 12 kHz sound like. If you can find the opportunity, it will be time well spent.

Complex Waves

In our daily lives we rarely hear pure sine waves, but they form the primary building blocks as well as a conceptual framework for all that we do hear. Complex sounds come from complex vibrations. Let's go back to the pendulums to understand this. Again, if it's inconvenient to actually perform this experiment, visualize it carefully in your mind. Take three pendulums, each significantly lighter than the preceding one, with string lengths of, say, four feet, two feet and one foot. Each by itself will naturally swing at a different frequency. Now, leave Pendulum #1 on the hook in the doorway, then tie the string from Pendulum #2 to the weight of pendulum #1, and the string from #3 to #2 to make a chain, large down to small. You have three pendulums, each with a different natural frequency, piggy-backed one upon the other. Pull back the small bottom weight and let 'er go (see fig. 2-3). Focus on the movement of that smallest weight. Its arc is no longer the smooth sine motion, at any of the frequencies, but a more complex vibration, a combination of the three. At any given instant one of the weights may be pulling forward in its arc, working either with or against the others, to make the smallest weight dance and dart as it swings along the larger path of the big weight.

Figure 2-3



Three Pendulums

It seems to me that many carnival thrill rides use the same principle, by means of the circular cousins of simple harmonic motion: You (not I…*ever*…) sit in the cart of a Tilt-a-Whirl, Octopus, Zipper, or any of those God-awful *big* rides and find yourself pushed, pulled, pulled harder, slowed down for a second, then absolutely jerked out of your body in a complex series of direction changes that is (evidently) fun. How do the ride designers come up with this seeming mayhem? Spend a half-hour looking at the rides instead of riding them. They put the cart and rider into a mix of circular motions—sometimes in three dimensions—of different diameters, going at different speeds. A very complex ride results from a group of simple circular motions, piggy-backed one on another. What's more, the ride isn't really chaotic, but flows according to a predictable, logical combination of forces. And periodically the same combination of swerves and jerks is repeated, just as the overall motion of our three pendulums repeats itself.

One other thing: if you were to able to describe the ride you might say, "I went this way, then I sped up, then turned really fast and went that way, then I went over there but more slowly, then I went around upside down, then…" You might have been most interested in where you were at any instant, because that would detail your journey in time, or the "shape" of your movement from beginning to end. The ride designers, on the other hand would be more interested in the circle sizes and speeds, and directions of all the individual movements that work together to make up the ride, because the key to controlling your body movement lies in controlling the nature of the mechanical building blocks that contribute to it. Both ways of describing the ride have their purpose: by its shape in time (which is the final result), and by its building blocks and their characteristics (the means by which to analyze and control it). The designers know the building blocks, and when they need to build the Next Big Thrill, they tweak their circle-motion combinations for maximum effect, without setting up forces that might tear the thing apart.

Back to complex waves. It turns out that the sine waves we hear can be combined to make complex waves (and complex sounds) just as the three pendulums or circular combinations on the Tilt-a-Whirl generate complex motions. What's more, our ears have the wonderful ability to sense any organization or logic in the combination. If you have the means to do so, generate a 400 Hz sine wave and play it through speakers or headphones. You will hear a very pure, colorless, perfect but kind of dull sound (no, I did not say earlier that a flute is a *pure* sine wave). The pitch is easy to define or sing with (in this case, near the G above middle C on a musical instrument). Now change the frequency to 800 Hz. If you have conventional music experience you will immediately recognize a relationship between the tones. The second tone is a musical **octave** above the first. Our ears and brains recognize the mathematical ratio of 2 to 1. A sine wave sounds an octave higher when its frequency is doubled.

If twice the frequency is recognized as an octave higher, what about three times the frequency? Another octave? No, another octave would require four times the original (doubling it two times = four times). Our ear can also recognize the frequency relationship of 3 to 1 or 3 to 2. 800 Hz sounds an octave higher, and 1200 Hz sounds what is termed a musical fifth above that. Music theory is beyond the scope of this book, but as it turns out, the intervals in the major scale and many other pitch collections in music of Western and many other cultures are based on mathematical relationships of frequencies like these. Even in those cultures using other scales, the simplest ratios fit together. Our ears do the math for us, the frequencies fit together well and we are aesthetically drawn to the sound combinations.

If we play three sine waves of 400, 800, and 1200 Hz together won't they just make a chord of sine waves, instead of some single mystical complex sound that is sort of like a carnival ride or something? Well, yes and no. The trick is to lower the amplitude of the higher frequency sine waves (i.e., make them quieter) until they "melt" into the lowest one in our ears. At some point we stop hearing the individual sounds and they become one, a sound with the pitch of the lowest sine wave, but some extra quality, some tone color.

If you actually perform this experiment you will get a sound like a cheesy electric organ note, and that's essentially how they work. A pipe organ works by controlling the flow of air in a group of pipes. All things being equal, a four-foot-long pipe will produce a wave that is one octave higher than an eight-foot-long pipe (big stuff = low frequencies; little stuff = you-know-what). The organist makes a complex sound wave by using stops (mechanical or electric switches) to send air through varying combinations of pipe lengths, in turn producing complex waves in predictable mathematical relationships. The key to building (or analyzing, or controlling) any complex repeating vibration or wave is to understand its particular recipe for the frequency and amplitude of its component sine waves. A Hammond electric organ works in similar fashion: pulling the various tone bars (labeled 16, 8, 4, 2 2/3 etc.) chooses frequency ratios, and the length to which they are pulled determines amplitudes.

The Big Concept we are learning here is that complex sounds are made from simple building blocks. The Big Therefore is that if we can learn to work with the building blocks, we can control complex sounds in powerful ways.

> In the early 19th century Jean Baptiste Joseph Fourier successfully proved an earlier theorem stating that any complex periodic (-ally repeating) wave can be analyzed as the sum of a combination of sine waves of varying frequency, amplitude and phase (we'll get to phase shortly). Modern computers make this **Fourier Analysis** practical, and if you've run across the phrase **Fast Fourier Transform (FFT)**, it essentially means a quick and dirty—but useful—breaking down of a complex wave into its component sine waves.

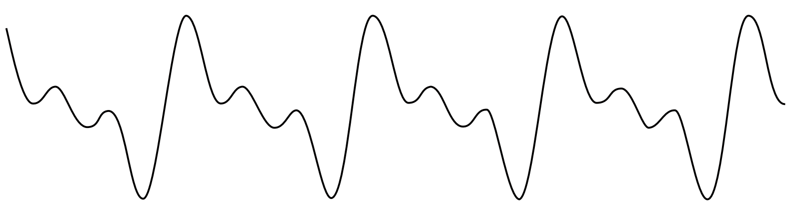
At this point we need to add a few more common and important terms to our vocabulary. We're already familiar with sine wave, frequency, amplitude, Hertz, and I just snuck in 'periodic' in the preceding paragraph. We've been concerned with what are termed **periodic waves**: waves produced by a vibration that periodically repeats itself, cycling over and over. Sine waves are periodic; the complex waves we're dealing with so far are periodic.

In a complex wave, the lowest frequency sine wave in our example is called the **fundamental**. The higher sine waves are called **partials**. So far, all the partials have been simple multiples ('integral multiples', in math terms) of the fundamental. 800 Hz is 2 times the fundamental of 400 Hz; 1200 Hz is 3 times the fundamental. When partials are integral multiples like this we give them a specific label: harmonic partials, or **harmonics**. Let's try out these new terms in a context:

> "When listening to a periodic, pitched wave such as comes from an organ, our ears and brain do the math, and we sense the ratio of harmonic partials to the fundamental. The pitch of the fundamental is reinforced, but the nature or tone color of the total sound becomes more complex than that of the fundamental alone."

Recall that we could trace a tangible representation of the shape of a sine wave on the blackboard, giving a smoothly curved squiggle (fig.2-2). Recall that the movement of three piggy-backed pendulums was more jerky. If we could plot the shape of these motions on the blackboard, they would have a more complex, but still repeating shape as shown in figure 2-4. We begin to understand that there are two ways to describe waves: by defining the shape of their motion over time, and by defining their components—just as the Tilt-a-Whirl ride can be described by each movement and direction, moment to moment, and also by the combination of the circular motions used to generate it. The two technical methods by which we describe sounds are thus 1) by their **waveshape** (over time) and 2) the combinations of building blocks from the entire spectrum of frequencies, sometimes termed **frequency spectrum**, or **spectral content**. Each method has its purpose and place in the sound arts.

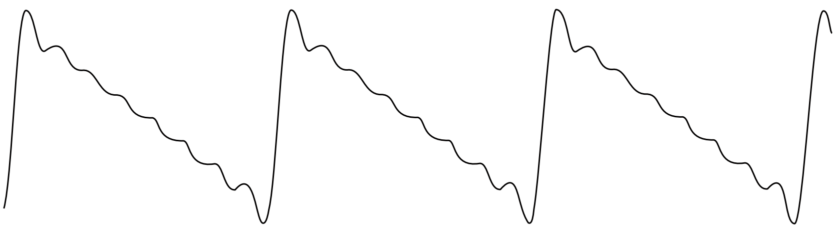
Figure 2-4



Three Sine Waves"Piggybacked"

You may have encountered a specific *waveshape* called 'sawtooth' (because when drawn it looks like one (fig. 2-5). The *spectral components* of a **sawtooth wave** are a fundamental sine wave, plus every harmonic partial above it in frequency. In other words, if the fundamental is at 200 Hz, then there are partials present at 400, 600, 800, 1000, 1.2 kHz, and so on. (Again, they are all termed 'harmonic' because they are integral multiples of the fundamental--2 times, 3 times, 4 times the fundamental frequency etc.) Also, each partial in a sawtooth wave has a lower amplitude than the one below it, until they shrink to insignificance.

Figure 2-5



Sawtooth Wave

So, we have a particular waveshape (sawtooth), built with a particular recipe of building blocks or spectral components (all harmonic partials, decreasing in amplitude), and it happens to make a particular sound, a very clearly pitched sound with a 'reedy' or 'buzzy' tone color; something like an oboe or violin, or one of those "Saw-…" presets on your digital keyboard. Sawtooth waves came to be very common in electronic sound art in the days of analog synthesis, because it is relatively easy to generate a sawtooth wave with electronic circuits. At some point, you may encounter a synthesis procedure called a "resonant filter sweep". If you sweep a resonant filter slowly over a sawtooth wave, you can hear each harmonic partial individually. (If you have the opportunity, try it—or have someone do it for you.) The first 16 harmonics are called the **harmonic series**, which sounds like the broken notes of a major chord (harmony!) and then a major scale as you go higher (sorry, music theory again…). The harmonic series also impacts everything from the notes available on a bugle to one reason that loudspeakers sound different in different rooms. Once again: the harmonics of any tone are partials that are integral multiples of the frequency of that tone.

You may be aware of other common waveshapes stemming from the analog days such as square waves, triangle waves and pulse waves. Each has a particular recipe of spectral components (generally harmonic partials, again because of the electronic circuits used at that time), and each has a distinctive tone color.

Let's add another term here: The common term for tone color in sound art is **timbre** (pronounced "tamber"). A very subjective term, "timbre" recognizes the differences in two sounds having the same pitch. A cello and trombone each can play middle C, but with different timbres. Or, think about "the velvety timbre of my new synth pad", or "the fat timbre of the old Oberheim 8 synth in my basement," etc.

Here's The Big Concept again: *complex sounds are composed of simple building blocks. Therefore, if you can control or alter the building blocks, you can control or alter the timbre of a sound.*

Up to this point, we have been looking exclusively at harmonic partials. Harmonics reinforce the fundamental and its pitch, but their complexity makes for beautiful, interesting sounds. We can see that the trick for the builders of trumpets and violins and guitars over the years has been to accentuate the harmonic partials in pleasing amplitude recipes; this creates beautiful, clear-pitched sounds. However, in the normal physical world, things don't necessarily vibrate in such an orderly fashion. A **non-harmonic partial** is a sine wave that doesn't have a simple integral mathematical relationship to the fundamental. For a fundamental of, say, 350 Hz, some non-harmonic partials might vibrate at 611 Hz, 1391 Hz, 2.483 kHz etc. In these sounds, the fundamental isn't reinforced in our ear, even though we still have sensation of pitch or pitches. Non-harmonic partials tend to give a complex wave a "clangy" or bell-like tone, depending upon their density and amplitudes.

It's difficult to make (analog) electronic circuits generate complex non-harmonic partials, which is why analog synthesizers had trouble simulating bells.

Non-harmonic partials are a vital part of the spice of any sound art, whether occurring naturally, or generated with technology.

Noise

We've discussed periodic waves: repeating vibration, sine waves, steady frequency, combining to make complex waves; either reinforcing the fundamental constant pitch or clanging against it. A great deal of what we hear in the world comes from the combination of simple harmonic motions, but it is written nowhere in natural law that *every* motion be based on sine motion. Sometimes things jerk around or back and forth without repeating, and with neither rhyme nor reason. Some motions are just random or chaotic. In sound building and analysis, random fluctuations are called **noise**. When our ear can recognize no order in a sound, it can discern no specific frequencies, so pure random noise has no pitch to it. Noise is the other component of the sounds we hear. Make your voice "hisssssssssssss" and you are generating noise. (Notice however, that hizzzzzzzzzzzzz—with a *z*—sneaks a pitched sine wave or two in there). A long rumble of thunder is also noise, even though it sounds completely different. This can be understood though two concepts:

1. A wave motion can have completely random features, yet still fall within a defined range. To better understand this, get a rat. A very energetic, but irrational, illogical rat. Now put him in a building and close all the entrances. Assuming there is neither food nor water (nor a second, sexy rat) in the building, after a day or so, at any given moment the rat's location is completely random. He could be anywhere in the building. Now, let's say you find the rat in Room 231 and close the door. After he's had time to scurry around a bit, the rat's position at any moment is still completely random, but now it has been constrained to a smaller area within the building. Randomness, but within a smaller portion of the entire spectrum of possibilities in the whole building. If you plop a cardboard box over him, he's really ticked off and bouncing off the walls in a small area, but his position is still random, unless you hold him perfectly still. Something can have a random characteristic even if constrained to less than the total of all possibilities.

2. The second concept took me awhile to fully grasp: when there are random fluctuations in an object or wave, even though they don't repeat enough to be able to discern a frequency of their repetition, each motion can be understood as being a *portion* of a complete cycle, which would have a frequency if it were repeated.

> Imagine that you filmed only portions of the swings of many pendulums, each swinging at a different frequency. If you were to cut the film into short segments, throw them on the floor and splice them back together, you would have a film of random motion, even though each pendulum had a specific frequency.

The upshot of these two concepts is that noise—random fluctuations—can be constrained to particular areas of the entire frequency spectrum (20-20,000 Hz in our case). When you "hisssssssssssssss", you are creating noise that is predominantly high frequency, while thunder rumbles at low frequency. The varying areas of the spectrum are called **noise bands**, often described as some number of octaves wide and centered around a frequency. A one-octave noise band centered on 1000 Hz will have a particular sound—random and with no pitch, but statistically predictable and repeatable over a period of time. Actually, total randomness in anything soon stops being an adventure and becomes old hat, sort of like a dull sine wave, except you can't sing along.

> Be aware that noise has a second definition: noise can also be "that which I don't want to hear right now". If I'm concentrating on hearing your snare drum recital (random noise), then the trumpet playing in the other room (lots of sine waves) might bother me to the point of yelling, "Can you stop that noise over there so I can hear these musical random fluctuations!" With luck, the musicians would understand the definition of the term "noise" as I mean it here, and the appropriate player would respond with a change in behavior.

Envelopes

We've now glanced at the concept of complex timbre, as described by waveshape and/or spectral content. This assumes that the sound just keeps going on and on and on. Never changing. In the real world, however, things change. The term we use for the manner in which a sound changes over time is **envelope**. The most common use of the term relates to amplitude (loudness) envelopes, although we will encounter others shortly.

The most common, simplified description of amplitude envelopes again comes from analog synthesis. After a sound begins, it reaches its highest level in a certain amount of time—the **attack** time. Then it immediately begins to lower in amplitude to a secondary point according to its **decay** time. The next parameter is the **sustain** level (*not* time): the amplitude at which a note is held until turned off (while the key is held down on a keyboard, for instance). Finally, there is the time it takes for the sound to die away after the energy causing the vibration is turned off, the **release** time. Attack, Decay, Sustain, and Release, or **ADSR**s comprised the four stages of the original envelope generators in analog synthesizers, and the term remains in common use. That's fine for us for now, but it's important to remember that complex waves from physical vibrations in the real world can have many more stages of ups and downs than the four in a classic ADSR.

Although it's generally more stable in the physical world, the *frequency* of a wave as well as its amplitude can change over time. Whistle hard through your fingers and the pitch probably changes from beginning to end. So does an air-driven fire siren. Even a trumpet note played by an expert will have a (very, very subtle) frequency envelope.

As it turns out, complex envelopes can be present in waves because each partial or noise band can be understood to have its own amplitude and/or frequency envelope. If you actually constructed the three-pendulum experiment, you probably noticed that before long the complex darting gave way to a more simple swinging, at the frequency of the largest weight. The amplitude envelope of the small, high frequency weight was shorter, which is usually the case in the physical world, because small masses (begetting high frequencies) tend to hold less energy and die away sooner.

Translate this concept to sound and you'll see that the differing amplitude and frequency envelopes of the building blocks (sine waves or noise bands) of a complex wave make for changes in the specific recipe of the wave over time, which in turn changes the timbre over time. This is the anatomy of what is known as a timbre envelope; it's related to 'filter envelopes' you may have encountered in some sound devices.

> Find an easy pitch for singing a long tone and change smoothly from vowel to vowel: "eeee-aayy-aahh-oohh-oooo". As you sang on one pitch, you changed the recipe of the various partials by the movement of your tongue and mouth, changing the amplitude envelope of each, giving your sung note a timbre envelope: a change in timbre (tone color) over time.

We differentiate sounds nearly as much by their envelopes as by their timbre recipes (made up of fundamentals, partials, and noise). For example, take a trumpet and an oboe, or a snare drum and some frying eggs: within each pair, the sounds are actually distinguished more by their envelopes than by their spectral content.

> I didn't really live a fast life as a 5-year old, and I can remember many times sitting alone at the piano in our living room, fascinated by a discovery: I'd pound about 30 piano keys with my forearms to make a crashing sound, put down the sustain pedal to keep it going, then make a C major chord with my fingers and let off the pedal. The remaining C chord notes sounded as though they were coming from an organ rather than a piano. What I was really doing was masking the distinctive attack of the piano envelope with the noisy bang of the many keys. The actual timbre recipe, sans envelope, sounded like a reed organ.

We now have understanding (if not control) of all the components of all sounds. Complex waves are composed of simple building blocks: sine waves (fundamentals, harmonic and non-harmonic partials) and noise bands. The more harmonic partials in a complex wave, the more completely our ear can discern the math relationships and the more clearly the pitch of the fundamental is reinforced. The more non-harmonic partials, the more the sense of pitch is blurred to give a 'clangy' or bell-like sound. As our ear loses capability to discern any periodicity (any repeating organization from one or more sine waves) it begins to sound random within certain frequency ranges—it becomes noise instead of pitch. These things are predictable, logical, and potentially controllable, but can be very complex in the physical world, and what makes them still more complex is that all of this changes over time. Each building block (sine wave) can have its own amplitude and/or frequency envelope, resulting in a complex timbre envelope. This can be analyzed as a changing waveshape, or as the evolving spectral content of a wave, depending upon our particular purpose in high-technology sound art.

We have also brought to one place (or learned for the first time), a number of terms that are encountered continually in modern sound art; terms which will also help define many more terms and concepts yet to come. We have encountered sine waves, frequency, amplitude, CPS, Hertz (Hz), fundamentals, partials (harmonic and non-), waveshape, spectral content, periodic, octave, Fourier analysis, FFT, timbre, noise, noise bands, envelopes, and ADSRs. Strangely, we haven't really defined sound itself yet (next chapter), and we've referred to a few terms such as analog that will return later, naked and exposed.

Through these basic elements, all actual sounds are made. A low note on a grand piano begins with a knock (noise) with a short envelope, then continues into a complex mix of many partials, the non-harmonic type with shorter decay times soon dwindling to nothing, the higher harmonics defining the timbre and reinforcing the pitch, then dying away, one by one, until the final remnant is nearly a pure sine wave at the fundamental frequency. This is essentially the entire length of the string vibrating, just as the three pendulums' darting motion gradually gives way to the motion of the largest mass, which has the most energy.

Up to now your work in sound and music art may have been at an earlier level on the Technology Curve (although not a lesser thing, remember). You may have knowledge of the nature of sound in your intuition and muscle memory instead of your intellectual understanding. You may coax beautiful timbres and expressive envelopes out of your fingers on the guitar or piano; or your lungs, throat, and lips on the sax or trumpet. If you're an arranger you have also developed some procedural skill, and you understand some complex, pre-designed recipes and envelopes with the names flute, timbale, clavinet, ride cymbal, etc. You've learned how to make more complex waves by combining them in ways that your ear remembers will work.

However, as you move further along the Curve, the means of controlling waves transfers from fingers and lips to buttons and switches and mice and keyboards and controllers… to worlds where you have far more power, and far more choices. At this point you may be cutting a new path for yourself: beginning to comprehend sound waves with your intellect instead of your ear, grasping some new concepts as well as clear terms for old ones. The good news is that eventually—if you build the solid foundation—the conscious thinking and studying become second nature. You will rediscover an intuitive, but now more powerful control of these new tools at the top of the Technology Curve, and ride the Curve even as it continues to climb higher.