Performance Media Industries, Ltd.

What's All This About Directivity?

9-10/2004

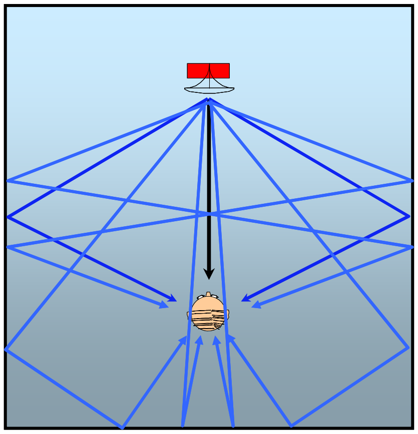
by A. Grimani & C. Walton

What If

It's 1:47 AM and you're staring at your computer screen. Staring back at you are two candidates for LCR speakers in the new dream home theater you are working on so diligently. You're faced with the dilemma of which speaker to use. Your favorite little 2-way worked great in the old room, but it will be overwhelmed in the incredibly massive new one. The two speakers on your screen now are identically-priced 3-ways that would both do the trick output-wise, but you have no idea which one to pick. The first is a traditional 3-way with a tweeter on top of a midrange on top of a woofer. The second is a vertical "tapered array" with a tweeter flanked by two midranges and then two woofers. Slowly you click on one, then shake your head, hit the back button, and click on the other one. It doesn't really strike you as being substantially better, though. You can't decide which one will most likely satisfy your discriminating taste… But you *must* decide, and with a little understanding of a simple thing called *directivity*, you *can* decide.

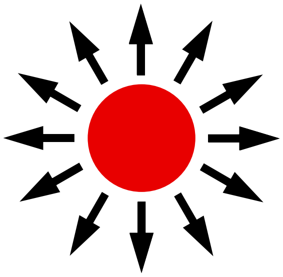
What is Directivity?

All speakers have directivity, but not all speakers have the same directivity. A speaker's directivity can make it an excellent choice for one application, but an awful choice for another. In simplest terms, directivity is the ratio between the amount of sound a speaker radiates on the listening axis versus the amount of sound it radiates in all other directions. It turns out that speaker directivity is one of the most important things affecting an audio system's sound quality, because you usually hear as much reflected sound energy from a room as direct sound from the speakers. You really want that sound returned from the room to work well with the direct sound character of the speaker.



At the listening position you listen to as much reflected sound as direct! The room plays an important part in the sound you hear, and speaker directivity affects those reflected sounds.

To accurately discuss directivity issues I would need to bring in wave theory, but that's just too tedious. Instead I will resort to intuitive descriptions and analogies. Is everyone OK with that?!



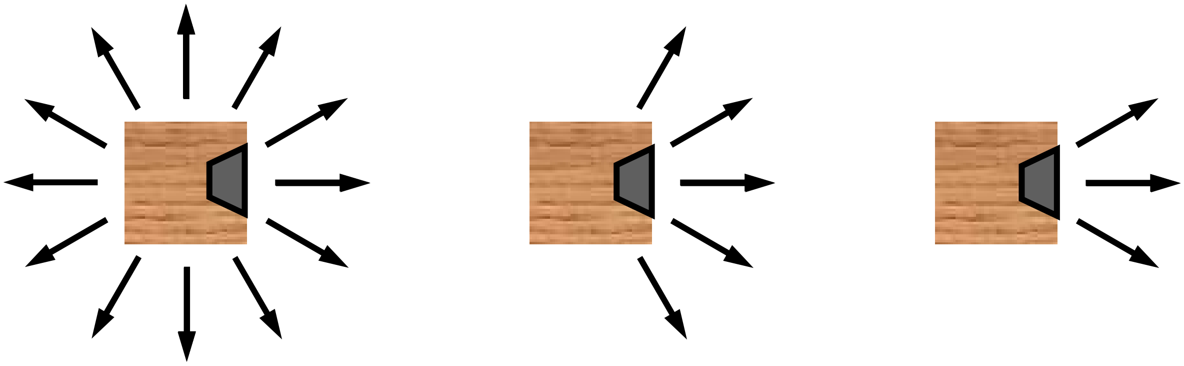
An Idealized Speaker:
The Pulsating Sphere
- Flat axial response
- Radiates evenly in all directions
- Flat sound power response

Audio academia uses a delightful little concept called a Pulsating Sphere to explain directivity. A Pulsating Sphere is a theoretical (meaning it doesn't really exist) device that is infinitely small and radiates all audible frequencies in all directions. Its listening axis, if one could be determined, gets no more or less sound than any other axis. As you can imagine, if two of these Pulsating Spheres could be put in a small listening room, they would sound unbelievably spacious, but there would little or no imaging because the room would be completely awash with sound energy.

Now imagine what would happen if a Pulsating Sphere were mounted in the front of a speaker cabinet like a transducer. At low frequencies, the sound waves emitted by the Sphere are very long and would wrap around the cabinet, filling the room as if the cabinet weren't even there. As the waves increase in frequency, they become shorter compared to the size of the cabinet and can't wrap around it as much. The effect is a gradual focusing of the sound into a hemispherical radiation pattern directly in front of the cabinet face where the Sphere is mounted.

A Pulsating Sphere in a cabinet would have a perfectly hemispherical radiation pattern above the frequency where the cabinet baffles the sound waves. But we don't have Pulsating Spheres in our cabinets; we have transducers. A transducer has a given size, measurable in inches, centimeters, etc. It will behave just like a Pulsating Sphere over some of the frequency range. However, unlike an infinitely-small Pulsating Sphere, transducers reach a point where the length of the sound waves they are trying to produce becomes small compared to the transducer diaphragm area. Above this point, the diaphragm itself focuses the sound – much like the mirror in a flashlight focuses light from the bulb forward through the lens. As frequency increases, the sound waves get more and more focused until they reach a point where all sound is radiated on a very tight beam.

A Real Speaker: Variable Dispersion

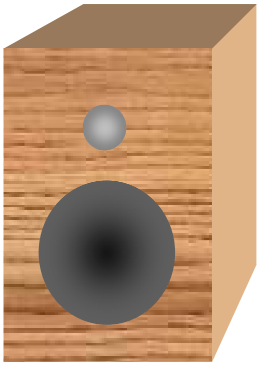


Low Frequency ~ 100 Hz
Spherical Radiation

Mid Frequency ~ 1 kHz
Hemispherical Radiation

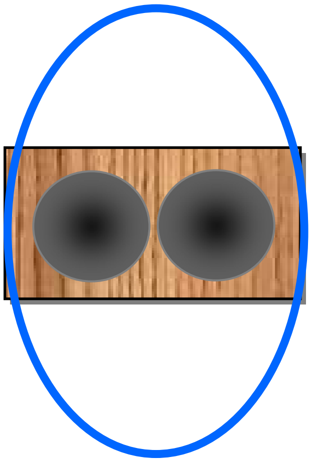
High Frequency ~ 10 kHz
Beaming Radiation

Because of this beaming problem, multiple transducers are used in full range speakers. The larger units play the low frequencies where large volumes of air need to be displaced but where beaming is not a problem. At high frequencies, smaller transducers are used to avoid beaming. I know most people think that tweeters are small so that they can move fast, and indeed that is one good reason. But know that a 6 ½" transducer can usually make it up to 10 kHz without too much trouble other than major beaming effects. So the main purpose of a small tweeter is to produce sound waves with wide dispersion that cover all the listeners evenly and energize the reverberant field of the listening room with about the same sound character as the direct path to the listener. It sounds better that way!



A Real Speaker: Cones and Domes
- Flat axial response
- Radiation depends on frequency
- Sound power response tilted down

When two transducers are placed side-by-side in a cabinet, some interesting acoustic interferences develop between them. Above some frequency, the pair of transducers create a beaming effect of their own, with the side-by-side pair acting pretty much like one large, oval transducer. As a result, the sound is focused into a narrower radiation pattern in one axis than the other, with the wide part of the oval producing a narrower beam of sound. This appears counter-intuitive at first, but think back to the flashlight reflector analogy. If you cut off the top and bottom quarters of the mirror, the light from the bulb will only be focused from the sides and will spill out over the top and bottom. By way of comparison, if the two transducers are stacked horizontally, the oval radiation pattern will be vertical.



Vertical Oval Sound
Radiation from Dual
Horizontal Transducers

These basic principles mix in different ways to determine the directivity of a speaker. Depending on the cabinet dimensions, transducer size, and transducer arrangement, the directivity of speaker can vary dramatically. The sound you hear from a speaker on the direct axis and the soundfield that fills the room will depend hugely on the speaker's directivity pattern – probably a lot more than you ever imagined!

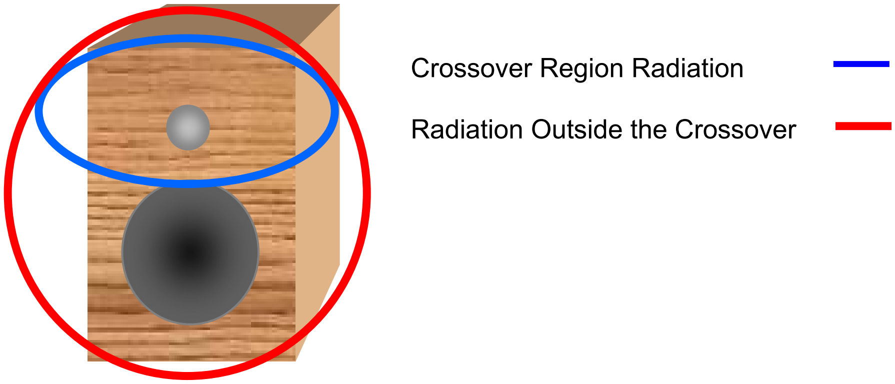
Examples of Directivity

Let's take a look at some common types of speakers and their typical directivity characteristics.

The first victim will be the world's most beloved design: a traditional 2-way with a tweeter on top of a woofer. The woofer radiates spherically at low frequencies because the waves are longer than the cabinet dimensions. At lower-mid frequencies, the cabinet will begin to have its effect, so the radiation pattern is hemispherical. The woofer will start to beam at upper-mid frequencies, and the radiation pattern narrows. When the woofer hands off to the tweeter, which isn't beaming, the radiation pattern goes back to hemispherical until the tweeter begins to beam. This usually occurs near the top of the audible range.

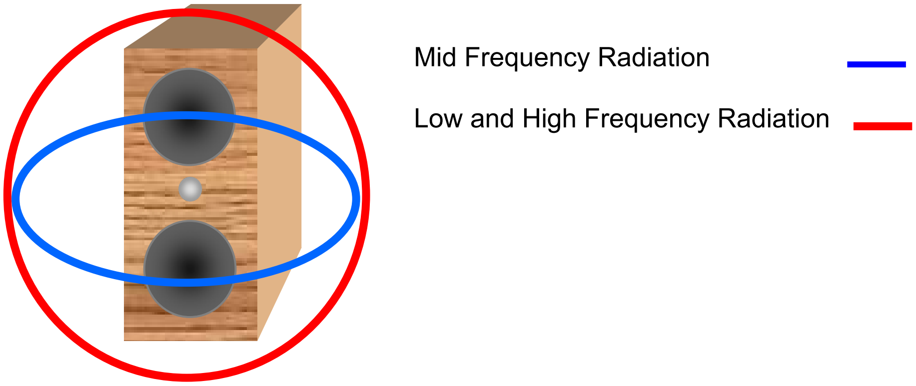
During the woofer-tweeter hand-off, which is known as the crossover region, things can get sticky because the woofer and tweeter are playing the same sounds at similar levels. If the woofer and tweeter are exactly in phase through the crossover region, the radiation pattern will be a horizontal oval. However, due to crossover-induced phase shifts, the timing of the woofer and tweeter will usually be off. This can cause the oval crossover region radiation pattern to shift its vertical axis, pointing either up or down. At the crossover frequency there will be areas of acoustic interference between the woofer and the tweeter that are called *crossover lobes*. In one direction there could be destructive interference cancellations, and in the other there could be additions of sound. All in all, the frequency response in the crossover lobes is typically rather rough.

Sound Radiation in the Crossover Region: The main lobe can be tilted up or down from the speaker.



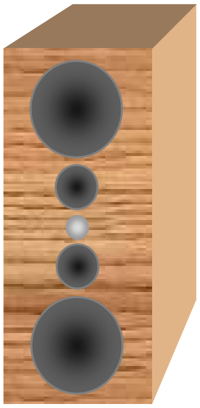
Traditional 3-way speakers (tweeter on top of midrange on top of woofer) and 4-way speakers have radiation patterns and crossover lobes similar to the ones for a 2-way, but between every pair of transducers.

Another type of speaker is the 2-way woofer-tweeter-woofer arrangement commonly referred to as a D'Appolito array. Although it is a 2-way speaker, its radiation pattern is very different from the traditional single-woofer 2-way in the mid frequencies. The dual woofers focus the midrange radiation patterns into ovals instead of hemispheres. This fact will come into play significantly later on when we discuss orientation of D'Appolito arrays.



A D'Appolito array speaker has a narrowing radiation in the mid frequencies.

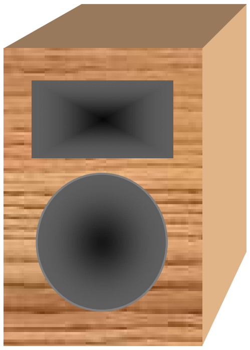
The 3-way, 5-driver woofer-midrange-tweeter-midrange-woofer stack, also known as a tapered array, is like a 2-way D'Appolito with an oval radiation pattern that extends both lower and higher in frequency.



The 3-way, 5-driver tapered array has a not-so-obvious radiation pattern that is similar to a D'Appolito array.

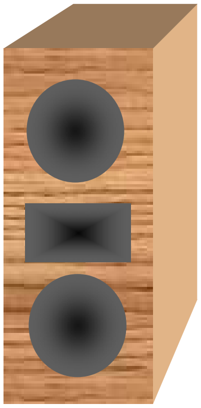
Keep in mind that, like traditional 2-ways, D'Appolito and tapered arrays still have crossovers lobes, but they are perpendicular to the cabinet face and usually less problematic because there are three devices working in unison in the crossover region.

Next up are 2, 3, or 4-way speakers with horn-loaded tweeters. They behave just like traditional speakers until the woofer(s) hand off to the tweeter. The horn acts like the mirror around a flashlight bulb, focusing the sound of the tweeter in a particular radiation pattern that is determined by the shape of the horn and doesn't vary with frequency for the better models.



The 2-way speaker with a horn-loaded tweeter has an obvious high frequency radiation pattern controlled by the horn.

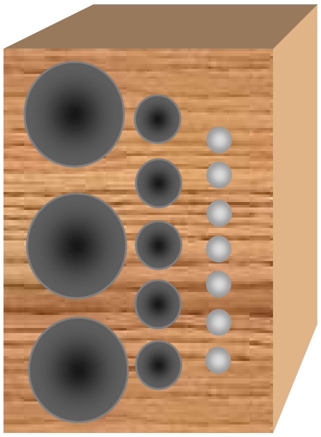
D'Appolito arrays can have horn-loaded tweeters, too. If it's designed properly, a D'Appolito array with a horn-loaded tweeter can have focused dispersion from very high frequencies all the way down to low frequencies.



A D'Appolito array with a horn-loaded tweeter has pattern control to lower frequencies.

In designing any horn-loaded speaker, it's important to set the crossover frequency above the point where the horn ceases to be able to focus the sound of the tweeter. Any horn will *unload* and turn hemispherical when the length of the sound waves being played through it becomes large compared to the dimensions of the horn's mouth. (Recall the discussion of low frequencies wrapping around a speaker cabinet.)

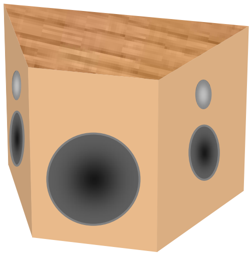
There are also speakers called line arrays that have many woofers, mids, and tweeters stacked vertically. The interaction of these groups of woofers and tweeters creates an even further flattening of the radiation pattern, almost resulting in a straight beam typically as wide as the array is long. This can be great as long as you listen within the radiation beam. There are virtually no reflected sounds off the floor or the ceiling, which makes for a huge and very solid soundfield character.



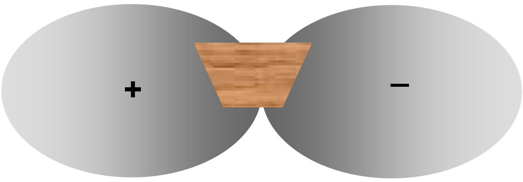
The line array is another speaker with not-so-obvious directivity focus. It provides pattern control over a broad range of frequencies.

Planar radiators (electrostatics, magnetics, and ribbons) come next. They behave very much like the straight arrays we just discussed, beaming straight in front of them with virtually no dispersion to the sides or top and bottom of the drive area. The actual radiation pattern of a planar is determined by the size, shape, and curve of the diaphragm rather than interaction between transducers. Additionally, planar radiators like electrostatics with no cabinets have an interesting figure-eight radiation pattern. It is caused by the opposite-polarity front and back waves of the diaphragm meeting to the sides of the speaker and canceling to form a perfect null. Such speakers are called dipoles.

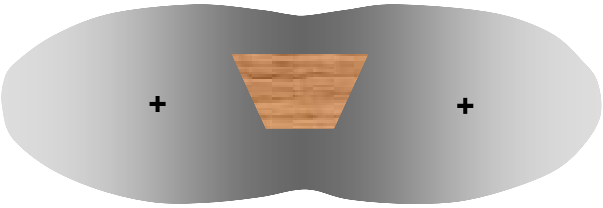
Lastly, we have transducer-based speakers with woofers and tweeters in both the fronts and backs of the cabinets. They are a combination of everything we have covered up to this point. They can be wide open, or focused D'Appolito arrays. They have crossover lobes, and they can be dipoles if the front- and rear-firing transducers are wired in opposing polarities. They can also be bipoles if the front- and rear-firing transducers are wired in the same polarity.



A Bidirectional Speaker



Radiation of a Bidirectional Dipole Speaker: Deep null and very diffuse when listened to in the null



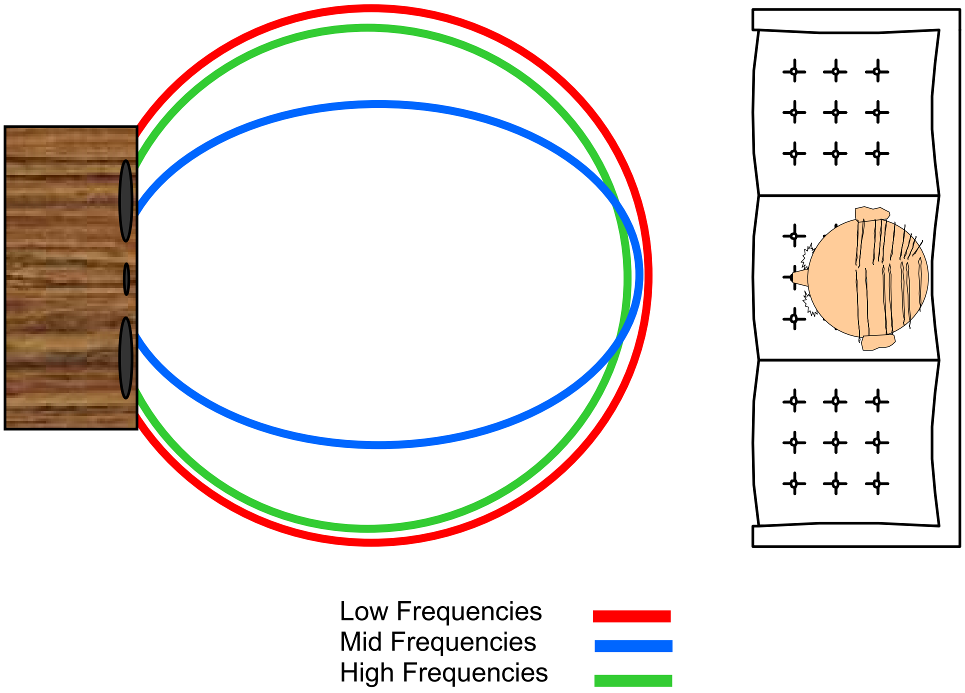
Radiation of a Bidirectional Bipole Speaker: Broader waistline and more directionality

Applications of Directivity

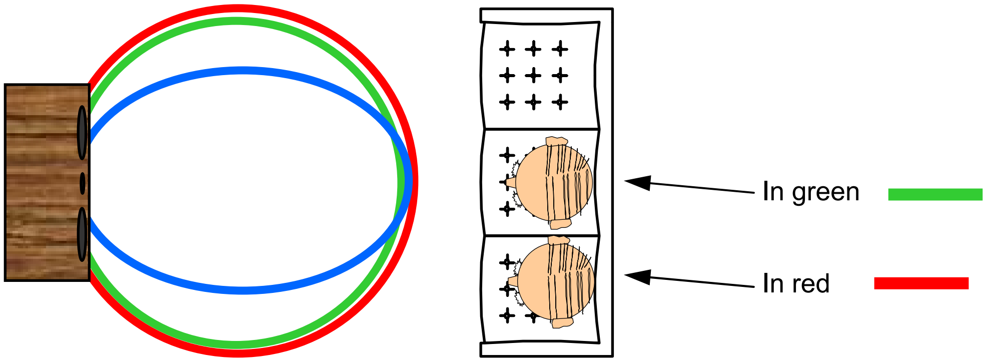
Now for the good stuff: How you use directivity to your advantage when you're designing a sound system.

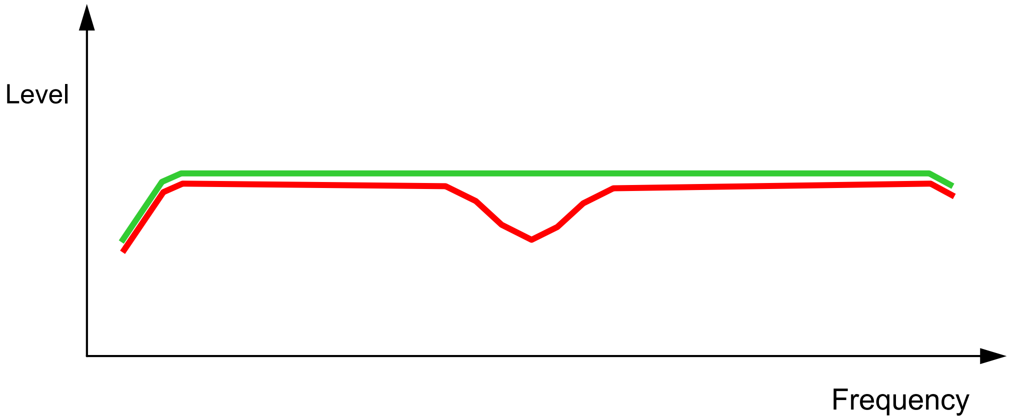
First, let's take a look at the concept of using a 2-way D'Appolito array as a center speaker. Continuing from the previous section, a D'Appolito array will have an oval radiation pattern in the midrange because of the dual woofers. The orientation of the oval is perpendicular to the woofers, so if the array is horizontal, then the oval is vertical. To the left and right of the vertical oval radiation pattern there will be a loss of sound level. This is in fact an *extremely* bad arrangement for a center speaker! A listener who is precisely in front of the speaker will hear good sound, but a person to that listener's left or right is going to be outside of the vertical oval mid frequency radiation pattern. The sound will be inarticulate and lack in presence. That's a bad thing for a speaker who's role is to precisely reproduce dialog and action sounds central to the soundfield!

Radiation Pattern of Traditional Center Speakers: Low, Mid, and High Frequencies



The frequency response of a traditional center speaker is shown in two locations: directly in front of the speaker and to the side of the speaker.

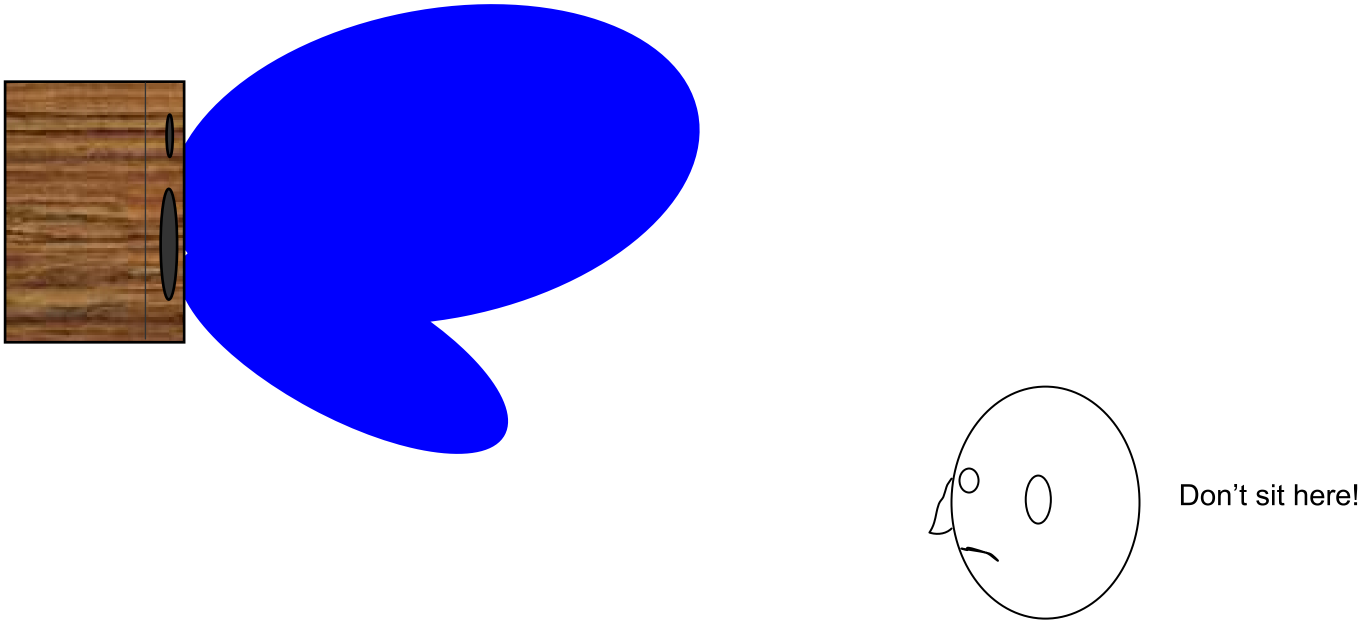




What to do? Simply turn the D’Appolito array vertically and aim it at the listeners! Every listener is within the oval radiation pattern, which is now horizontal.

Second, directivity can tell us how to orient a traditional 2-way speaker if it must be placed significantly above or below listeners and cannot be aimed. As we discussed, there will be crossover lobes firing away from the speaker at angles that are typically diagonal to the front of the speaker cabinet. That means listeners who are located at a diagonal from the cabinet face are probably in a crossover lobe. Usually, the frequency response in one of the two lobes is better than the other. One direction could actually have sound cancellations. The speaker should be oriented with the better lobe firing at the listeners. That's much more important than merely trying to keep the tweeters close to seated ear height. Traditional 3- and 4-way speakers can be oriented using this same principle. In their case, consider primarily the lobe between the tweeter and the midrange, and don't worry about the midrange-woofer lobes.

Radiation Pattern of a 2-way Speaker in the Crossover Region

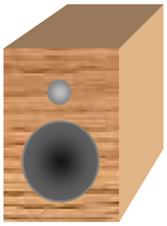


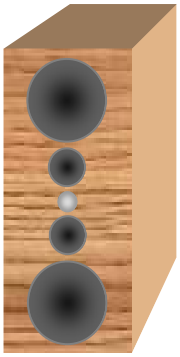
Speaker manufacturers will usually tell you which lobe is better, but there may be times when you don't trust the manufacturer or they aren't available for comment. Regardless, you can determine the better lobe by listening to the speaker playing pink noise and moving your head up and down through the crossover region.

Third, you can use directivity to pick the type of LCR speaker to use in a particular application. Knowing that speakers with higher directivity provide tighter imaging and that speakers with lower directivity provide more sense of envelopment, you have several decisions to make in the process of model selection. Also, it is well-documented in psychoacoustics research reports that ceiling and floor reflections are the most detrimental to imaging accuracy, so speakers with focused vertical dispersion are *always* a good idea in a room with no acoustic treatments on the floor or ceiling. (That's most rooms, folks.) Well, what kind of speaker has focused vertical dispersion? One answer is a 2- or 3-way D'Appolito array.

Say you work really hard to acoustically treat a room. What kind of speaker should go in there? One with highly focused dispersion may sound too sharp and tight, so think about a speaker with broader dispersion. A traditional 2-way might be the best choice. Conversely, in a big, reverberant room where the listeners are far away from the speakers, you should head toward a focused D'Appolito array – particularly one with a horn-loaded tweeter. In the case of a large room, focused dispersion provides two advantages. One is that the speaker doesn't excite as much of the room's reverberant soundfield. The second is that the speaker experiences less sound pressure loss over distance. D'Appolito arrays and horns work very much like a nozzle on a garden hose. Without the nozzle, water pours randomly from the hose. With the nozzle, water is focused in a tighter pattern and projects much further. Sound works the same way.

The traditional 2-way speaker is the magic balance for 2-channel music and for multi-channel sound in a small room. It produces good envelopment and sufficient directional cues at high frequencies.





Multi-channel music and film in a larger room may need more focused front speakers to avoid cacophony.

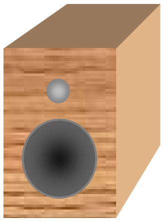
Fourth, directivity can go a long way toward solving the surround speaker conundrum that everyone is endlessly debating these days. Human beings' directional delineation does not remain constant around the head in a 360 degree circle, so surround speakers positioned to the sides and rear of the head should not necessarily have the same directivity as LCR speakers positioned in front of the head.

In a small, treated room, several methods can be employed to reduce the directivity of surround speakers so that they disappear yet form nice, clear images with the LCR speakers. One method is to use a surround speaker with broader dispersion, such as a dipole or bipole.

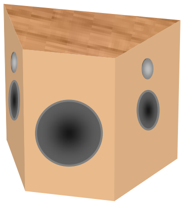
Large rooms naturally enhance the reverberant field of a speaker, so dipoles or bipoles are often unnecessary. Surround speakers can be more directional without becoming distracting and without integrating poorly with the LCR speakers.

Directivity Choices for Surround Speakers

The traditional 2-way speaker is OK in larger rooms. The sound is dominated by reflections from 3 kHz down.



Multi-channel music and film may need more envelopment in smaller rooms to avoid distractions. Use dipoles and bipoles.



And We're Out

The quality of any sound system is really determined by the sum of the speakers and the room. In most rooms, listeners hear more reflected energy from the room than direct energy from the speakers. Thus, a speaker's directivity, the way it radiates sound into the room, is vitally important. If you don't consider it, you'll end up doing something goofy like putting that traditional 3-way rather than the 3-way tapered array in your massive new dream home theater. It's now 2:05 AM. Are you nuts? Go to bed already!

This article is based on a column published by A. Grimani in Residential Systems magazine September and October 2004. Chase Walton contributed to this article.