Basic Speaker Concepts



A Modern Stereo with Classic Speakers

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Chapter 1
What Makes A Good Speaker?

A loudspeaker has a deceptively simple job: convert an electrical signal into sound. Doing that is easy. Doing it accurately is extraordinarily difficult.

Every loudspeaker changes the signal to some degree. Its diaphragms bend. Its cabinet vibrates. Its drivers interact. Sound reflects from its surfaces and from the room. The challenge is not eliminating every imperfection. That is impossible. The challenge is identifying which imperfections matter most and solving them in the right order.

Start With the Driver

A loudspeaker driver should behave as much like a simple piston as possible within the range of frequencies assigned to it.

Real diaphragms are not perfectly rigid. At some frequency, portions of a cone or dome begin moving differently from other portions. This is called breakup. Breakup can create resonances, distortion, stored energy, and changes in the way sound spreads into the room. A crossover network can reduce some of the symptoms, but it cannot make an unsuitable driver suitable.

This is why good loudspeaker design begins with selecting drivers that naturally behave well over the frequencies they are expected to reproduce.

Control Resonance

Strike a bell and it continues ringing after the strike. A loudspeaker should not.

Energy stored in a diaphragm, cabinet, or other structure continues producing sound after the original musical event has changed or stopped. That sound was not present in the electrical signal. The loudspeaker added it.

This can make voices sound colored, obscure fine detail, and make different recordings acquire a suspiciously similar character. A good loudspeaker releases energy when the music tells it to, then stops.

Make the Drivers Work Together

Most loudspeakers use more than one driver because no practical driver reproduces the entire audible range equally well. A woofer handles lower frequencies. A tweeter handles higher frequencies. Some systems add a midrange driver. The difficult part is making several sound sources behave as though they were one. At the crossover between drivers, their outputs overlap. Their relative position, phase, dispersion, and frequency response all affect what reaches the listener. A poorly integrated loudspeaker may sound like bass coming from one place and treble from another. Voices may subtly change character as their frequencies move between drivers. A well-integrated loudspeaker should become difficult to hear as a collection of individual parts. It should simply produce a coherent acoustic event.

Sound Goes Everywhere

Frequency-response graphs are usually measured directly in front of a loudspeaker. Listeners, however, hear much more than that. Sound also travels toward the floor, ceiling, and walls before being reflected back toward the listener. Consequently, the sound a loudspeaker produces away from its central axis is extremely important.

A speaker with excellent response directly in front of it but badly irregular response elsewhere may behave quite differently in a normal room. Good loudspeaker design therefore considers not merely how much sound is produced, but where that sound goes.

Music Happens in Time

Frequency response matters, but music is not a collection of steady test tones. A drum is struck. A string is plucked. A singer begins a syllable. These events happen in time.

The loudspeaker must start, stop, and change rapidly enough to preserve the relationships within the original performance. Stored energy, poorly integrated drivers, and other time-related errors can blur those relationships even when a conventional frequency-response graph looks impressive. This is why a flat graph alone does not define a good loudspeaker.

Distortion Matters

Every loudspeaker produces some distortion. The objective is to keep it sufficiently low that it does not obscure the music. This becomes especially difficult at low frequencies because producing bass requires moving considerable air. As a diaphragm moves farther, its suspension and magnetic system become less linear. Distortion rises. There is no substitute for adequate radiating area, appropriate excursion capability, and sensible engineering.

Measurements and Listening

Measurements are indispensable. They reveal problems, test predictions, and allow one design change to be compared objectively with another. But a measurement is evidence, not a verdict. A loudspeaker ultimately exists to reproduce music. For that reason, a serious design should survive both objective measurement and careful listening against known references. When the two disagree, neither should simply be discarded. The disagreement should be investigated. That is often where something important is learned.

Solve the Right Problems First

Good loudspeaker design is largely a matter of hierarchy. Correct a serious diaphragm resonance before worrying about a tiny frequency-response irregularity. Choose compatible drivers before designing an elaborate crossover to force incompatible ones together. Control stored energy before attempting to disguise its effects with equalization.

Every decision affects the decisions that follow. When the fundamental problems are solved first, the rest of the design becomes easier. When they are not, complexity tends to accumulate as one compromise is used to conceal another.

A good loudspeaker is therefore not defined by exotic materials, an impressive specification, an elaborate crossover, or a fashionable technology. It is defined by something much simpler: It reproduces the musical signal while adding as little of itself as practical.

Chapter 2
What Makes Good Stereo?

Stereo requires two loudspeakers. But two loudspeakers do not necessarily produce good stereo. The purpose of stereophonic reproduction is not merely to put different sounds into the left and right channels. Its purpose is to create a convincing auditory illusion.

Close your eyes in front of a good stereo system, and the loudspeakers themselves should become surprisingly difficult to locate. A singer may appear directly between them. A piano may occupy a believable space to one side. A drum kit may extend across part of the room. Some sounds may appear closer while others seem farther away. None of those sounds actually originate there. Two loudspeakers and the room have persuaded your hearing that they do.

The Phantom Center

The simplest stereo illusion is a sound directly between the loudspeakers. There is no loudspeaker in the center. When the same sound reaches both ears with the appropriate relationships, the brain interprets it as coming from a position between the two actual speakers. This is called a phantom image.

Change those relationships, and the apparent sound can move left or right. A recording engineer uses this phenomenon to construct a stereo panorama containing apparent sound sources distributed between, and sometimes beyond, the loudspeakers. Reproducing those relationships accurately is fundamental to good stereo.

Loudspeakers Must Disappear

A loudspeaker can have excellent tonal balance yet reproduce stereo poorly. One reason is that a multiway loudspeaker contains several physical sound sources. If the woofer and tweeter do not integrate properly, the ear may begin identifying them separately. Instead of hearing one trumpet occupying one position in space, portions of its sound may seem to originate from slightly different locations. The illusion weakens.

For convincing stereo, each loudspeaker should behave as nearly as possible like a single coherent source. The listener should hear the recorded event, not the individual drivers producing it.

Position Matters

Stereo depends upon differences between what reaches the two ears. Consequently, loudspeaker placement matters. The two speakers should normally form a reasonably symmetrical relationship with the listener. Large differences in distance alter arrival times and sound levels. Nearby walls and furniture can also change what each speaker contributes. Perfect symmetry is neither always possible nor always necessary, but gross asymmetry makes the stereo illusion more difficult to preserve. Speaker spacing matters too. Move the speakers too close together and the stereo panorama becomes narrow. Move them too far apart and the center may weaken, producing the familiar impression of sound coming from the left speaker, the right speaker, and nowhere in between. The proper spacing is the one that creates a continuous, stable panorama.

The Room Is Part of the System

We do not listen only to the direct sound from the loudspeakers. We also hear reflections. Sound reaches the floor, walls, ceiling, furniture, and other surfaces, then arrives at our ears slightly later. These reflections contribute to our perception of tonal balance, spaciousness, and image location.

That means a loudspeaker cannot be completely separated from the room in which it operates. A good stereo system does not require an acoustically dead room. In fact, an excessively dead room can sound unnatural. What matters is that reflections do not overwhelm or seriously contradict the spatial information contained in the recording.

Dispersion Matters

A loudspeaker does not radiate every frequency equally in every direction. At some frequencies, its radiation may be broad. At others, it may become narrow. If this change occurs abruptly, reflected sound can have a substantially different tonal character from the direct sound reaching the listener. That affects more than tone. It can also affect spatial stability. For this reason, smooth dispersion is an important part of stereo reproduction. The loudspeaker should behave sensibly not only directly in front of it but throughout the useful listening area.

Stereo Is More Than Left and Right

A convincing stereo recording can contain much more than horizontal position. It can suggest width, depth, distance, scale, and the acoustic character of the recording space. A small jazz ensemble recorded in an intimate room should not occupy the same apparent space as a symphony orchestra in a concert hall.

A close microphone should sound close. A distant microphone should sound distant. When a playback system preserves these relationships, the listener begins perceiving the recording as a space rather than merely a collection of sounds.

That is when stereo becomes fascinating.

The Recording Matters

No playback system can reproduce spatial information that the recording does not contain. Some recordings deliberately create artificial spatial effects. Others capture a natural acoustic environment. Some contain wonderful stereo information. Others contain very little. A good stereo system should not impose the same enormous soundstage on every recording. Quite the opposite. It should reveal the differences.

A mono recording should remain essentially mono. An intimate recording should remain intimate. A spacious recording should be allowed to become spacious. When every recording produces the same spectacular stereo effect, the system may be entertaining, but it is adding something of its own.

The Objective Is the Illusion

Good stereo is therefore not measured by how far sounds appear from the loudspeakers or by how enormous the soundstage seems. The real question is simpler: Does the reproduced acoustic event make sense? Are positions stable? Are instruments believable in size? Does the center remain convincing? Can you perceive relationships among performers rather than merely left and right? Does the apparent space change when the recording changes? And, most importantly, can you stop thinking about the two loudspeakers sitting in front of you? When that happens, stereo has accomplished its purpose.

The equipment disappears, and in its place is a convincing illusion of a musical event.

Chapter 3
What Makes a Good Loudspeaker Driver?

A beautifully made loudspeaker driver can be completely wrong for a particular loudspeaker. So can an expensive one. The specifications may look impressive, or its materials may sound exotic. The manufacturer may have an excellent reputation.

None of these things answers the most important question: Is this driver suitable for the job we are asking it to do? That distinction is fundamental to loudspeaker design.

There Is No Best Driver

A woofer designed for very deep bass may be inefficient. A highly efficient woofer may require a large cabinet. A small woofer may reproduce the midrange beautifully but lack the ability to produce adequate bass at realistic listening levels. None is necessarily better than the others. They were designed to do different jobs.

Choosing a driver, therefore, begins by defining its job. How low must it reproduce? How loudly? How high in frequency must it operate before another driver takes over? How much amplifier power is available? How large can the cabinet be? Only then do specifications become meaningful.

Firstly, Look for Bad Behavior

One of the first things we examine is breakup. Ideally, a loudspeaker cone moves forward and backward as one rigid surface. Real cones cannot do this indefinitely. At sufficiently high frequencies, different portions of the diaphragm begin moving somewhat independently. The cone has entered breakup. This can create resonances, stored energy, distortion, and abrupt changes in the way sound radiates into the room. A frequency response graph may show the result as a prominent peak. Sometimes the problem is less obvious. The important question is not simply, “How high can this woofer play?” A better question is, “How high can this woofer play well?” Those are very different questions.

Look Sideways Too

Most published frequency response graphs show what a driver does directly in front of it. That is useful, but incomplete.

As frequency rises, a large driver generally begins concentrating its sound into a progressively narrower area. This is called increasing directivity.

Suppose a woofer becomes quite directional before reaching the tweeter. The tweeter may suddenly spread sound over a much wider angle. Directly in front of the loudspeaker, the frequency response might look excellent. Move sideways and it may not.

The room also receives this uneven sound and reflects some of it back toward the listener. Good driver selection therefore requires examining not merely frequency response, but dispersion. The drivers must work together in space as well as in frequency.

Resonances Have Consequences

Every physical object has resonances. A loudspeaker driver contains a cone or dome, suspension, voice coil, former, surround, and other structures. Each can store and release energy. A strong resonance is particularly troublesome because the driver continues emphasizing that frequency regardless of whether the music asks it to.

This is one reason two drivers with similarly flat frequency response graphs can sound surprisingly different. One may stop cleanly while the other may ring.

Distortion Changes With Level

A driver that behaves beautifully at low volume may behave quite differently when asked to play loudly. Producing sound requires moving air. Producing bass requires moving a great deal of it. As a diaphragm travels farther, its suspension and magnetic system may become less linear. Distortion increases. Eventually, the driver reaches its safe mechanical limits. This is why bass extension, loudness, diaphragm size, and excursion cannot be considered independently. There is no magic material that eliminates physics.

Specifications Need Context

Driver specifications are extremely useful when properly understood. They can help predict bass performance, enclosure requirements, electrical loading, sensitivity, and power requirements. Yet individual numbers should not become trophies. A huge magnet does not guarantee a good driver. A lightweight cone does not guarantee good transient response. A high advertised power rating does not guarantee that the driver will play loudly without objectionable distortion. An exotic diaphragm material does not guarantee freedom from breakup. Engineering requires looking at how the characteristics interact.

The Crossover Cannot Fix Everything

It is tempting to select an attractive driver and assume that any undesirable behavior can be corrected later with the crossover. Sometimes it can. Often it cannot.

A crossover can reduce the electrical signal sent to a driver outside its useful range. It can compensate for some frequency response irregularities. It cannot make a badly behaving diaphragm stop behaving badly. It cannot restore broad dispersion after a driver has become highly directional. It cannot remove energy that has already been stored mechanically. The better approach is to choose a driver that behaves naturally well over the range where it will be used. Then the crossover has a much easier job.

Measurements, Then Ears

Measurements tell us where to look. Listening tells us whether we have understood what we found. A promising driver should therefore survive both. Does its measured behavior make sense? Are resonances controlled? Is its dispersion appropriate? Does distortion remain reasonable at the required level? Then listen. Does a voice retain its natural character? Do cymbals acquire an artificial metallic signature? Does bass remain articulate as level increases? Does the driver become tiring after extended listening? When measurements and listening agree, confidence grows. When they disagree, investigate.

Suitability Is What Matters

A good driver is not necessarily the newest, most expensive, or most technically exotic one. Nor is it necessarily the driver with the flattest published frequency response. A good driver is one whose strengths match the requirements of the design and whose weaknesses can be kept safely outside the range in which it will operate. That leads to one of the simplest rules in loudspeaker engineering: Do not ask how impressive a driver is. Ask how well it does the job.

Chapter 4
What Makes a Good Speaker Cabinet?

At first glance, a loudspeaker cabinet seems simple. It is a box that holds the drivers. Unfortunately, acoustics has other ideas. A loudspeaker cabinet is actually part of the machine, and its size, construction, shape, internal damping, and interaction with the woofer can substantially affect what you hear. The best cabinet has a curious objective: that it should do its job without being heard doing it.

Why Have a Cabinet at All?

When a woofer moves forward, it pushes air in front of it. At the same time, the back of the cone moves in the opposite direction and produces another sound wave behind it. Those two waves have opposite polarity, so if they are allowed to meet freely at low frequencies, they begin cancelling each other. Put a woofer on a table without a cabinet or sufficiently large baffle, and you may hear plenty of midrange but surprisingly little deep bass.

The cabinet controls what happens to the sound from the rear of the driver. How it does that determines the alignment of the loudspeaker and has an enormous influence on its bass performance.

The Cabinet and Woofer Form a System

You cannot properly design a cabinet independently of the woofer. The moving mass of the cone, stiffness of its suspension, electrical characteristics of its motor, and other properties interact with the air inside the enclosure. Change the cabinet volume, and you change the behavior of the entire system.

This is why putting a good woofer into an arbitrary box does not necessarily produce good bass. The woofer and enclosure must be designed to work together. Cabinet volume, woofer characteristics, and the chosen alignment are all parts of the same engineering problem.

Sealed, Vented, and Aperiodic

There are many enclosure types, but three illustrate the basic choices particularly well. A sealed enclosure traps the woofer's rear radiation inside the cabinet. The enclosed air acts partly as a spring and contributes to controlling the woofer. Properly designed sealed systems can provide excellent transient behavior and predictable low-frequency performance.

A vented enclosure, often called a bass-reflex enclosure, uses an opening, vent, or duct tuned to work with the woofer over part of the bass range. Properly designed, this can increase low-frequency output or extension. Poorly designed, it can produce excessive resonance, delayed energy, and the familiar impression of bass in which certain notes seem much more prominent than others.

An aperiodic enclosure allows controlled airflow through an acoustically resistive vent. Rather than using a strongly tuned resonance to increase output, it emphasizes damping and control. None of these alignments is automatically superior. The correct choice depends upon the driver, cabinet size, desired bass extension, efficiency, maximum output, and intended application.

The Box Should Not Sing

A violin body is designed to resonate. A loudspeaker cabinet generally should not. Pressure changes inside a loudspeaker can cause its walls to vibrate. If a cabinet panel becomes an effective radiator, it adds sound of its own, and that sound was not present in the electrical signal. Worse, cabinet vibration may continue briefly after the original musical event has stopped. The result can be coloration, blurred detail, and reduced spatial clarity.

Good cabinet construction therefore uses appropriate materials, bracing, and geometry to control unwanted vibration. This does not necessarily mean making the enclosure extraordinarily heavy. Mass can be useful, but stiffness, damping, and the distribution of resonances also matter. The objective is not simply to build a massive box. The objective is to build a quiet one.

More Damping Is Not Always Better

Absorbent material inside a cabinet can reduce reflections and control unwanted acoustic energy, but its type, quantity, and placement matter. Too little may leave troublesome internal reflections, while excessive or indiscriminately placed material may alter the intended behavior of the system.

This illustrates a recurring principle in good engineering. If some damping is beneficial, it does not follow that the greatest possible amount must be better. Engineering rarely consists of maximizing one characteristic. It consists of finding the appropriate relationship among several characteristics.

Sound Can Escape Through the Cone

The rear radiation from a driver does not simply disappear when it enters the cabinet. Some strikes the interior surfaces and is reflected, some is absorbed, and some can return through the diaphragm itself. This can be particularly troublesome through the midrange, where internal reflections may pass through a relatively thin cone and mix with the sound being produced from its front.

The cabinet interior therefore deserves as much attention as its exterior. Bracing, damping material, dimensions, and internal geometry can all help control this unwanted energy. An enclosure that looks beautifully finished from the outside may still behave badly if its interior was treated merely as empty space.

Shape Matters

The outside of the cabinet affects sound too. When sound traveling across the front of a loudspeaker reaches an edge, part of it can be diffracted or redirected. Sharp changes in geometry around a driver can therefore become small secondary sources of sound, arriving slightly later than the direct radiation from the diaphragm.

Driver position, cabinet width, edge treatment, and even grille construction can influence this behavior. This does not mean every loudspeaker needs an exotic curved cabinet or elaborate sculpted baffle. It means the cabinet's geometry should be chosen deliberately rather than treated merely as decoration.

Bass Is Always a Compromise

People understandably want small loudspeakers with deep, powerful bass. Physics is less enthusiastic about the idea. Deep bass requires moving substantial amounts of air, and reducing cabinet size while demanding greater bass extension generally requires sacrifices elsewhere. Those sacrifices may include lower efficiency, reduced maximum output, greater diaphragm excursion, or increased amplifier power.

Modern drivers and electronic equalization can change where these compromises occur, sometimes quite dramatically, but they cannot abolish them. A good cabinet design accepts this reality and chooses its compromises intelligently rather than attempting to conceal them.

The Room Eventually Gets Involved

Even a perfectly engineered cabinet cannot determine the bass response you ultimately hear because the listening room participates. Walls, floor, and ceiling reinforce some frequencies and reduce others, and moving a loudspeaker within the room changes those relationships.

Consequently, the best bass alignment is not necessarily the one producing the most impressive graph under laboratory conditions. It is one that behaves predictably and integrates successfully into real listening rooms. Ultimately, the loudspeaker and room become parts of the same acoustic system.

The Cabinet Should Disappear

Beautiful woodwork is desirable. Fine materials are pleasurable, and good craftsmanship matters. None of these things, however, defines an acoustically successful loudspeaker cabinet.

The cabinet has a more important responsibility. It must control the rear radiation of the drivers, provide the required acoustic loading, resist unwanted vibration, manage internal energy, and support predictable radiation into the room. Ideally, it should accomplish all of this while calling no attention to itself.

A good musical instrument has a recognizable voice partly because its enclosure contributes to its sound. A good loudspeaker cabinet has almost the opposite objective.

Hold the drivers. Control the air. Control the energy. Then stay out of the music.

Chapter 5
What Makes a Good Crossover?

A crossover is often described as the part of a loudspeaker that sends low frequencies to the woofer and high frequencies to the tweeter. That is true, but it is only the beginning.

A good crossover must do much more. It affects frequency response, phase, directivity, power handling, impedance, lobing, and the apparent position of sound. Most importantly, it determines whether several physically separate drivers behave like several sound sources or combine into one believable loudspeaker.
The real objective of a crossover is therefore not simply to divide frequencies. It is to make several drivers speak with one voice.

Why Do We Need a Crossover?

No practical loudspeaker driver reproduces the entire audible range equally well. A woofer is designed to move enough air to reproduce bass, but its relatively large diaphragm eventually becomes directional and enters breakup at higher frequencies. A tweeter is small enough to reproduce high frequencies well, but usually cannot move enough air safely to reproduce deep bass. The crossover allows each driver to operate primarily within the range where it behaves best. Low frequencies are gradually reduced before they reach the tweeter, while high frequencies are gradually reduced before reaching the woofer. The word gradually is important. A crossover is not a brick wall. There is usually a region where both drivers are operating at the same time. That overlap is where things become interesting.

Two Drivers Must Become One

Suppose a woofer and tweeter are both producing sound near 2,000 Hz. The listener does not want to hear two separate 2,000 Hz sources. Their outputs must combine acoustically into one convincing result. Whether they do depends upon more than their individual frequency responses. Their relative phase, physical spacing, acoustic centers, directivity, and crossover slopes all influence the sound that finally reaches the listener. If the two drivers combine properly, their outputs reinforce one another smoothly. If they do not, parts of the spectrum may become too loud, too soft, or uneven with listening position. This is why crossover design cannot be reduced to choosing a frequency and calculating a few components.

The Crossover Frequency Is Not Arbitrary

A designer should not begin by deciding, "I want to cross these drivers at 2,000 Hz," and then force the drivers to cooperate. The drivers should determine the sensible crossover region. A woofer may appear capable of operating to 4,000 Hz according to its published frequency response, but its diaphragm may begin breaking up or its radiation may become too narrow well below that point. A tweeter may reproduce 1,500 Hz on a laboratory graph yet produce excessive distortion or require too much excursion if asked to operate there at realistic levels. A good crossover works within the comfortable operating ranges of both drivers.
The crossover should protect the drivers, not challenge them.

Phase Matters

When two sound waves meet, their timing relationship affects how they combine. If they arrive appropriately aligned, they reinforce one another. If their relationship is wrong, they can partially cancel. This timing relationship is called phase. A crossover changes phase as well as amplitude, and the physical positions of the drivers introduce additional differences in arrival time. For that reason, electrical crossover behavior and physical loudspeaker geometry cannot be considered separately. The objective is not necessarily to make every phase measurement mathematically perfect. It is to create predictable acoustic summation throughout the crossover region and useful listening area.

Crossovers and Lobing

Because the woofer and tweeter occupy different physical positions, sound from them travels slightly different distances to different points in the room. Where both drivers are reproducing the same frequencies, their outputs may reinforce in some directions and partially cancel in others.

This produces areas of stronger and weaker sound called lobes. Some lobing is inevitable in most conventional multiway loudspeakers. The problem arises when it becomes severe enough that the speaker changes character significantly as the listener moves vertically or horizontally. Good crossover design, sensible driver spacing, and appropriate crossover frequencies can reduce these effects considerably. This is one reason placing drivers close together is often desirable. The more nearly several radiators behave as though they occupy the same physical position, the easier it becomes to create a stable acoustic image.

Directivity Must Match Too

Imagine a woofer whose radiation has become very narrow by the time it reaches the crossover frequency. Now imagine handing the sound abruptly to a tweeter that radiates very broadly. Directly in front of the loudspeaker, the frequency response might still look excellent. Elsewhere in the room, however, there may be a sudden change in radiated energy at the crossover. The room hears that discontinuity even if the microphone directly in front of the speaker does not. This is why crossover design and directivity are inseparable. A good transition requires not only similar sound levels but reasonably compatible radiation patterns.

More Components Are Not Automatically Better

A complex crossover can perform useful functions. Additional components may correct response irregularities, control impedance, suppress resonances, or produce a desired acoustic slope.

But complexity is not a virtue by itself. Every component introduces cost, tolerance, resistance, and another opportunity for unintended interaction. Conversely, an extremely simple crossover is not automatically superior either. A single capacitor may be elegant, but elegance does not excuse poor integration. The correct crossover contains as much complexity as necessary and no more than the design requires. Neither the fewest components nor the greatest number wins.

Passive or Active?

A traditional passive crossover operates between the power amplifier and the loudspeaker drivers. It uses components such as capacitors, inductors, and resistors to divide and shape the signal. An active crossover performs this job before the power amplifiers. Each frequency range is then amplified separately and sent directly to its appropriate driver.

Both approaches can work very well. Active systems offer greater flexibility and remove some difficult interactions between passive crossover components and driver impedance. Passive systems can provide simplicity and allow the loudspeaker to operate from a single conventional amplifier. As always, the appropriate method depends on the objectives of the design.

A Crossover Cannot Rescue Bad Decisions

This may be the most important point. A crossover can shape the electrical signal reaching a driver, but it cannot transform an unsuitable driver into a suitable one. It cannot eliminate severe diaphragm breakup, restore wide dispersion to a driver that has become directional, or make widely separated acoustic sources occupy the same physical location.
By the time crossover design begins, many of its possibilities have already been determined by driver selection, cabinet geometry, and physical layout. Good crossover design therefore begins long before the first capacitor or inductor is chosen.

One Loudspeaker, Speaking With One Voice

When a crossover works properly, the listener should not be conscious of it. Nor should the listener hear a woofer operating below a certain frequency and a tweeter taking over above it.

A voice should remain a voice as its harmonics pass from one driver to another. A piano should not appear to change size with pitch. Instruments should occupy stable positions in the stereo panorama instead of shifting as different drivers become dominant. That is the real test.

A good crossover does not merely divide the music into pieces and distribute them among the drivers. It puts the pieces back together.

Chapter 6
How Do You Know a Loudspeaker Is Good?

A loudspeaker can have excellent specifications, beautiful construction, and impressive measurements. It can also sound spectacular during a five-minute demonstration. None of those things, by itself, tells us whether it is a good loudspeaker.

The final test is whether the loudspeaker reproduces music convincingly, consistently, and without imposing a persistent character of its own. Determining that requires listening, but useful listening is more disciplined than simply playing a favorite recording and deciding whether the sound is pleasant.

Listening and Measurement Are Partners

Listening is sometimes described as the subjective part of loudspeaker design, while measurement is considered the scientific part. That distinction is misleading. Measurements tell us what a loudspeaker is doing. Listening tells us what the audible consequences are. A measurement may reveal a resonance, irregular dispersion, or rising distortion, while listening tells us whether that behavior actually interferes with the music.

The opposite is equally important. Listening may reveal that something sounds wrong without explaining why. What initially sounds like too much treble may actually result from diaphragm breakup, a narrow resonance, poor crossover integration, or excessive reflected energy from the room. The ear reports the experience. Measurement helps explain it. When the two disagree, the proper response is not to choose sides but to investigate.

Firstly, Control the Conditions

Comparisons become unreliable if several things change at once. Loudspeaker position, listening distance, toe-in, amplifier, source equipment, and playback level can all alter what we hear.

Playback level is particularly deceptive. A slightly louder loudspeaker will often seem to have better bass, greater clarity, and stronger dynamics even when the listener does not consciously notice the difference in loudness. Meaningful comparisons therefore require careful level matching. The same principle applies during development. Change one meaningful variable, return to the same program material and level, and listen again. Otherwise, a loudspeaker may improve without revealing why it improved, which is not very useful engineering.

Listen to More Than One Kind of Music

No single recording can evaluate an entire loudspeaker. Different sounds reveal different weaknesses.

Human voice is exceptionally useful because we spend our lives hearing voices. Small colorations can become obvious, and a voice that changes character, size, or position as its pitch changes may reveal poor crossover integration.

Piano music tests an enormous portion of the system at once. It combines a wide frequency range, sharp attacks, complex decay, dynamics, and closely spaced pitches.

Strings can reveal resonances and roughness. Brass exposes hardness and compression. Percussion tests transient response and recovery. Bass instruments reveal whether low frequencies retain actual pitch instead of becoming generalized thumps and rumbles.

It is also useful to play ordinary recordings as well as superb ones. A loudspeaker that works beautifully only with a handful of demonstration-quality recordings is not especially useful. At the same time, a loudspeaker that makes every recording sound equally pleasant may simply be concealing information. A good system should reveal differences without making those differences punitive.

Listen for What Remains the Same

One of the most revealing questions is whether unrelated recordings begin acquiring the same character. Do all voices sound slightly chesty? Do all cymbals have the same metallic sheen? Does every recording possess unusually warm bass? Does every orchestra seem to occupy the same enormous space? If so, you may be hearing the loudspeaker rather than the recordings.

A neutral loudspeaker should allow recordings to remain different. A dry recording should sound dry. A reverberant hall should retain its reverberation. A close microphone should sound close. A distant ensemble should sound distant. Neutrality does not mean dullness. It means that the loudspeaker does not insist upon performing alongside every musician.

Listen to the Stereo Image

A centered monaural voice is one of the simplest and most revealing stereo tests. It should appear as a stable sound between the loudspeakers rather than as two voices coming from two boxes. Its position should not wander as pitch changes. Its apparent size should remain plausible, and the individual loudspeaker drivers should not become identifiable as separate sources.

Stereo recordings should produce a continuous panorama rather than isolated left, center, and right regions. Depth should change according to the recording. Some recordings should appear intimate and forward, while others may extend considerably behind the loudspeakers. If every recording produces spectacular depth and width, the system may be manufacturing an effect rather than reproducing one.

Move Around

A loudspeaker should not sound correct only when your head occupies one precisely marked location. Moving sideways, vertically, or changing listening distance will naturally alter the presentation somewhat. The important question is whether those changes occur gracefully. An abrupt tonal change caused by moving your head a few inches may reveal crossover lobing or irregular directivity.

Every multiway loudspeaker also has some distance at which its individual drivers become perceptually integrated. A near-field monitor should integrate at a short distance. A large theater system can reasonably require more. What matters is that the required listening distance suits the intended application. A domestic loudspeaker that needs a ballroom before its drivers become one source has a practical problem.

Turn It Up, and Turn It Down

A loudspeaker should retain its basic character over a useful range of levels. At low levels, listen for fine detail and the ability to preserve subtle changes. At moderate levels, tonal balance and integration become important. At higher levels, listen for compression, hardness, congestion, cabinet noise, port noise, and loss of bass pitch. A loudspeaker approaching its limits often announces the fact before obvious distortion appears. The stereo image may flatten, brass becomes aggressive, bass loses definition, or dynamic peaks stop growing naturally even though the volume continues increasing. Good dynamics should sound easy. The listener should hear the music becoming more powerful, not the machinery working harder.

The Five-Minute Test Is Not Enough

Some loudspeakers are designed, intentionally or otherwise, to make a strong first impression. Elevated treble can initially sound detailed. Emphasized bass can sound powerful. Extremely sharp image outlines can seem remarkably precise.

An hour later, those same characteristics may become exhausting. Listening fatigue is therefore useful information. A loudspeaker that continually directs attention toward some aspect of its own sound is likely doing something worth investigating. On the other hand, a system that never becomes tiring because it suppresses transients or information is not necessarily accurate either. The goal is a loudspeaker that remains revealing without becoming irritating. Long listening sessions tell us something short demonstrations cannot: whether we continue wanting to play music.

Does the Music Still Communicate?

There is one final test that is difficult to put on a specification sheet. Technical accuracy and emotional involvement are not opposites. If resonances, distortion, timing errors, and tonal imbalances are reduced, the musical distinctions through which emotion is communicated should become easier to hear. Phrasing, tension, release, dynamics, rhythm, and interaction among musicians should become clearer. The loudspeaker should not manufacture excitement, warmth, drama, or intimacy. Those qualities should change with the performance. A restrained performance should remain restrained. A powerful one should become powerful. The loudspeaker should not tell you what to feel. It should allow the musicians to do that.

When Is It Good?

A good loudspeaker survives more than one impressive demonstration. It works with varied music, realistic levels, long listening sessions, different positions, and reasonable rooms. Bass retains pitch, instruments retain recognizable timbre and scale, stereo images remain stable, dynamics grow without obvious strain, and different recordings remain distinctly different. Most importantly, after a while, the listener stops evaluating the loudspeaker. The equipment ceases to be the subject, and attention returns to the music.

Chapter 7
What Is the Reference?

Suppose two loudspeakers sound different. Which one is more accurate? Comparing them tells us that they are different, but it does not tell us which one is closer to the truth. The same problem appears when someone describes a loudspeaker as warm, bright, detailed, spacious, or natural. Compared with what? Every meaningful evaluation needs a reference outside the equipment being evaluated.

The Problem With Familiar Recordings

A favorite recording can be extremely useful because we know it well. After hearing it through many systems, we quickly notice when something changes. But an important limitation exists. Unless we were present when the recording was made, we usually do not know exactly what it originally sounded like.

The microphone affected the sound. So did its position, the recording room, microphone preamplifier, console, recorder, equalization, compression, mixing, mastering, and final release medium. Any characteristic we hear may have originated at one of those stages. If a recording sounds bright, perhaps the loudspeaker is bright. Perhaps the microphone was bright. Perhaps equalization was added during mixing. Perhaps the mastering engineer made the decision. Without knowing the recording process, we cannot be certain. A familiar commercial recording is therefore a useful reference to the recording, but not necessarily to the original musical event.

Begin With Real Sound

The most useful reference for understanding reproduced sound is live sound. Hearing real instruments and voices establishes expectations that audio equipment cannot teach us. Brass can be tremendously powerful without sounding electrically harsh. A violin contains abundant high-frequency energy without sounding like a tweeter. A snare drum can be startling without producing cabinet noise. A piano combines attack, resonance, weight, and scale in ways that challenge almost every part of a loudspeaker.

Live music also reminds us that natural sound is not always polite or smooth. Fidelity does not mean making everything agreeable. It means preserving what was actually there. The purpose is not to make every recording resemble an unamplified concert. Much recorded music was never intended to do that. The value of the live reference is that it teaches us how naturally produced sound behaves before playback equipment begins adding habits of its own.

Record the Event You Heard

An especially useful reference can be created by recording a musical event whose original sound is known. Now some of the mysteries disappear. You know the room. You know where the musicians were. You know the microphones and where they were placed. You know the signal path and whether equalization, compression, or other processing was used. You can hear the musicians directly, then hear what the microphones captured, and later reproduce that recording through the loudspeaker. The comparison is not perfect.

Human auditory memory is imperfect, microphones do not hear exactly as two human ears do, and the playback room is not the recording room. Nevertheless, the number of unknown variables has been greatly reduced.

Instead of asking, “Does this loudspeaker sound impressive?” we can ask a much more useful question: “Does it preserve a believable relationship to the event that was recorded?”

Preserve Relationships, Not Just Frequencies

A musical event contains much more than frequency response. It contains relationships among instruments, the timing of attacks, the decay of the room, differences in dynamics, the apparent positions of performers, the scale of the ensemble, and the distinct tonal character of each instrument. A system can reproduce every audible frequency and still damage these relationships.

Compression can reduce the difference between restraint and intensity. Poor microphone placement can enlarge one instrument while diminishing another. A loudspeaker resonance can impose one tonal character on several different instruments. Poor crossover integration can disturb the relationship between an instrument’s fundamentals and harmonics. The important question throughout the entire recording and playback chain is therefore not simply, “Did all the frequencies survive?” but instead, “How much of the musical relationship survived?”

Fewer Unknowns Make Better References

A useful reference recording does not need an elaborate signal chain. In fact, unnecessary complexity can make evaluation harder because every additional device introduces another variable.

An appropriate microphone in the right position, a quiet preamplifier with adequate headroom, and a trustworthy recording system may be all that is required. Equalization, compression, limiting, and reverberation are valuable tools when they solve real problems, but each changes something. For reference work, the important requirement is not ideological purity. It is understanding. Every device should have a reason for being there, and its effect should be known. The reference recording should not flatter the loudspeaker. It should expose it.

The Microphone Is Part of the Reference

Microphone placement is particularly important because instruments do not radiate sound equally in every direction. Move around a guitar, piano, violin, or brass instrument, and its tonal balance changes. A microphone placed very close to an instrument may capture tremendous detail but an unnatural overall perspective. Move farther away, and the instrument may become more integrated while the room contributes more strongly.

This teaches an important lesson about loudspeakers as well. Sound does not exist only along one measurement axis. Instruments radiate into rooms, microphones receive sound from particular directions, and loudspeakers radiate into rooms again. Sound is an event occurring in space, not merely a line on a frequency-response graph.

Preserve the Differences

One of the most important qualities of a reference system is its ability to preserve differences. Different instruments should sound different. Different microphone positions should produce different perspectives. Different rooms should retain different acoustic signatures. Different recordings should not all become warm, spectacular, intimate, spacious, or detailed in exactly the same way.

A loudspeaker that gives everything one attractive personality may be enjoyable, but it is contributing to the performance rather than simply reproducing it. Fidelity is not the production of one ideal sound. It is the preservation of differences.

Commercial Recordings Still Matter

Known recordings do not eliminate the need for commercial recordings. Quite the opposite. Commercial music exposes a loudspeaker to an enormous range of instruments, production techniques, musical styles, recording periods, and technical quality. It also represents what the owner will actually play.

The two kinds of reference simply answer different questions. A minimally processed recording made under known conditions asks, “How faithfully does this system preserve a known event?” A large collection of commercial recordings asks, “How successfully does this loudspeaker reproduce the real world of recorded music?” Both questions matter.

The Reference Is Evidence, Not Perfection

No reference method can recreate an original acoustic event perfectly. Auditory memory changes. Microphones have their own characteristics. The recording and playback rooms are different. A two-channel system cannot reconstruct every physical aspect of the original sound field.

The objective is therefore not absolute certainty. It is better evidence. A good reference removes enough unknowns that departures become easier to identify and understand. It gives the engineer something more useful than another loudspeaker against which to compare the design. Ultimately, the microphone and loudspeaker occupy opposite ends of the same process. The microphone begins with music and converts it into an electrical signal. The loudspeaker receives that signal and attempts to turn it back into music. Everything between those two moments exists for one reason, which is to preserve as much of the original musical event as practical.

Chapter 8
What Do Measurements Really Tell Us?

Modern loudspeaker measurements can produce an astonishing amount of information. A computer can generate beautifully detailed graphs of frequency response, distortion, impedance, phase, decay, and other characteristics within seconds. The danger is assuming that more data automatically produces more understanding.

A measurement is useful only when we understand what it represents. No single graph tells us whether a loudspeaker is good, and no collection of graphs can listen to music. Measurements are valuable because they reveal physical behavior that may be difficult or impossible to identify reliably by ear alone. The important question is not, “Does this loudspeaker measure well?” but, “What do these measurements tell us about how this loudspeaker behaves?”

Frequency Response

Frequency response is probably the most familiar loudspeaker measurement. It shows how strongly the loudspeaker reproduces different frequencies under specified conditions. A reasonably smooth response is desirable because large peaks can emphasize parts of the music while deep depressions can obscure information.

A flat frequency-response curve, however, does not guarantee a good loudspeaker. Two speakers can have remarkably similar response curves while sounding quite different because frequency response does not fully reveal stored energy, distortion, directivity, or transient behavior. The shape of an irregularity also matters. A broad, gentle variation may be relatively unobtrusive, while a narrow resonance of similar amplitude can repeatedly announce itself whenever music excites it. Frequency response is therefore important evidence, but it is not the verdict.

Off-Axis Response

A loudspeaker does not radiate sound only toward the person sitting directly in front of it. Much of its acoustic output travels toward the walls, floor, ceiling, and furnishings before being reflected toward the listener. Those reflections contain the loudspeaker’s off-axis response.

If the loudspeaker changes character abruptly as the listening angle changes, the reflected sound may have a substantially different tonal balance from the direct sound. The ear eventually receives both and combines them into one impression. A loudspeaker with an exceptionally smooth response directly in front of it can therefore sound less natural in a room than one whose forward response is slightly less perfect but whose radiation changes smoothly with angle. Off-axis measurements are among the most revealing tools available. They tell us whether the loudspeaker behaves sensibly as an acoustic radiator rather than merely at one convenient microphone position.

Impedance

A loudspeaker advertised as “8 ohms” is not actually an 8-ohm load at every frequency. Its impedance rises and falls as its drivers, cabinet, and crossover interact. An impedance measurement tells us whether the loudspeaker presents a reasonable electrical load to the amplifier, but it can reveal much more. Resonances often appear in the impedance curve.

Changes in enclosure damping and loading can become visible there, as can some crossover interactions and characteristics of the driver's motor system. Impedance is therefore not merely a number printed beside the speaker terminals. Properly interpreted, it becomes a diagnostic tool that can reveal what is happening mechanically and electrically inside the system.

Distortion

Frequency response tells us how much output exists at particular frequencies. Distortion measurements help reveal sound that the loudspeaker creates which was not present in the original signal. As a driver is asked to move farther or operate closer to its limits, its suspension, magnetic system, and other components become less linear. Harmonic distortion may increase, and different frequencies reproduced simultaneously may interact to produce intermodulation distortion. These effects often become much more significant as playback level rises. The objective is not simply to chase the smallest possible percentage. Human hearing is more sensitive to some kinds of distortion than others, and the same numerical amount can have very different consequences at different frequencies. Distortion measurements are most useful when they help identify the physical mechanism causing audible degradation.

What Happens in Time?

Music does not consist of continuous laboratory tones. Sounds begin, change, and stop, which means the behavior of a loudspeaker in time matters. Impulse response, decay measurements, group delay, and measurements of stored energy can reveal behavior that an ordinary frequency-response graph may conceal. A resonance, for example, may not appear particularly alarming in amplitude yet continue producing sound after the original stimulus has stopped. That lingering energy can blur transients and add coloration to music. Two loudspeakers with similar frequency-response curves may therefore behave quite differently when reproducing rapidly changing musical events. Time-domain measurements help show us why.

What Happens When It Gets Loud?

A loudspeaker measured quietly may behave beautifully while becoming a very different system at realistic listening levels. Voice-coil heating, suspension nonlinearity, excursion limits, and thermal compression often become important only when significant power is applied. Measurements at increasing levels reveal whether the loudspeaker maintains its frequency response, whether distortion rises gradually or suddenly, and whether increased electrical input continues producing a corresponding increase in acoustic output. A loudspeaker that compresses dynamically may survive high power without obvious failure while still losing the contrasts that make music sound alive. This information is generally more useful than a large "maximum power" number on a specification sheet.

What matters is not merely whether the loudspeaker survives the power. It is whether it continues behaving properly while using it.

Measurements Reveal Causes

This is perhaps their greatest value. If a loudspeaker sounds aggressive, listening alone may tell us that something is wrong. Measurements can help determine whether the cause is a response peak, breakup, distortion, stored energy, irregular directivity, or something else entirely.

If the stereo image becomes unstable through the crossover region, measurements of phase, summation, and radiation pattern can help reveal why. Conversely, a graph may contain an unusual feature that appears alarming until further investigation shows that it has little audible consequence. A measurement must always be interpreted according to the physical mechanism producing it and the conditions under which it was obtained.

Measurements describe reality. Engineering requires understanding what that description means.

No Graph Contains Music

Some questions test instruments cannot answer directly. A microphone and computer cannot decide whether a piano retains believable weight and attack, whether a voice sounds naturally human, whether a stereo image remains convincing throughout a performance, or whether several hours of listening become tiring.

Those questions require listening because the purpose of the loudspeaker is not to produce excellent graphs. Its purpose is to reproduce music. The most useful measurements, therefore, do not replace listening. They make listening more informative by helping us understand why we hear what we hear.

Measurements tell us what the loudspeaker is doing. Listening tells us whether what it is doing serves the music.

Chapter 9
Measurement Philosophy

Measurements are indispensable to loudspeaker engineering. Without them, the designer is forced to depend upon assumptions, memory, and impressions that may be incomplete or misleading. Yet measurements are not the design itself, nor can they determine whether a loudspeaker ultimately succeeds at reproducing music. The useful position lies between two extremes. One claims that everything important about a loudspeaker can be determined from measurements. The other dismisses measurements and insists that the ear alone should decide. Experience has convinced me that both approaches discard valuable information.

Measurement and listening answer different questions. Good engineering requires both.

Measure With a Purpose

Every measurement should begin with a question. Does this driver enter breakup within its intended operating range? Is the cabinet storing unwanted energy? Does the crossover combine the drivers correctly? Does directivity change smoothly? Is the amplifier seeing a reasonable load? Does distortion increase rapidly when the loudspeaker approaches realistic listening levels?

Beginning with the question matters because modern measurement systems can generate enormous amounts of data. It is quite possible to accumulate dozens of beautiful graphs without gaining much understanding. Knowing what we are trying to discover tells us what to measure, how to measure it, and, most importantly, how to interpret the result.

Measurement should replace uncertainty with evidence, not replace thought with data.

Measure in the Right Order

Testing should follow the same hierarchy as the design itself. Begin with the individual driver because every later decision depends upon knowing how that driver behaves. Frequency response, resonance, impedance, sensitivity, dispersion, breakup, and distortion establish its useful operating range.

Once the driver is understood, the enclosure can be examined. Cabinet resonances, internal standing waves, damping, diffraction, and low-frequency alignment can then be identified without confusing them with crossover problems. Only after the individual components are understood does it make sense to evaluate crossover summation, phase relationships, lobing, and the behavior of the completed system. This order makes diagnosis much easier. If the finished loudspeaker contains a problem, we already know what the individual parts were doing before they were combined.

Change One Thing at a Time

A basic principle of useful experimentation is to change one meaningful variable whenever practical. If a designer simultaneously modifies crossover components, damping material, cabinet geometry, and driver position, the loudspeaker may improve dramatically, but there is no reliable way to know which change produced the improvement.

Understanding why something improved allows the result to be repeated, adapted to another design, or corrected later if a related problem appears. An unexplained success is useful once. An understood success becomes engineering knowledge. This is why measurements should be repeated after meaningful changes. The objective is not simply to watch the graph improve. It is to establish cause and effect.

A Perfect Graph Can Still Describe an Imperfect Loudspeaker

Measurement invites the temptation to optimize whatever is easiest to display. Frequency response is an obvious example. Because a smooth curve is visually satisfying, the designer may gradually begin treating straightness as the objective rather than one indication of good behavior. An equalizer or complicated crossover can sometimes flatten the visible response while leaving the underlying mechanical problem intact. A diaphragm in severe breakup does not become well-behaved because its resulting response peak has been electrically reduced. A cabinet resonance does not cease storing energy because equalization lowers its apparent amplitude. An abrupt change in directivity cannot be repaired simply by making the on-axis response straighter.

The purpose of measurement is to understand the physical behavior of the loudspeaker, not to manufacture attractive graphs.

Interpretation Matters More Than Numbers

Measurements do not explain themselves. A five-decibel irregularity caused by a broad change in radiation may have a different significance from a narrow five-decibel resonance caused by diaphragm breakup. A small distortion component in a sensitive part of the audible range may matter more than a numerically larger one somewhere else. Engineering judgment remains necessary even with exceptionally sophisticated instrumentation. The instrument reports what occurred under the measurement conditions. The engineer must determine what physical mechanism produced it, whether the test represents actual use, and whether the behavior is important enough to require correction.

Numbers acquire meaning only when connected to causes.

A Technical Standard Is a Boundary, Not a Preference

Over time, a technical standard stops being a target and becomes a boundary condition. It defines what is acceptable and what is not. If a loudspeaker does not meet that standard, it is not considered “almost good enough” or “good in some ways.” It is a failure of execution, and it does not proceed further in development or into production.

This is not a matter of taste or severity. It is the consequence of a simple question that originally motivated the work: what is the difference between a loudspeaker that merely reproduces sound and one that convincingly preserves the character and emotional intent of the music? That question came from listening to claims in commercial descriptions that certain loudspeakers “captured the emotion of the music.” Repeated comparison showed that some designs did, in fact, preserve that quality, while others did not, even when their specifications appeared similar. The difference was not rhetorical. It was physical, measurable, and repeatable.

The technical standard that emerged from that inquiry is therefore not arbitrary. It is a distilled set of conditions that must be satisfied for a loudspeaker to be considered successful. If those conditions are not met, the design is not refined further. It is rejected.

Measurement Protects Us From Ourselves

Designers are particularly vulnerable to attachment. An expensive driver, beautiful cabinet, or crossover that required days of difficult work naturally encourages the hope that the effort produced something better. Expectation can influence listening, especially when the designer already knows what has been changed.

The measurement instrument has no such emotional investment. It does not care how expensive the component was, how elegant the theory appeared, or how long the modification took. If a resonance remains, it remains. If distortion increased, it increased.

This does not make the instrument infallible. The wrong measurement, poorly performed, can produce equally misleading conclusions. Its value lies in providing independent physical evidence that can challenge our expectations.

Reality deserves the final vote.

Listening Completes the Measurement

Whenever a measurement reveals something unexpected, I want to know whether I can hear its consequences. Whenever listening reveals something unexpected, I want to find the mechanism responsible.

Suppose a resonance appears near 3,000 Hz. The next question is whether voices or instruments acquire a persistent emphasis in that region. If extended listening produces fatigue despite a smooth forward response, it may be useful to investigate breakup, stored energy, distortion, or irregular off-axis behavior. If the stereo image shifts with pitch, crossover phase, driver spacing, lobing, and channel matching deserve examination.

Neither process weakens the other. Listening gives measurements relevance, while measurements give listening explanation. When they appear to disagree, the disagreement is valuable because it usually means something has not yet been understood.

Document Everything

A measurement has limited value if nobody can later remember how it was obtained. Driver, cabinet, crossover revision, microphone position, distance, amplifier, test level, and important room conditions should therefore be documented along with the result.

This becomes increasingly important during long development projects. Months or years later, an old measurement may explain why an abandoned prototype behaved strangely or reveal a solution applicable to a completely different design. Photographs, measurements, and listening notes collectively transform individual experiments into accumulated engineering knowledge.

Memory changes. Documentation preserves the evidence.

Measure, Listen, Understand, Improve

The purpose of measurement is not to prove that a loudspeaker is good. It is to reveal how the loudspeaker behaves, test predictions, expose problems, and provide repeatable evidence from which better decisions can be made.

The final judgment remains musical. A design must withstand objective measurement, but it must also survive careful listening against a meaningful reference. Confidence becomes justified when the physical evidence and the listening experience tell the same story. When they do not, neither should be conveniently ignored.

That cycle forms the basis of a useful measurement philosophy: measure what matters, understand what the measurement means, listen for its consequences, and use what you learn to improve the design.

Measure. Listen. Understand. Improve.

Chapter 10
How Do Amplifiers and Loudspeakers Interact?

A loudspeaker does not operate by itself. It is the final electrical load connected to the power amplifier, and the behavior of each can influence the other. This relationship has accumulated an extraordinary amount of mythology involving watts, cables, damping factor, amplifier type, and the mysterious concept of “matching.”

The reality is both simpler and more interesting. Amplifiers matter, but they do not matter equally under all conditions. The important requirement is not mystical compatibility. It is engineering compatibility.

Keep the Problems in Perspective

The loudspeaker is usually the least accurate component in a modern audio system. Even excellent loudspeakers produce considerably more distortion, frequency-response variation, and acoustic irregularity than a competent amplifier operating comfortably within its limits.

This does not mean all amplifiers sound identical. It means that changing amplifiers cannot correct a woofer in severe breakup, a resonant cabinet, an improperly integrated crossover, or badly controlled dispersion. If those problems dominate the reproduction, changing from one competent amplifier to another is unlikely to transform the system.

Good engineering solves the largest problems first. Improve the loudspeaker, then make sure the amplifier is capable of driving it properly.

How Much Power Do You Need?

The first requirement is enough clean power. Power requirements depend upon loudspeaker sensitivity, listening distance, room size, musical material, and desired volume. A highly sensitive loudspeaker used for moderate listening may require surprisingly little amplifier power. A less sensitive system reproducing demanding music at realistic levels may require considerably more. Average listening level can be misleading because music contains brief peaks far above its average energy. Those peaks are part of the performance and should be reproduced without the amplifier running out of capability. This reserve is called headroom. An amplifier should have enough of it that ordinary musical peaks do not continually push the amplifier into overload.

What Is Clipping?

An amplifier can only produce so much voltage and current. Ask for more, and it eventually reaches its limits. Instead of continuing to reproduce the waveform correctly, the tops and bottoms of the signal become flattened. This is called clipping. Clipping produces severe distortion and additional high-frequency energy. This creates an interesting paradox: an amplifier that is too small can sometimes damage a tweeter more readily than a larger amplifier used responsibly because the smaller amplifier is continually being driven beyond its clean operating range.

The lesson is not that everyone needs an enormous amplifier. It is that the amplifier should be appropriately sized for the loudspeaker and the way it will actually be used.

The Loudspeaker Is Not Simply “8 Ohms”

A loudspeaker marked 8 ohms does not present an 8-ohm resistance at every frequency. Loudspeaker impedance changes because drivers, crossover components, and enclosure resonances create a complex electrical load. At some frequencies, the impedance may rise considerably. At others, it may fall below the nominal rating. The electrical phase of the load also changes, meaning that voltage and current do not always rise and fall together as they would in a simple resistor. A good amplifier should remain stable while driving this real loudspeaker load rather than behaving properly only when connected to a laboratory resistor. Some loudspeakers make modest demands. Others require greater current capability or place more difficult reactive loads on the amplifier.

That is genuine amplifier and loudspeaker matching. It is electrical engineering, not personality.

What Is Damping Factor?

Damping factor describes the relationship between loudspeaker impedance and amplifier output impedance. In broad terms, a lower amplifier output impedance gives the amplifier greater electrical influence over the motion of the driver, particularly around resonance. It is tempting to conclude that if a damping factor of 50 is useful, 500 must be ten times better and 5,000 better still. Real systems do not work that way.

The loudspeaker is connected to the amplifier through cable, connectors, crossover components, and the resistance of the driver’s voice coil. All of these contribute resistance. Eventually, they dominate the improvement available from making the amplifier output impedance still lower. The first improvements in damping can matter considerably. Beyond a reasonable point, progressively larger damping-factor numbers usually produce progressively smaller benefits. This is a classic case of diminishing returns.

The Cable Is Part of the Circuit

Loudspeaker cable has inspired claims ranging from reasonable to extraordinary. From a basic engineering standpoint, one of its most important characteristics is simply resistance. Every foot of cable adds some resistance between the amplifier and loudspeaker. Excessive resistance can reduce effective damping, slightly alter crossover behavior, and change the low-frequency alignment of the system. Long cable runs or wire that is too small for the required current therefore deserve attention. The solution is not mysterious. Use an appropriate wire gauge for the distance and current, avoid unnecessary length, and use reliable connectors with sound mechanical contact. Once those requirements are satisfied, the cable should largely disappear from the engineering problem.

A cable’s finest achievement is to provide no reason to think about it.

Tube or Solid-State?

Arguments about tube and solid-state amplifiers often become ideological, although both technologies are capable of excellent performance when properly engineered. Solid-state amplifiers usually provide relatively low output impedance, substantial power, and wide bandwidth economically.

Tube amplifiers often have higher output impedance and therefore interact somewhat more strongly with variations in loudspeaker impedance. Their output transformers introduce additional engineering considerations, but a well-designed tube amplifier appropriately matched to the loudspeaker can produce excellent results. Neither technology guarantees quality. An expensive tube does not rescue a poor circuit, and a fashionable transistor does not create a good amplifier automatically. The engineering surrounding the active devices matters more than allegiance to the devices themselves.

What About Active Loudspeakers?

In an active loudspeaker system, the crossover operates before the power amplifiers, and each amplifier usually drives its assigned driver directly. This removes large passive crossover components from the high-power signal path and allows level, crossover frequency, and other characteristics to be adjusted more easily.

Active systems can therefore provide excellent engineering flexibility. They are particularly useful during development because changes can be evaluated without repeatedly rebuilding passive crossover networks. They can also allow amplifiers to be selected according to the particular requirements of the woofer, midrange, or tweeter. This does not mean passive crossovers are inherently inferior. It means active and passive systems solve the same problem differently, and each approach has advantages depending upon the design objective.

Good Matching Is Not Mysterious

A properly matched amplifier should possess enough clean power for the intended use, remain stable into the loudspeaker's actual impedance, provide reasonable electrical damping, contribute acceptably low noise and distortion, and operate reliably.

Some loudspeakers require substantial current. Very efficient loudspeakers may make amplifier noise particularly important. A high-output-impedance tube amplifier may interact more noticeably with a varying loudspeaker impedance than a low-output-impedance solid-state design. These are real effects and can be understood without invoking mysterious synergy.

Once those requirements are satisfied, amplifier differences can certainly remain worth exploring, particularly in a highly refined system. They should simply be kept in proportion to the errors elsewhere in the reproduction chain. The amplifier exists to provide the loudspeaker with the electrical signal and power it requires, without becoming the limiting factor. Choose an amplifier that can drive the loudspeaker properly. Then stop listening to the amplifier and return to listening to the music.

Chapter 11
The Room Is Part of the Loudspeaker System

We often talk about a loudspeaker as though its performance ends at the cabinet. It does not. The moment sound leaves the loudspeaker, it enters another acoustic system created by the room. Walls, floor, ceiling, furniture, openings, speaker position, and listener position all influence what finally reaches your ears. The loudspeaker creates the sound field, but the room helps determine what you actually hear. This is why the same loudspeaker can sound remarkably different in two rooms, or even in two positions within the same room.

You Hear More Than the Direct Sound

Some sound travels directly from the loudspeaker to the listener. Other sound travels toward the floor, ceiling, and walls, reflects, and arrives shortly afterward. The listener hears all of it. These reflections are not automatically bad. Real musical performances occur in acoustic spaces filled with reflections, and a completely reflection-free listening room would be both impractical and unnatural. The important question is whether the reflected sound supports the direct sound or contradicts it.

This is one reason loudspeaker directivity matters so much. If a loudspeaker changes character drastically away from its forward axis, the sound sent toward the room boundaries may have a substantially different tonal balance from the sound sent directly toward the listener. The room then returns that different balance through reflections.

A loudspeaker with smooth off-axis behavior gives the room more sensible material to work with.

Walls Affect Bass

Low frequencies have wavelengths comparable to the dimensions of ordinary rooms, so they interact strongly with boundaries. Move a loudspeaker closer to a wall, and low-frequency output usually increases. Move it near two intersecting walls, such as into a corner, and the reinforcement may become greater still. This can be useful when understood and troublesome when accidental.

Placement therefore becomes part of low-frequency system design. A loudspeaker engineered to produce balanced bass well away from boundaries may sound excessively heavy when pushed into a corner. Another design may have been intended to use wall reinforcement deliberately. No universally correct distance from the wall exists because the answer depends upon the loudspeaker, room dimensions, listening position, and intended alignment.

Rooms Have Resonances Too

A room is itself an acoustic enclosure and therefore possesses resonances, often called room modes. At some frequencies, reflected waves reinforce one another and produce excessive bass. At other positions or frequencies, they partially cancel and create deep reductions in output. This explains why moving a chair or loudspeaker by a surprisingly small distance can sometimes produce a large change in bass. The loudspeaker may not have changed at all. What changed is the relationship among the loudspeaker, listener, and standing-wave pattern within the room.

Trying to correct every bass problem with equalization can therefore be misleading. If the listening position sits in a strong cancellation, adding more electrical power at that frequency may accomplish little except forcing the woofer to work harder.

Before changing the loudspeaker, investigate the room.

The Floor Is a Boundary Too

The floor is easily overlooked because the loudspeaker has to stand somewhere, but it is one of the nearest major reflective surfaces. Direct sound from the woofer reaches the listener along one path, while another portion reflects from the floor and travels a slightly longer path. At some frequencies, these two arrivals can partially cancel, producing what is commonly called floor bounce.

Driver height, listening distance, and listener height all influence where this occurs. Moving the loudspeaker, changing the listening position, or altering the height of the system can change the result. The effect is another reminder that what reaches the listener depends upon geometry as well as the loudspeaker's electrical frequency response.

Sidewalls Affect More Than Tone

Early reflections from sidewalls influence stereo reproduction as well as tonal balance. Depending upon their strength, timing, and spectrum, they can increase apparent spaciousness, blur image location, or pull attention toward one side of the room.

Speaker spacing and toe-in, therefore, interact with the room. Turning a loudspeaker inward changes not only where its forward axis points but also the amount and spectral balance of energy reaching the sidewalls. The correct amount of toe-in is not determined by fashion or by making the speakers form some theoretically perfect geometric shape. It is the position that allows the loudspeaker's dispersion pattern, the room, and the listening position to work together sensibly.

Symmetry Helps Stereo

Stereo reproduction depends upon the left and right loudspeakers establishing reasonably similar relationships with the listener. If one loudspeaker is close to a solid wall while the other faces an open doorway, their reflected environments are different even if the loudspeakers themselves are perfectly matched. This can weaken the phantom center or alter image position. Moving the loudspeakers, adjusting the listening position, or changing nearby furnishings may correct what initially sounds like a defect in the speakers themselves. Perfect symmetry is rarely available in an ordinary home, nor is it always necessary. The objective is reasonable acoustic balance rather than architectural perfection.

The Listening Chair Is Part of the Setup

People often spend considerable time positioning loudspeakers while assuming the chair has only one possible location. Moving the listener can be just as important. A listening position near the center of certain room dimensions may coincide with strong modal cancellations. Sitting very close to a rear wall may produce excessive bass and strong early reflections.

Moving forward or backward a relatively modest distance may substantially improve both tonal balance and stereo imaging. This is especially useful because moving the chair costs nothing and introduces no new electronics. Before redesigning the system, move something.

Do You Need Acoustic Treatment?

Sometimes. Absorption can reduce troublesome reflections and excessive reverberation. Diffusion can scatter reflected energy rather than simply absorbing it. Bass trapping can reduce the severity of some low-frequency resonances.

The mistake is assuming that more treatment is always better. An excessively absorptive room can sound unnatural and may remove useful spatial information while leaving difficult low-frequency problems largely untouched. Acoustic treatment should solve an identified problem rather than become decoration applied according to a formula. Furniture, rugs, curtains, bookshelves, and irregular room surfaces already provide useful absorption and diffusion in many domestic rooms. A normal living room need not be transformed into a recording studio to support good reproduction.

Do Not Design for One Perfect Point

A reference listening position is valuable because it makes comparisons repeatable, but people move. They change posture, lean forward, sit at slightly different heights, and occasionally listen with someone else.

A good loudspeaker should therefore change gracefully as the listener moves. Stereo precision will naturally diminish outside the preferred area, but tonal balance should not collapse suddenly because the listener moved a few inches. This is another reason smooth directivity and well-controlled crossover lobing matter. The goal is not identical sound everywhere. It is a useful listening area rather than one theoretically perfect coordinate.

The Room Should Be Investigated, Not Blamed

When something sounds wrong, it is tempting either to blame the loudspeaker immediately or to dismiss every problem as “the room.” Neither approach teaches us much.

If bass is excessive, determine whether the cabinet alignment, boundary position, or a room mode is responsible. If the phantom center pulls to one side, investigate speaker matching, placement, and room asymmetry. If the sound is aggressive, consider whether early reflections are contributing before altering the crossover. Changing one thing and observing the result often reveals the cause surprisingly quickly.

A loudspeaker cannot be made immune to rooms. The objective is to design one whose behavior is predictable enough that sensible placement and ordinary acoustic conditions allow it to perform well in many rooms rather than only in the room where it was developed. The cabinet, drivers, and crossover create the loudspeaker. The room completes the system.

Good reproduction begins with a well-designed loudspeaker, but it ends only when the loudspeaker, room, and listener work together.

Chapter 12
Speaking Speaker-Speak

Loudspeaker engineering has its own vocabulary. Unfortunately, perfectly simple ideas can sound intimidating when described with unfamiliar technical terms. Here are some of the terms you will encounter, translated into reasonably normal English.

Alignment - The overall way a woofer, cabinet, and any vent or other acoustic loading are designed to work together. Sealed, vented, and aperiodic systems are different alignments. Think of alignment as the operating arrangement of the bass system, not simply the shape of the box.

Aperiodic - An enclosure that deliberately allows a carefully controlled amount of air to escape through a resistive vent. It falls somewhere between a completely sealed box and an open one. The resistance helps control the woofer and reduce resonance.

Breakup - A loudspeaker diaphragm is supposed to move as one piece. Eventually, it doesn't. At sufficiently high frequencies, different portions of the cone or dome begin moving somewhat independently. This is called breakup and can produce resonances, distortion, and changes in radiation.

Crossover - The part of a loudspeaker system that determines which frequencies go to which drivers. The woofer gets the lows. The tweeter gets the highs. In a three-way system, the midrange gets the frequencies between them. The region where responsibility passes from one driver to another is the crossover region.

Damping / Damped - Damping is the control or removal of unwanted motion or resonance. Imagine striking a bell. It rings. Now put your hand against it. The ringing stops quickly. You have damped it. In a loudspeaker, damping can be mechanical, electrical, or acoustic. Good damping helps the speaker stop producing sound when the signal tells it to stop.

Directivity - A description of how strongly a loudspeaker sends sound in different directions. A driver may radiate broadly at one frequency and much more narrowly at another. Directivity matters because you hear not only the sound traveling directly from the loudspeaker to your ears, but also sound reflected from the room.

Dispersion - Closely related to directivity, dispersion describes how sound spreads from a loudspeaker. Wide dispersion spreads useful sound over a broad angle. Narrow dispersion concentrates it into a smaller area. Neither is automatically good or bad. What matters is whether the dispersion is appropriate and changes smoothly with frequency.

Driver - The component that actually converts electrical energy into sound. Woofers, midranges, and tweeters are all drivers. The complete box containing them is a loudspeaker or loudspeaker system. Calling the entire loudspeaker a "driver" is rather like calling an automobile an engine.

Efficiency - How effectively a loudspeaker converts electrical power into acoustic power. An efficient loudspeaker produces more acoustic output from a given amount of electrical input. Efficiency and sensitivity are related, but they are not technically the same thing.

F3 - A useful indication of how far a loudspeaker's frequency range extends. F3 is the frequency at which output has fallen by 3 decibels from its reference level. When someone says a speaker has an F3 of 40 Hz, he is giving you considerably more useful information than simply claiming that it "goes down to 20 Hz."

Frequency - How rapidly something vibrates, measured in Hertz (Hz), or cycles per second. Low frequencies are perceived as bass. High frequencies are perceived as treble. Humans with excellent hearing can roughly hear frequencies between 20 Hz and 20,000 Hz, although the upper limit normally decreases with age.

Frequency Response - A measurement showing how a device responds to different frequencies. For a loudspeaker, it tells us whether some frequencies are reproduced more strongly or weakly than others. Frequency response is important. It is not, however, a complete description of sound quality.

Impedance - The opposition a loudspeaker presents to the electrical signal from the amplifier, measured in ohms (Ω). Impedance is somewhat like resistance, except that a loudspeaker's impedance changes with frequency because a loudspeaker is an electromechanical device rather than a simple resistor. This is why an "8-ohm loudspeaker" is not necessarily 8 ohms at every frequency.

Lobing - When two sound sources reproduce some of the same frequencies, their sound waves can reinforce each other in some directions and partially cancel in others. The resulting radiation pattern develops areas of stronger and weaker output called lobes. Poorly controlled lobing can make a loudspeaker sound different when you move your head or change listening height.

Off-Axis - Any listening or measurement position that is not directly in front of the loudspeaker. Zero degrees is usually considered on-axis. Move sideways or vertically and you are off-axis. Off-axis performance matters because most of the sound radiated into a normal room does not travel directly toward the listener.

Phase - The timing relationship between repeating waves. Two waves arriving together may reinforce each other. Change their relative phase and they may partially or completely cancel. Phase becomes particularly important where two loudspeaker drivers operate simultaneously, such as through a crossover region.

Q - A number describing how strongly a resonant system tends to resonate. A high-Q resonance is strong and relatively narrow. A low-Q resonance is more heavily damped and spread over a wider range. An easy mental picture is a bell. A bell that rings strongly for a long time behaves somewhat like a high-Q system. Touch it with your hand, and the ringing dies quickly. You have lowered its effective Q by adding damping. In loudspeaker design, you may encounter several different Q values, such as Qts, Qes, Qms, and Qtc. They describe different aspects of the driver's or completed system's behavior.

Radiation - The act of sending acoustic energy into the surrounding air. A loudspeaker diaphragm moves. That movement disturbs the air. The disturbance travels away as sound. That is acoustic radiation. The directions in which that energy travels form the loudspeaker's radiation pattern.

Resonance - The tendency of a physical system to respond particularly strongly at a certain frequency. A wineglass has resonance. So does a guitar string. So does a loudspeaker cone, cabinet panel, column of air, and listening room. Some resonances are useful. Others add sound that wasn't present in the original signal. Much of good loudspeaker engineering involves knowing the difference.

Sensitivity - How loudly a loudspeaker plays for a specified electrical input, usually measured at a specified distance. A more sensitive loudspeaker requires less amplifier power to produce a given sound level. Sensitivity should not be confused with sound quality. A speaker can be extremely sensitive and terrible, or relatively insensitive and excellent.

Stored Energy - Energy that remains in a loudspeaker after the original signal that excited it has changed or stopped. Think again of the ringing bell. If a musical event stops but some part of the loudspeaker wants to continue vibrating, the speaker is adding its own little contribution to the performance. Generally, we don't want it to.

Transient - A rapid change in a signal. The initial strike of a drum, pluck of a string, or attack of a piano note contains transient information. Transients are important because they help the ear identify instruments and perceive timing, position, and musical relationships.

Tweeter - A driver designed primarily to reproduce high frequencies. Because high-frequency wavelengths are short, tweeters are usually much smaller than woofers.

Woofer - A driver designed primarily to reproduce lower frequencies. Contrary to popular usage, not every driver producing bass is a subwoofer. A woofer normally reproduces bass as part of the main loudspeaker's operating range.

The Important Part

You do not need to memorize any of this. When you encounter one of these terms elsewhere in the Library, come back here and look it up. Before long, Q, impedance, directivity, damping, and lobing will stop sounding like mysterious engineering language and start describing things you can actually visualize. And once you can visualize what a loudspeaker is doing, understanding why it sounds the way it does becomes much easier.