The Real Science Behind Audio Speaker Wires

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Abstract

A lot of pseudoscience are being tossed around audiophile shops, manufacturers and the internet regarding speaker wiring and how it affects sound quality. Manufacturers and resellers want you to believe that spending thousands of dollars on speaker wires are justified as it can make a substantial difference in audio quality when compared to cheaper wires.

In this article I will investigate some of these claims by applying scientific analysis to the electrical circuit formed by speaker wiring, and comparing the science with these claims. I will establish baseline criteria for when an effect is considered audible, in order to gauge the scientific results with human perception. The article will conclude by summarising that most of these claims are indeed false and with no scientific basis.

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Chapter 1

Introduction

In the audiophile industry there seems to be an abundance of misinformation and downright lies regarding the choice of speaker wiring for hi-fi equipment. It appears to be motivated by a need to exploit wealthy individuals with pseudoscience and marketing propaganda. When buying in to a high end audio system, the cost of the system can easily surpass the $100,000 mark. Since it is mostly wealthy individuals that can afford these systems, they make easy targets for manufacturers of audio cables to exploit their ignorance by convincing them of advantages their products have above the competition, that are largely just untrue and then charging ridiculous amounts of money for these supposedly superior wires.

To be more specific, there are many options to choose from when trying to connect your high end speakers to your amplifier / receiver. You can be cheap and buy something like this for $0.46 per foot or these cables for $302 per foot. And those are not just the extremes. Here are run of the mill high end audio cables from a run of the mill hi-fi shop in my neighbourhood for $312 per foot (these come with batteries, mind you...).

In order to keep this article manageable, I have limited the claims I will investigate to the following:

1. OFC (Oxygen Free Copper)
2. Skin Effect
3. Directional Cables
4. Break-in
5. Bi-wiring

6. Dielectric / Capacitance

7. Phase Shifts & Dispersion

These are just some of the more common terms thrown around by hi-fi specialists and manufacturers. The problem with many of these concepts is that most of them are based on real, scientific concepts. What I want to prove is that while some of these claims are just wrong, those that have some scientific basis are just not important, the same way you will not miss a very faint star you never knew was there, disappearing one night from the sky.

Chapter 2

Claims Investigated

2.1 OFC (Oxygen Free Copper)

Most manufacturers claim that copper cable that is free in oxygen is somehow superior to normal copper cable. To understand this claim, one first needs to understand a little bit more about metallurgy.

No commercially available copper is truly oxygen free. Some come very close though, having only 0.0005% oxygen content. Standard (cheap) copper wires are based on ETC copper (Electrolytic-Tough-Pitch) - also known as C11000 according to ASTM/UNS. It has a conductivity rating of 101% IACS (International Annealed Copper Standard) and oxygen content of approximately 0.03%. High grade OFC audio wires are based on C10200, which has a conductivity rating of 101% IACS and has an oxygen content of approximately 0.001%. It has exactly the same conductivity as the much cheaper copper. Super high grade OFC audio cable is made out of C10100, and it has a conductivity rating of 101% IACS and oxygen content of approximately 0.0005%. Ultra pure copper has a conductivity rating of 102.75%.

Therefore, from an electrical conductivity point of view, OFC cables and standard ETP based copper cables perform identically.

Conclusion: OFC is irrelevant. All speaker cables are already “OFC”, i.e. low in oxygen.

2.2 Skin Effect

When a change in current occurs in a conductor (such as with alternating current), a magnetic field forms in concentric circles around the conductor. This changing field creates an electric field that opposes the change in current, also known as the back e.m.f. (electromotive force), which causes new magnetic fields to form and repeating the process. Eventually a steady state condition is reached whereby the electric field inside the conductor is reduced compared to the outside, forcing the current to flow closer to the surface of the conductor. A picture is worth a thousand words:

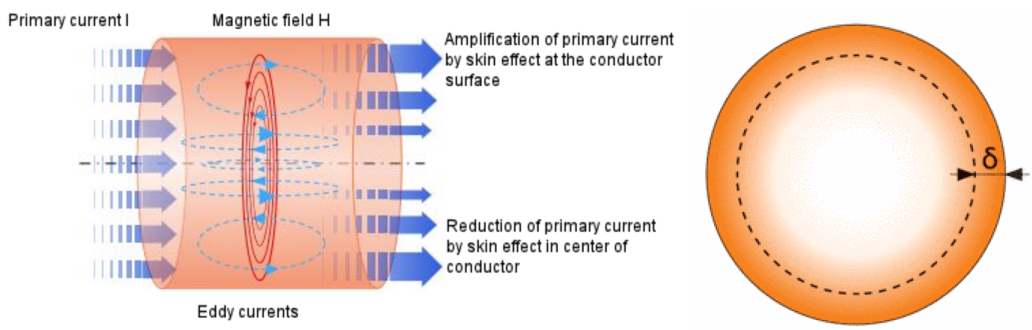

Figure 2.1: Skin Effect showing cross section of a speaker cable

Above is an illustration of a cross section of a copper wire. Brown indicates the current (electrons) moving through the conductor. The darker regions towards the outer edge of the conductor indicate that current tends to migrate outwards and flow on the surface only, increasing density there. In specific, 63% $(1 - 1/e)$ of the current will be flowing in the cylindrical section marked by δ and called the skin depth (remember, this applies to alternating current, which is the kind of current that flows through ALL external analogue wires in a home theatre system. Direct current does not exhibit skin effect).

The problem manufacturers try to address is that, according to them, skin effect affects audio quality as it effectively reduces the area available for current to flow, thereby increasing resistance. Additional claims are that this introduces phase shifts due to changing impedance vs. frequency, and that larger conductors makes things worse as it enhances the skin effect. They go to great lengths to reduce skin effect, including making use of thinner Litz wire (individually isolated thin copper strands bundled and weaved together to try and maximise surface area and reduce skin effect - very useful for high frequency applications such as RF).

Let's dig a bit deeper into this issue. The skin depth can be calculated using the following formula:

$$\delta = \sqrt{\frac{2\rho}{\omega\mu}}\sqrt{\sqrt{1+(\rho\omega\epsilon)^2}+\rho\omega\epsilon} \tag{2.1}$$

ρ is the resistivity of the conductor in $\Omega\,\mathrm{m}$
ω is the angular frequency of the current, given by $2\pi f$ with f in Hz
μ is the absolute magnetic permeability of the conductor in $\mathrm{H\,m^{-1}}$
ϵ is the absolute permittivity of the conductor in $\mathrm{F\,m^{-1}}$

For frequencies much below 10^{18} Hz in a good conducting metal such as copper, the equation can be simplified to:

$$\delta = \sqrt{\frac{2\rho}{\omega\mu}} \tag{2.2}$$

No audio amplifier or speaker in an audiophile setting even comes close to 10^5 Hz, which is 13 orders of magnitude lower than above, so the formula is applicable to our use case. To determine skin depth, let's calculate it for the lowest of audio frequencies as well as the highest. Firstly, a human ear cannot hear below 12 Hz or higher than 28 kHz in ideal laboratory conditions. In non ideal conditions (those outside of laboratories or anechoic chambers), the human ear can detect a maximum range of 15 Hz - 22 kHz. That said, all people gain a gradual hearing loss in the upper frequencies as they age, which just gets worse the older you get. Most adults cannot hear much above 16 kHz. Let's calculate skin depth at these upper bound frequencies:

$$\begin{aligned}
\delta_{15Hz} &= \sqrt{\frac{2(1.68\times10^{-8})}{2\pi(15)(0.999994\times1.256\,637\,53\times10^{-6})}} \\
&= 16.8\,\mathrm{mm} \\
\delta_{22kHz} &= \sqrt{\frac{2(1.68\times10^{-8})}{2\pi(22000)(0.999994\times1.256\,637\,53\times10^{-6})}} \\
&= 0.440\,\mathrm{mm}
\end{aligned}$$

assuming $\rho = 1.68\times10^{-8}\,\Omega\,\mathrm{m}$ for copper, $\mu_r = 0.999994$ for copper and $\mu_0 = 1.256\,637\,53\times10^{-6}\,\mathrm{H\,m^{-1}}$.

Let's analyse these results. At 15 Hz, 63% of the current will be flowing through a hollow cylinder with a thickness of almost 17 mm. There is a North American standard for classifying wire based on its diameter, called AWG. The lower the number, the thicker the wire and vice versa. Below are some common sizes used in the audio industry:

AWG	Diameter (mm)	Cross Sectional Area (mm^2)	Resistance ($\mathrm{m\Omega\,m^{-1}}$)
8	3.264	8.37	2.061
10	2.588	5.26	3.277
12	2.053	3.31	5.211
14	1.628	2.08	8.286
16	1.291	1.31	13.17
18	1.024	0.823	20.95
24	0.511	0.205	84.22

Table 2.1: AWG wire sizes

So let's consider AWG14 wire - very common for speaker cables. At 15 Hz, the skin depth vastly exceeds the radius of the wire (16.8 mm vs 0.814 mm). That means the skin effect is negligible and the whole cross sectional area of the conductor will carry current. At 22 kHz, the skin depth is just more than half the radius of the wire (0.440 mm vs 0.814 mm). That means the skin effect is not negligible and some losses will occur. These losses are what they claim affects audio quality and degrades performance. To determine whether that is true, we need to dig a bit deeper into exactly how skin depth affects resistivity.

$$R_{ac} = \frac{\rho l}{A_{eff}} \tag{2.3}$$

ρ is the resistivity of the conductor in $\Omega\,\mathrm{m}$.
l is the length of conductor in m.
A_{eff} is the effective cross sectional area used in m^2.

For the remainder of this article I am going to use a 20 m run of AWG14 copper wire, having a total length $l = 40\,\mathrm{m}$ (including the return path) and a conductor diameter of 1.628 mm. The two conductors are spaced apart by 4 mm and isolated in PVC (zip cord). Regardless whether this is "OFC" or not, it will have a resistivity $\rho = 1.68\times10^{-8}\,\Omega\,\mathrm{m}$ at 20 °C.

Skin effect will change A_{eff} such that the effective area will become smaller as the frequency increases. Using http://www.g3ynh.info/zdocs/comps/Zint.pdf A_{eff} can be calculated:

$$A_{eff} = \pi(d\delta' - \delta'^2)(1 + Y) \tag{2.4}$$

with

$$\begin{aligned}
\delta' &= \delta[1 - e^{-d/(2\delta)}] \\
Z &= \frac{0.62006d}{2\delta} \\
Y &= \frac{0.189774}{(1 + 0.272481[Z^{1.82938} - Z^{-0.99457}]^2)^{1.0941}}
\end{aligned}$$

with δ the skin depth and d the diameter of the wire, in m. For our case this becomes:

$$\begin{aligned}
Z &= \frac{0.62006 \times 1.628\times10^{-3}}{2 \times 0.440\times10^{-3}} \\
&= 1.14761 \\
Y &= \frac{0.189774}{(1 + 0.272481[1.14761^{1.82938} - 1.14761^{-0.99457}]^2)^{1.0941}} \\
&= 0.180513 \\
\delta' &= 0.440\times10^{-3}[1 - e^{-1.628\times10^{-3}/(2\times0.440\times10^{-3})}] \\
&= 0.0003707 \\
A_{eff} &= \pi(1.628\times10^{-3} \times 0.0003707 - 0.0003707^2)(1 + 0.180513) \\
&= 1.728\,59\times10^{-6}\,\mathrm{m}^2
\end{aligned}$$

Substituting back in 2.3:

$$\begin{aligned}
R_{ac,22kHz} &= \frac{1.68\times10^{-8} \times 40}{1.728\,59\times10^{-6}} \\
&= 0.388\,\Omega
\end{aligned} \tag{2.5}$$

and for 15Hz:

$$
\begin{aligned}
R_{ac,15Hz} &= \frac{1.68\times10^{-8} \times 40}{2.081\,22\times10^{-6}} \\
&= 0.322\,\Omega \qquad (2.6)
\end{aligned}
$$

This means, for a 40 m run of AWG14 copper wire, there is a resistance of $0.388\,\Omega$ at 22 kHz caused both by the DC resistivity of copper as well as the AC skin effect at 22 kHz.

Let's calculate the resistance for DC (where $A_{eff} = A_{total}$):

$$
\begin{aligned}
R_{dc} &= \frac{1.68\times10^{-8} \times 40}{\pi \times [\frac{1.628\times10^{-3}}{2}]^2} \\
&= 0.322\,\Omega
\end{aligned}
$$

Therefore, the contribution of skin effect to the total resistance of the 40 m run of speaker wire is $R_{ac} - R_{dc} = 0.066\,\Omega$. This additional resistance causes a voltage drop of:

$$P = I^2 R$$

for an amplifier delivering 150 W into an $8\,\Omega$ speaker assuming lossless speaker cables the current flowing will be:

$$
\begin{aligned}
I &= \sqrt{\frac{P}{R}} \\
&= \sqrt{\frac{150}{8}} \\
&= 4.33\,\mathrm{A}
\end{aligned}
$$

Therefore, the voltage drop caused by this resistance will be:

$$
\begin{aligned}
V_{loss} &= IR_{loss} \\
&= 4.33 \times 0.0066 \\
&= 0.028\,578\,\mathrm{V} \\
V_{in} &= IR_{load} \\
&= 4.33 * 8 \\
&= 34.64\,\mathrm{V} \\
V_{out} &= V_{in} - V_{loss} \\
&= 34.64 - 0.028578 \\
&= 34.6114\,\mathrm{V}
\end{aligned}
$$

From this we can calculate the gain (i.e. loss) in dB:

$$
\begin{aligned}
G &= 20 \log \frac{V_{\mathrm{out}}}{V_{\mathrm{in}}} \\
&= 20 \log_{10} \left[\frac{34.6114}{34.64} \right] \\
&= -0.007\,\mathrm{dB}
\end{aligned}
$$

Humans can detect changes in loudness of approximately 1 dB. A change in loudness of -0.007 dB will be inaudible by a a factor of at least 100.

Another claim made is that skin effect causes varying amount of resistance as the frequency changes, introducing phase shifts which causes high and low frequency sounds to become somehow shifted in time and hence out of phase. This is pure nonsense from multiple different point of views.

Firstly, skin effect causes increased resistance with increasing frequency (up to a certain point, called the characteristic impedance). That means, the high frequency signals will be attenuated more than the lower frequency signals. This is not a shift in phase - although a phase shift is introduced as a consequence of this circuit now becoming a "lossy" conductor as will be explained later. Capacitance and inductance can introduce a phase shift. However, the phase shift will be between the voltage and current signals, which will only lower power output (as power is the product of voltage and current) but it will not somehow alter the phase between frequencies - remember, it is the current delivered to the speakers that make them move, a change in phase between voltage and current only alters the power level as power is calculated as $P = V_{rms} I_{rms} \cos(\theta)$, with θ the phase shift or power factor.

Conclusion: Skin effect is negligible and has no perceivable effect on audio quality.

2.3 Directional Cables

Many speaker cable manufacturers will have you believe that speaker cables somehow are directional, meaning if you swopped the endpoints and connected the cable the other way round (between the amplifier and speakers), it would somehow not sound as good. They say things like "All cables are directional" or "The difference will be clear - in the correct direction the music is more relaxed, pleasant and believable. While cable directionality is not fully understood, it is clear that the molecular structure of drawn metal is not symmetrical, providing a physical explanation for the existence of directionality.". Some claim that the reason is due to wires being "diodic" (exhibiting a diode or rectification effect whereby current is allowed better in one direction than the other) due to the crystal lattice in the wire and the way the wire was drawn when it was manufactured.

Let's analyse that claim. Firstly, I am going to apply logical deductive reasoning. A speaker cable carries alternating current. Alternating current looks as follow:

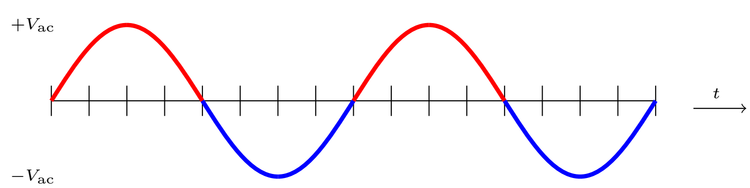

Figure 2.2: Two complete wavelengths of AC

The red parts indicate positive current flow, i.e. current flows in one direction. Blue parts indicate negative current flow, i.e. current flows in opposite direction. For audio signals, exactly half of the time current is flowing in one direction, the rest of the time it is flowing in the opposite direction. If a speaker wire was indeed directional by nature, this would introduce the exact same amount of distortion regardless whether the cable is connected one way or the other, as the "directionality" would affect either the red parts of the wave or the blue parts depending on the direction the cable was connected. Since the red part pushes the speaker forwards, and the blue part causes it to retract - the question now becomes whether your ear can detect distortion differently between a speaker pushing or pulling air.

To answer that, let's consider how a speaker makes sound. If a positive voltage is applied to the speaker terminals (the red part of the voltage waveform in Figure 2.2), the cone pushes forward at a certain speed (which correlates with the frequency of the sound). As the voltage reverses (the blue part of the wave), the cone pulls backwards. When the cone pushes forward, it compresses the air molecules and creates a high pressure zone; when it pulls back it creates a low pressure zone. A high pressure zone will propagate through air until it reaches your ear, where it will cause your eardrum to move inwards. When the low pressure reaches your eardrum, it will cause your eardrum to move outwards.

When your ear drum vibrates, it eventually transfers these vibrations to the foot bone, which produces waves in the inner ear fluid. These waves are transferred to tiny hairs, which causes even smaller trapdoors to open and close, allowing ions to enter the cell. These ions generate electrical signals that travel to the brain and are interpreted as sound. It is straight forward to see that this whole process is symmetrical - meaning a distortion in the red part of the original wave will have the same effect than a distortion in the blue part - hence, ultimately, you would be substituting one distortion for another, identical distortion that you are unable to tell apart, assuming a conductor has "directionality" in the first place.

Conclusion: Cable directionality - whether it is a real phenomenon or not - cannot be perceived by the human ear due to the nature of audio waves, therefore it is meaningless.

2.4 Break-in

Many manufacturers and hi-fi specialists support the idea that somehow a speaker cable needs time to "break in" - i.e. that it will sound better after being in use for a while. Continuing from directional cables, one manufacturer makes the following claim:

"When cables are manufactured they do not have any directionality. However, as they break in, they acquire directionality. Although the cable signal is an alternating current, small impurities in the conductor act as diodes allowing signal flow to be better in one direction over time. This effect is also called quantum tunneling, which has been observed in experiments over 25 years ago. Regardless of the purity of the metal used, there are still diode effects in all conductors. In addition, the insulation material will change when it is subjected to an electrical field."

Firstly, the statement above is a direct contradiction of an earlier statement by another audio cable company, where they stated that:

“[...]it is clear that the molecular structure of drawn metal is not symmetrical, providing a physical explanation for the existence of directionality.”.

Either a cable is manufactured with directionality, or it does not. It cannot be both. This is a good sign of snake-oil.

By applying deductive reasoning yet again, we can approach this claim as follows. I have already shown that alternating current will cause the electrons to move exactly the same distance in both directions along the wire over the course of the audio system's lifetime. It is therefore clear that break-in cannot exist. Break-in refers to a scenario where a directional force alters the characteristic of the subject over time due to repeated applications. One can break in a horse by continually trying to tame it. It is a directional force applied over time that has a net effect.

However, if I apply a random force over a period of time where the randomness is truly random (exactly like the electron movement in speaker cables), it is in principle impossible to have a net effect on the subject (the wire). Whatever occurs when the current is flowing in one direction - if anything at all - is wiped out by the current flowing in the other direction.

The claim above is especially inconsistent, as directionality cannot be attained through the application of a non-directional force.

Their claim also refers to the tunneling effect, which is a real phenomenon but requires so called “p” and “n” type material to form a broken band gap, through which electrons can quantum tunnel. This band gap is typically 10 nm wide. “p” type semiconductors contains an excess of electron holes (which are positive), and “n” type semiconductors contain an excess of electrons (which are negative). These semiconductors need to be part of the same semiconductor and exist as impurities only, otherwise a grain boundary would introduce scattering which would mostly negate the effect. Copper is not a semiconductor. The idea that impurities can cause semiconducting effects has no basis, as the process of creating copper wire causes random crystal boundaries to form and impurities will also be randomly oriented due to the annealing and compression applied. Therefore any non-linear rectification effect that may potentially exist, would be completely random and would negate each other on the large scale.

This same manufacturer makes the following claim:

“How long do my cables have to break in? Normally, we recommend at least 168 hours. However, our Reference level cables require at least 336 hours.”

For a copper conductor to change its conductivity you have to either change its dimensions, crystalline structure or temperature. Its dimensions will not change - it is set at the time of manufacturing. The crystalline structure will only change at temperatures approaching or exceeding 371 °C, which is ETP copper's starting annealing temperature. In normal use, the speaker wires will never approach this temperature. The only factor left is temperature. Copper's resistivity changes with temperature, however this change will attenuate the signal uniformly (a small phase shift is also introduced but the effect is almost incalculably small as the temperature changes in speaker wires due to normal use is insignificant - not more than a couple of °C as the power dissipated $P = I^2 R_{loss} = 4.33^2 \times 0.388 = 7.3\,\mathrm{W}$ over a surface area of $0.2\,\mathrm{m}^2$. A temperature increase of $5\,^\circ\mathrm{C}$ will increase power losses by $0.11\,\mathrm{W}$). When the amplifier is switched off and the temperature drops back to ambient, the resistivity will drop back to what it was - no permanent effect will occur. Therefore, it is not possible to achieve any kind of permanent change in copper wire by sending audio signals at hi-fi power levels through the speaker wires - unless perhaps you create a short circuit.

As to changes to the insulation material, nothing permanent will occur. Whatever changes occur during "break-in" will be reversed when the cable is not in use. The insulator is a dielectric, thus it can be polarized. Any polarization due to "break-in" will be reversed when an alternating current flows through the wires and disturbs the electric field many thousand times per second.

Conclusion: Break-in is a flawed concept as copper wire does not change its characteristic significantly under normal audiophile usage.

2.5 Bi-wiring

The general idea behind bi-wiring (not to be confused with bi-amping, which is very different and actually beneficial if implemented properly), is two speaker cables are connected between the same amplifier speaker terminal but one goes to the low frequency terminal on the speaker, and the other to the high frequency terminal, thereby creating isolated paths for the high and low frequencies.

One manufacturer makes this claim: "Biwiring is done in order to substantially reduce the distortion caused by speaker cable. In a biwire set-up the cable feeding the higher ranges no longer has to handle the large magnetic fields caused by the high current needed to produce bass. The bass fundamentals are not affected by biwiring, but the treble signal now travels a less distorted path.". Let's analyse it.

Considering a typical mid to high range speaker, one would usually find four binding posts at the back of the speaker. Two are for high frequency, and two for low frequency. Usually these speakers, which allows for bi-amping and bi-wiring, have a metal plate (indicated by the orange wires in the figure) connected between the positive high frequency and low frequency binding posts, and likewise between the

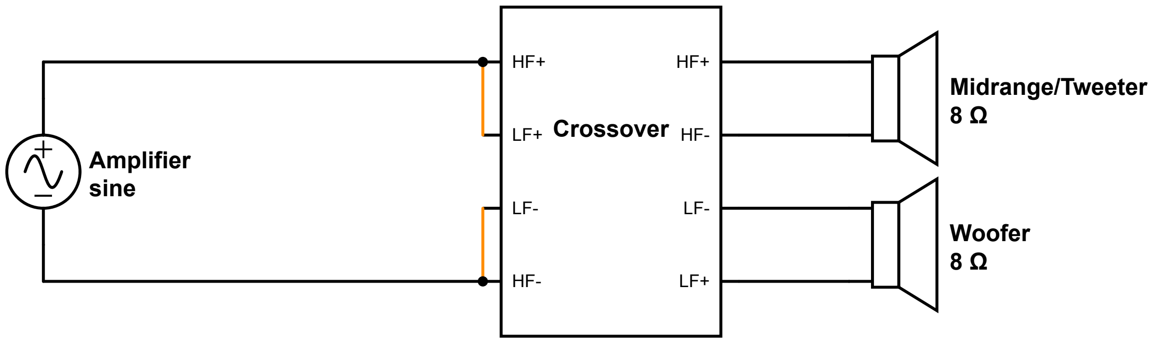

Figure 2.3: Standard single wiring of speakers

two negative posts. This effectively bridges the two circuits and negates bi-wiring.

Speakers can have various different internal configurations in terms of how these binding posts connect to the crossover inside, and how much electrical separation there is between the high and low pass filters. For now, I am going to assume that the crossover is designed such that the high and low frequency filters are completely isolated such that we have the best possible chance of improving audio quality if we extend this isolation all the way back to the amplifier. In the end, I am not analysing the crossover network, I want to determine a best case scenario for bi-wiring.

In Figure 2.3, we have a single electrical path between the binding posts on the amplifier and the (shorted) binding posts on the speaker. All the calculations for skin effect, resistance etc. I have performed thus far are true for this configuration.

The magnetic field generated by an electrical current flowing down a wire in a return circuit has four major effects:

1. Skin Effect
2. Proximity Effect
3. Internal Self Inductance
4. Mutual Inductance

Consider Figure 2.4 - it represents two conductors parallel to each other, as is common in speaker cables (the one conductor is the forward path, the other is the return path of the current). This is the scenario for a single wired speaker (two conductors).

These two conductors are close to each other - typically $\sim 1.2{\times}2a$ apart (D). Each have radius of a. The run length of the wire is L, and the total circuit length is $2L$ (including return path). The current flows in opposite directions in each conductor.

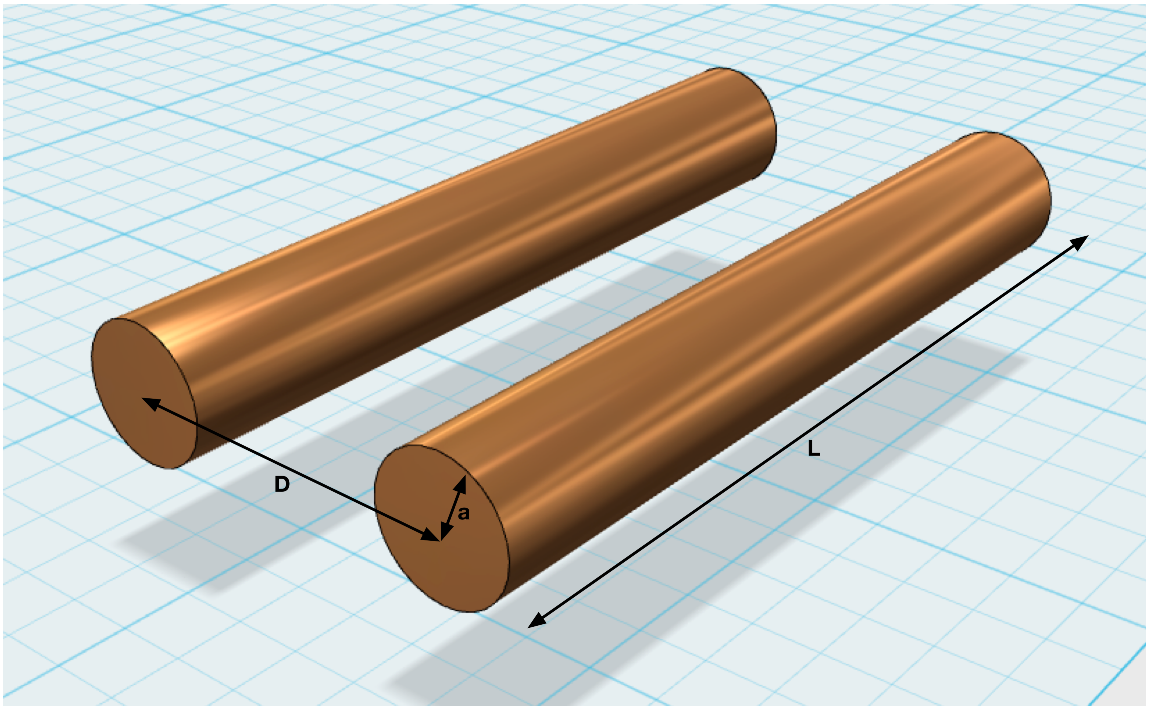

Figure 2.4: Parallel copper wires

Let's complicate this by introducing bi-wiring as per Figure 2.5.

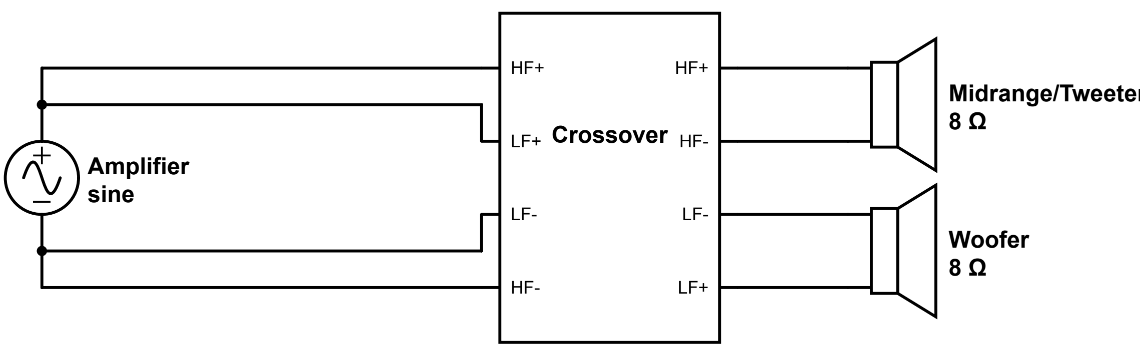

Figure 2.5: Bi-wiring of speakers

It is clear that with the removal of the metal plate short circuiting the terminals, and by extending the binding ports via identical but separate speaker wires all the way back to the amplifier binding posts, we have changed the circuit somewhat.

Assuming an isolated crossover design, we now have separate speaker wires end to end to each filter. How does this affect the electrical characteristics of the circuit?

Each speaker wire will be matched with a different filter, one with a high pass filter and the other with a low pass filter (I am simplifying by not considering midrange - the same principle applies). The supposed reasoning is that by doing this, we somehow reduce the large magnetic fields caused by high currents and thus reduce its effect on the high frequency signals.

Let's consider each effect caused by the magnetic field:

2.5.1 Skin Effect

As explained, skin effect is due to the back-emf induced in the conductor by itself. Adding or removing conductors do not change this behaviour as it is intrinsic to each conductor.

2.5.2 Proximity Effect

I have not yet discussed proximity effect. Consider Figure 2.6. Depicted here is the effects due to magnetic fields in the current carrying conductors. Firstly, keep in mind that each conductor generates its own magnetic field due to the alternating current flowing through it. The right hand rule tells us that each wire generates an alternating magnetic field anticlockwise when grabbing the wire with your right hand and your thumb pointing in the direction of current flow (that is, for one half a cycle as the current will reverse, and so too will the magnetic field). Since the two conductors carry current in opposite directions, the magnetic field will look as per Figure 2.6.

It is clear that the magnetic field lines will tend to cancel each other out on both the left and right sides of the left and right conductors, respectively, as they flow in opposite directions. The inner field lines between the two conductors flow in the same direction, reinforcing each other. This causes a net back-emf to be induced in each conductor from outer edge to inner edge, such that there is an increase in current on the inner two faces of the conductors. See Figure 2.7.

Proximity effect (caused by external magnetic influences from neighbouring conductors) together with skin effect (caused by internal magnetic influences from within the conductor itself) tends to increase the AC resistance of the wire with increasing frequencies. When multiple conductors are used such as in bi-wiring, the close proximity of the wires to each other negates any potential benefits of bi-wiring as the magnetic field lines will cut the opposing conductors the same as if there had

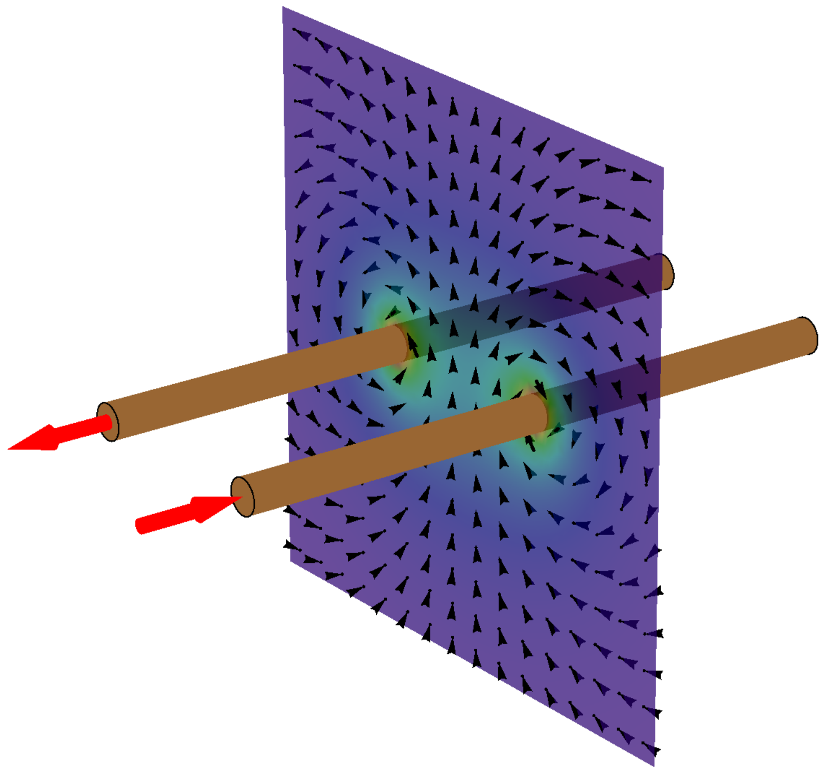

Figure 2.6: Magnetic field of two wires with opposing currents

only been two conductors (one pair). The fact that one conductor is connected to a high pass filter and the other to a low pass filter means that lower frequencies will be carried by one conductor, and higher frequencies by the other. Since both wires are identical, the effect of separating the cables would be identical compared to a single cable carrying a superposition of both frequency ranges. Remember, I have already proven cable directionality is irrelevant (if it even exists), hence that cannot be a factor here.

Proximity effect does however contribute with skin effect to increase AC resistance. Specifically, it will increase R_{ac} by a factor K, which is determined by the ratio $(2a)/D$. According to this paper, for our case we have:

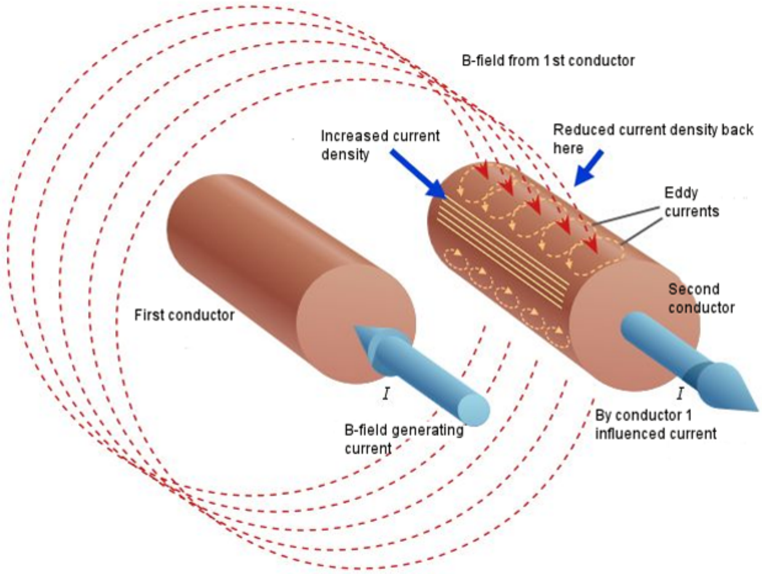

Figure 2.7: Proximity Effect

$$K = 1 + F(x) + \frac{\alpha^2 G(x)}{1 - \alpha^2 A(x) - \alpha^4 B(x) - \alpha^9 C(x)}$$

with $\alpha = 2a/D$ and $x = 2\sqrt{2\pi f 10^{-7}/R_{dc}}$. For our case at 22 kHz:

$$\begin{aligned}
\alpha &= \frac{2a}{D} \\
&= \frac{1.628\times 10^{-3}}{4\times 10^{-3}} \\
&= 0.407 \\
x &= 2\sqrt{2\pi f 10^{-7}/R_{dc}} \\
&= 2\sqrt{\frac{2\pi 22000 \times 10^{-7}}{0.322/40}} \\
&= 2.6208
\end{aligned}$$

(Take note that we need unit length resistance, hence the reason why I divided R_{dc} by 40 m). Considering the definitions for $F(x)$, $G(x)$, $A(x)$, $B(x)$ and $C(x)$, we do not meet the condition that $x < 1.4$, so we can not use the formulas and need to use the tables:

$$\begin{aligned}
F(x) &= 0.2059 \\
G(x) &= 0.3230 \\
A(x) &= 0.2854 \\
B(x) &= -0.0091 \\
C(x) &= 0
\end{aligned}$$

$$\begin{aligned}
\therefore K &= 1 + 0.2059 + \frac{0.407^2(0.3230)}{1 - 0.407^2(0.2854) - 0.407^4(-0.0091) - 0.407^9(0)} \\
&= 1.26204
\end{aligned}$$

Therefore, the proximity effect changes our R_{ac} from Equation 2.5 as follows:

$$\begin{aligned}
R_{ac,pe+se} &= R_{dc} \times K \\
&= 0.322 \times 1.26204 \\
&= 0.406 \\
R_{ac,pe} &= R_{ac,pe+se} - R_{ac} \\
&= 0.406 - 0.388 \\
&= 0.018\,\Omega
\end{aligned}$$

That surmounts to an increase in resistance of 18 mΩ - completely negligible at 22 kHz. We can therefore ignore proximity effects in audio applications.

2.5.3 Internal Self Inductance

Internal self inductance is the cause for skin effect, raising the AC resistance with frequency. It also is responsible for causing inductive reactance losses inside the conductor. Since this effect is due to the conductor's magnetic field on itself, separating the high and low frequencies makes no difference to the net inductive reactance.

2.5.4 Mutual Inductance

Instead of having two opposing currents flowing in two conductors in close proximity, we now have four conductors with two of these flowing in opposite direction. Each circuit carries a different frequency range, and will have different magnetic field strengths. The frequency it carries dictates the rate of change of the magnetic field. Proponents of bi-wiring sometimes claim that the strong magnetic field from the lower frequencies causes distortion of the higher frequencies when carried by the same conductor as opposed to separating via bi-wiring. The flaw in this line of reasoning is that the magnetic field from the conductor carrying the low frequency current will affect the conductor carrying the high frequency current just as much if separated, since the proximity of the two conductor pairs is still for all practical purposes identical.

Let me take another approach in analysing the bi-wiring configuration. Remember that the claim made was that the magnetic field is somehow the cause of the distortion that are supposedly fixed by bi-wiring. Copper conductors are linear components, that is, for any given potential difference applied to the conductor, the current will change linearly according to the impedance of the conductor. The impedance is the combination of the resistivity, the capacitive and inductive reactances. Furthermore, an audio signal is the superposition of multiple individual sinusoidal waves of different frequencies. The superposition (sum) of all individual frequencies will produce the final audio waveform. See Figure 2.8.

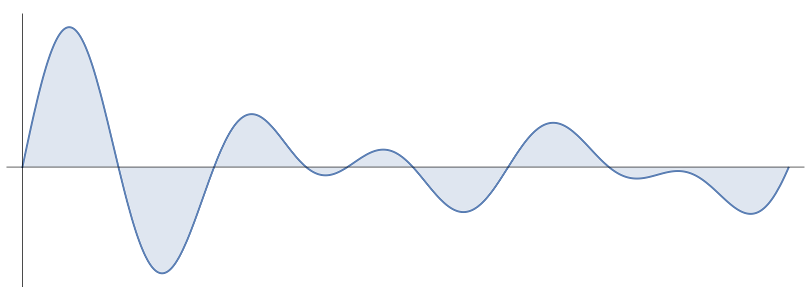

Figure 2.8: Audio Wave

This is a fragment of an audio signal. We can deconstruct that wave as per Figure 2.9.

Figure 2.9 shows that the audio wave is composed of three chords - A (blue), C# (orange) and E (green) (440 Hz, 554.37 Hz and 659.26 Hz respectively). When applying superposition, we can sum these three individual signals and have an exact

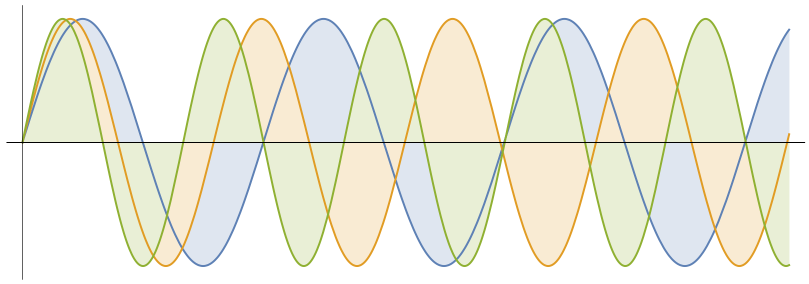

Figure 2.9: Audio Wave Deconstructed

reproduction of the original audio signal.

Superposition works because this is also a linear relationship. It therefore follows that whether one calculates the conductor losses based on the final audio waveform in a single conductor, or partially deconstructed waveforms in two conductors, in the end the relationship between voltage and current is still linear, and dictated by the sum of the individual conductor impedances.

Take note that I have made one major error in my reasoning. Having two conductors of a given wire gauge versus one conductor does make a difference in the impedance - it will lower it. The sum total of the conductor cross sectional area that the current can utilise is double of what it is with a single conductor. I did not mention this as simply choosing a thicker gauge single conductor will have the exact same effect. It has nothing to do with separation of frequencies by utilising multiple conductors, just the simple impedance versus conductor thickness relationship.

If we were to assume that somehow my statement about a copper conductor being a linear component is flawed, that it is non linear (the "diode-effect"), then my argument still holds. The waveform will still be distorted during one half of each frequency cycle. Separating the frequencies in to two wires will merely cause the distortion to be applied to those frequencies separately. In fact, if the length of the two wires are not exactly the same, there is a very real chance of introducing phase shifts between the lower and upper frequencies as the electromagnetic wave will take slightly longer to propagate via one of the conductors. That said, we will show that this effect will not be audible in a later section.

Conclusion: Bi-wiring has no benefits to audio, except to reduce impedance and power losses. The same effect can be had by choosing a thicker gauge conductor.

2.6 Dielectric / Capacitance

You will often hear the terms "dielectric" and "capacitance" thrown around when discussing audio speaker cables with some audiophile shops and manufacturers. These are very real concepts and have real effects on the impedance of speaker wires; the question is whether it makes a perceivable difference.

To answer that one needs to understand what exactly these two terms refer to and how it affects speaker wires. Up to now I have completely ignored the effects of capacitance on audio quality, so let's change that.

Capacitance is the ability to store an electric charge. A basic capacitor (which is an electronic device that has capacitance) consists of two conductive plates separated by an insulator, also known as a dielectric. A dielectric is any material that does not conduct electricity and can be polarized when placed in an electric field. There are many kinds of dielectrics, even air is a dielectric.

It is clear from this definition that our speaker wire can be considered a capacitor of some sorts. It consists of two conductive elements in close proximity separated by an insulator - usually PVC, and when the system is turned on there is a varying electric field between the wires due to the alternating current creating varying magnetic fields. Capacitance is proportional to the surface area of the wires facing each other and inversely proportional to the separation between the wires. Usually for zip cord and other speaker cables, the distance between wires rarely exceed $1.2 \times 2a$.

Let's calculate the capacitance for our setup:

$$C_w = \frac{\pi \epsilon_0 \epsilon_r L}{\operatorname{arcosh}\left(\frac{D}{2a}\right)}$$

ϵ_0 is the permittivity of a vacuum $8.854\,187\,817\,620 \times 10^{-12}\,\mathrm{F\,m^{-1}}$.
ϵ_r is the relative permittivity of the dielectric, we will use PVC.
L is the length of wire run in m.
D is the distance between the wires in m.
a is the radius of each conductor in m.

Clearly, the capacitance will increase with longer wires and the closer the conductors are to each other. Wire gauge has no effect on capacitance as long as the inner edge to edge distance between the conductors is kept the same.

$$C_w = \frac{\pi \times 8.854\,187\,817\,620{\times}10^{-12} \times 3 \times 20}{\operatorname{arcosh}\left(\frac{4\times10^{-3}}{2\times1.628\times10^{-3}/2}\right)}$$

$$= 1.08\,\mathrm{nF} \tag{2.7}$$

So is that significant? To answer that we need to calculate its effect on the speaker wire circuit. We can model the speaker wire and speaker as follows:

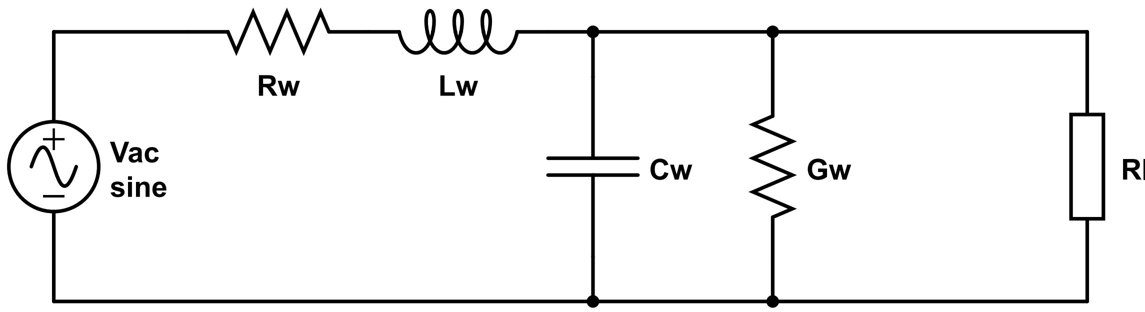

Figure 2.10: Lumped Equivalent Model Of Speaker Wire Circuit

We have made some simplifications. For one, the lumped model only applies if we ignore wave reflection - which we can do as our cable is 40m long, much less than a quarter wavelength of light at 22 kHz (3.4 km). Only for cables in excess of several hundred meters would you need to start considering wave reflections. Also, wave reflections can be largely eliminated by matching amplifier and load impedances.

Secondly, I have simplified the speaker to a purely resistive load. I will explain in a bit why that simplification is valid.
The parameters in this equivalent circuit is as follow:

V_{ac} is the AC voltage source originating from the amplifier terminals in V.
R_w is the AC resistance of the wire in Ω.
L_w is the inductance of the wire in H.
C_w is the capacitance of the wire in F.
G_w is the conductance of the dielectric in ℧.
R_l is the simplified resistive load of the speaker in Ω.

Working in the complex plane, solving this circuit at 22 kHz is pretty straight forward application of Ohm's law:

$$Z_{tot} = Z_{R_w} + Z_{L_w} + \frac{1}{\frac{1}{Z_{C_w}} + \frac{1}{Z_{G_w}} + \frac{1}{Z_{R_l}}} \tag{2.8}$$

$$\tag{2.9}$$

Let's calculate the individual impedances. We have already calculated the AC resistance, which includes the DC resistance of copper and skin effect at 22 kHz. It does not include proximity effect though. From Equation 2.5:

$$Z_{R_w} = 0.388\,\Omega$$

Inductive reactance can be calculated by:

$$\begin{aligned} Z_{L_w} &= j\omega L \\ &= j(2\pi f)L \end{aligned}$$

To calculate the inductance L, we can use the following formula (refer to Figure 2.4):

$$L_w \approx \frac{\mu_0 \mu_r}{\pi} \operatorname{arcosh}(\frac{D}{2a})L$$

μ_0 is the magnetic permeability of a vacuum, which is defined as $4\pi{\times}10^{-7}\,\mathrm{N\,A^{-2}}$
μ_r is the relative magnetic permeability of the conductor, which for copper has a value of 0.999994.
The other variables are as per Figure 2.4. Therefore:

$$\begin{aligned} L_w &\approx \frac{4\pi{\times}10^{-7} \times 0.999994}{\pi} \operatorname{arcosh}(\frac{4{\times}10^{-3}}{2 \times 1.628{\times}10^{-3}/2}) \times 20 \\ &\approx 12.4\,\mu\mathrm{H} \end{aligned}$$

Therefore, inductive reactance is:

$$\begin{aligned} Z_{L_w} &= j(2\pi 22000)12.4\times 10^{-6} \\ &= j1.71\,\Omega \end{aligned}$$

Capacitive reactance is calculated by:

$$\begin{aligned} Z_{C_w} &= \frac{1}{j\omega C} \\ &= \frac{1}{j(2\pi f)C} \end{aligned}$$

We have already calculated C_w in 2.7 so:

$$\begin{aligned} Z_{C_w} &= \frac{1}{j(2\pi 22000)1.08\times 10^{-9}} \\ &= -j6709.24\,\Omega \end{aligned}$$

The conductance of the flexible PVC dielectric is approximately $1\times 10^{-17}\,\mho$. Therefore:

$$\begin{aligned} Z_{G_w} &= \frac{1}{G_w} \\ &= \frac{1}{1\times 10^{-17}} \\ &= 1\times 10^{17}\,\Omega \end{aligned}$$

Compared to the load resistance, this is clearly negligible. However, for thoroughness sake I will include it.

For the load impedance we have:

$$Z_{R_l} = 8\,\Omega$$

Substituting in 2.8 and simplifying:

$$
\begin{aligned}
Z_{tot} &= Z_{R_w} + Z_{L_w} + \frac{1}{\frac{1}{Z_{C_w}} + \frac{1}{Z_{G_w}} + \frac{1}{Z_{R_l}}} \\
&= 0.388 + 1.71j + \frac{1}{-\frac{1}{6709.24j} + \frac{1}{1\times 10^{17}} + \frac{1}{8}} \\
&= 8.388 + 1.7005j
\end{aligned}
$$

The magnitude of this vector is:

$$
\begin{aligned}
|Z_{tot}| &= \sqrt{8.388^2 + 1.7005^2} \\
&= 8.559\,\Omega
\end{aligned}
$$

The inductive and capacitive reactances combined are only 2% of the total impedance of the circuit. The AC resistance of the wire due to skin effect and copper's resistivity is 4.5% of the total impedance. Consider that at this frequency, the speaker will no longer be an ideal $8\,\Omega$ load but have a significantly higher impedance, thus making the impact of the conductor much less significant.

To answer our original question - whether the capacitance of the wire is significant, let's re-calculate but assuming Z_{C_w} and Z_{G_w} are infinite (i.e. no capacitive effects exist):

$$
\begin{aligned}
Z_{tot} &= Z_{R_w} + Z_{L_w} + \frac{1}{\frac{1}{Z_{C_w}} + \frac{1}{Z_{G_w}} + \frac{1}{Z_{R_l}}} \\
&= 0.388 + 1.71j + \frac{1}{\frac{1}{0+0+\frac{1}{8}}} \\
&= 8.388 + 1.71j \\
|Z_{tot}| &= \sqrt{8.388^2 + 1.71^2} \\
&= 8.560\,\Omega
\end{aligned}
$$

Capacitive effects due to speaker wires are therefore negligible on the impedance of the circuit. Inductive effects are more significant, though still small. The only effect capacitance has, especially in wire with higher than usual capacitance, is to introduce a phase shift in the higher frequencies between voltage and current. This may become problematic at very high capacitances. Please keep in mind that I am not considering the effects of amplifier and speaker impedance matching.

Conclusion: Capacitance and dielectrics have negligible effect on total impedance or phase shifts.

2.7 Phase Shift & Dispersion

The only thing that can cause different frequencies to become retarded out of phase with each other (called dispersion), is a lossy conductor. When reviewing the formula for the speed of electromagnetic waves in a conductor one would mostly encounter the formula:

$$v_w = \frac{1}{\sqrt{LC}} \tag{2.10}$$

This formula is indeed valid, but what most sources do not explicitly mention, is that it is only valid for a lossless conductor. Referring to Figure 2.10, if we drop the load and the voltage source we get the model as per Figure 2.11.

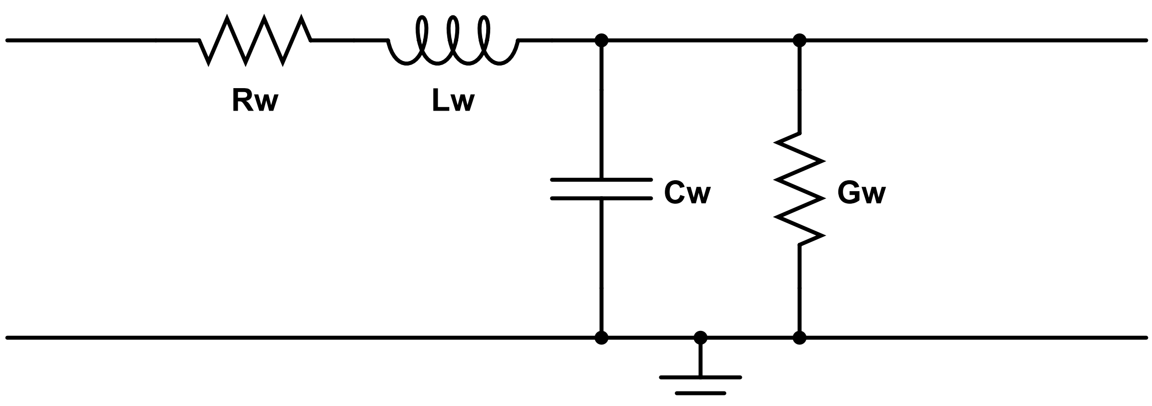

Figure 2.11: Lumped Equivalent Model Of Speaker Wire

If R_w and G_w were zero and infinite, respectively, the transmission line model would be considered lossless - that is, energy will move between the electric and magnetic fields but it will not be attenuated or dissipated as heat. We have already shown that these two parameters cannot be ignored, so Equation 2.10 is invalid.

The following equation includes the effects of these lossy aspects (source):

$$\mathbb{v}_w = \frac{1}{\sqrt{\mathbb{L}\mathbb{C}}} \tag{2.11}$$

Here $\mathbb{L}$ is the complex version of inductance and $\mathbb{C}$ the complex version of the capacitance.

$$\begin{aligned}
\mathbb{L} &= L + j\frac{R}{\omega} \\
\mathbb{C} &= C + j\frac{G}{\omega}
\end{aligned}$$

we have already mentioned that $\omega = 2\pi f$. Therefore:

$$\mathbb{v}_w = \frac{1}{\sqrt{(L + j\frac{R}{2\pi f})(C + j\frac{G}{2\pi f})}} \tag{2.12}$$

It follows that the velocity $\mathbb{v}_w$ is dependent on the frequency of the electromagnetic wave. This implies that for a lossy transmission line, electromagnetic waves will experience dispersion. Let's calculate how much.

$$\begin{aligned}
\mathbb{v}_{w,15Hz} &= \frac{1}{\sqrt{(12.4\times10^{-6}/20 + j\frac{0.322/40}{2\pi15})(1.08\times10^{-9}/20 + j\frac{1\times10^{17}/20}{2\pi15})}} \\
&= 1.0458\times10^{7} - 1.038\,22\times10^{7}j \\
|\mathbb{v}_{w,15Hz}| &= 14\,736\,177\,\mathrm{m\,s^{-1}} \\
\mathbb{v}_{w,22kHz} &= \frac{1}{\sqrt{(12.4\times10^{-6}/20 + j\frac{0.388/40}{2\pi22000})(1.08\times10^{-9}/20 + j\frac{1\times10^{17}/20}{2\pi22000})}} \\
&= 1.7226\times10^{8} - 9.730\,91\times10^{6}j \\
|\mathbb{v}_{w,22kHz}| &= 172\,534\,561\,\mathrm{m\,s^{-1}}
\end{aligned}$$

These results seem surprising. The lower the frequency, the more the electromagnetic wave is retarded due to losses in the conductor. Let's calculate the impact this has on audio. Firstly, we know the speed light in a vacuum is $c = 299\,792\,458\,\mathrm{m\,s^{-1}}$. Remember, light is an electromagnetic wave - the same kind of wave that travels down a copper wire (albeit at a much lower frequency). We are not looking at actual electron drift velocity as it is the speed of the electromagnetic waves that affects the speed of the different frequency sounds being generated by the speaker. Just like when you turn on the switch for your light and the light turns on virtually instantaneously, so too does the speaker start to move when an electrical field is applied to the terminals. The fact that the speeds, as calculated above, are slower than the speed of light, confirms the fact that there is indeed a slight delay in the signal reaching the speaker. Clearly there are many other delays too internal to the amplifier and the speaker, but I am only concerned about the delays introduced by the wire.

To determine whether this has a perceivable effect on the audio signal, let's determine the amount of time the signal is being delayed by considering a 40 m AWG14 copper wire. Keep in mind that there are two delays we are interested in. The first is the delay of the signal compared with the speed of light (this can affect audio sync - where the audio is out of sync with the picture image), and the second is the phase shift between the lowest audible frequencies and the highest - which can distort the audio signal.

To calculate the audio sync delay, we will look at the worst case delay which occurs at 15 Hz (realistically one should look at a higher frequency which corresponds with human speech, but this is the worst case):

$$\begin{aligned} v &= \frac{l}{t} \\ \therefore t_c &= \frac{l}{v_c} \text{ and} \\ t_w &= \frac{l}{v_w} \\ \therefore \Delta t &= t_w - t_c \\ &= \frac{l}{v_w} - \frac{l}{v_c} \\ &= \frac{40}{14736177} - \frac{40}{299792458} \\ &= 2.58\,\mu\mathrm{s} \end{aligned}$$

Sound waves propagate at $343.2\,\mathrm{m\,s^{-1}}$ in dry air at $20\,°\mathrm{C}$. How far can sound waves travel in $2.58\,\mu\mathrm{s}$?

$$
\begin{aligned}
v &= \frac{l}{t} \\
\therefore l &= vt \\
&= 343.2 \times 2.58{\times}10^{-6} \\
&= 885\,\mu\text{m}
\end{aligned}
$$

Let's calculate the wavelength of an audio signal of 15 Hz:

$$
\begin{aligned}
\lambda &= \frac{v}{f} \\
&= \frac{343.2}{15} \\
&= 22.9\,\text{m}
\end{aligned}
$$

Shifting a wave that is almost 23 m long by 0.003% will make no audible difference. What about higher frequency sounds? Let's go to the opposite side of the spectrum. At 22 kHz:

$$
\begin{aligned}
\Delta t &= \frac{l}{v_w} - \frac{l}{v_c} \\
&= \frac{40}{172534561} - \frac{40}{299792458} \\
&= 98.4\,\text{ns}
\end{aligned}
$$

In 98.4 ns sound waves can travel a distance of:

$$
\begin{aligned}
v &= \frac{l}{t} \\
\therefore l &= vt \\
&= 343.2 \times 98.4{\times}10^{-9} \\
&= 33.8\,\mu\text{m}
\end{aligned}
$$

Let's calculate the wavelength of an audio signal of 22 kHz:

$$
\begin{aligned}
\lambda &= \frac{v}{f} \\
&= \frac{343.2}{22000} \\
&= 15.6\,\mathrm{mm}
\end{aligned}
$$

Shifting a wave that is 15.6 mm long by 0.2% is more significant, but it still will make no audible difference. Adjusting the amplifier or source's lip sync or audio sync feature will not correct for this effect as it will not apply the correction proportional to the propagation delay caused by the speaker wires - it will adjust based on a fixed offset. However, as I mentioned, a maximum shift of 0.2% will not be detectable.

Let's move on to the second issue related to propagation delay - that of dispersion in the audio signal. For that we repeat above calculations but we will not be using the speed of light in a vacuum as reference, rather we will calculate the propagation delay between a 15 Hz and a 22 kHz signal.

$$
\begin{aligned}
\Delta t &= \frac{l}{v_{w_{15}}} - \frac{l}{v_{w_{22k}}} \\
&= \frac{40}{14736177} - \frac{40}{172534561} \\
&= 2.48\,\mathrm{\mu s}
\end{aligned}
$$

In 2.48 µs sound waves can travel a distance of:

$$
\begin{aligned}
v &= \frac{l}{t} \\
\therefore l &= vt \\
&= 343.2 \times 2.48{\times}10^{-6} \\
&= 852.02\,\mathrm{\mu m}
\end{aligned}
$$

Shifting a wave that is 15.6 mm long by 5.5% might be significant. However, do realize I am comparing a low frequency non directional wave with wavelength of 22.9 m with a ultra high frequency wave of 15.6 mm. 5.5% is how much the low frequency sound wave is retarded relative to the high frequency sound. Our ears are not very sensitive to timing as it relates to low frequency sounds. If we recalculate, we find that relative to the low frequency, the high frequency is being moved forward by 0.003%. This change is much smaller. Remember, the dispersion occurs smoothly with frequency. It is not an abrupt phenomenon. What is clear, is that we want to keep cable impedance low.

Conclusion: Phase shift and dispersion are real phenomena in speaker wires, but their influences are negligible as long as cable impedance is not excessive.

Chapter 3

What Does Matter?

3.1 Wire Length

You may be wondering why I am mentioning wire length and gauge separately? Surely one can compensate for a longer wire just by choosing a thicker gauge. But it does not work that way. To understand why, keep in mind that for our AWG14 40 m wire at 22 kHz we had the following inductance and capacitance:

$$C_w = 1.08\,\mathrm{nF}$$
$$L_w = 12.4\,\mu\mathrm{H}$$

Let's change this and use a 100 m (200 m return length) cable length - I know it is longer than you would ever encounter, but it is to prove a point - that wire gauge does not fix reactances:

$$C_{w_{100m}} = 5.4\,\mathrm{nF}$$
$$L_{w_{100m}} = 62\,\mu\mathrm{H}$$

So the capacitive and inductive losses are 5 times more - exactly what you'd expect. However, the AC resistance increased from $R_{ac} = 0.388\,\Omega$ to $R_{ac} = 0.855\,\Omega$. Let's try and compensate by using AWG8 wire:

$$C_{w_{100m}} = 6\,\mathrm{nF}$$
$$L_{w_{100m}} = 56\,\mu\mathrm{H}$$

The capacitance increased slightly, and the inductance decreased slightly. For AWG8 wire the AC resistance for this longer wire is $R_{ac} = 0.171\,\Omega$. It is clear that the thicker wire reduced the AC resistance (even considering skin effect), but keeping the reactances pretty much unchanged compared to the AWG14 wire.

Also, for a 100m length of wire the propagation delays will be longer too. This may become problematic.

Conclusion: Use the shortest wires you can.

3.2 Gauge

As just explained, gauge is important to keep AC resistive losses to a minimum. In general, you want to try and keep the AC resistive losses to below 5% of the load impedance. That means, below $0.4\,\Omega$ for an $8\,\Omega$ speaker. If the resistive losses are higher, it may audibly attenuate the signal. I do not see any problem with picking too a thick gauge other than it might be expensive and harder to work with. It does not measurably increase inductance or capacitance per unit length. The AWG14 gauge we have been using was shown to be just below 5% for a 40 m length of wire (20 m run).

It is not necessary for speaker wires to make use of Litz construction. Litz wire usually has much higher capacitance and some older amplifiers might struggle with that, creating oscillations. That said, with any modern, well designed amplifier Litz wire should be just fine to use - albeit expensive. Also keep in mind that stranded copper wire is not Litz wire, as the strands are not individually isolated from each other and not interwoven in the pattern necessary to reduce inductance and proximity effect.

If you use too small a gauge, you may run into some issues. The impedance losses are the biggest concern. They will definitely cause large losses in power. Let's calculate AC resistance and phase shift for a 40 m return length of AWG24 copper wire at 22 kHz:

$$R_{ac} = 3.282\,\Omega$$

AC resistance is now 41% of the load impedance, meaning almost half of the amplifier's power will be dissipated as heat in the amplifier and wires, and will never reach your ears. In specific:

$$
\begin{aligned}
V_{loss} &= IR_{ac} \\
&= 4.33 \times 3.282 \\
&= 14.2111\,\mathrm{V} \\
V_{out} &= V_{in} - V_{loss} \\
&= 34.64 - 14.2111 \\
&= 20.429\,\mathrm{V}
\end{aligned}
$$

From this we can calculate the gain (i.e. loss) in dB:

$$
\begin{aligned}
G &= 20 \log \frac{V_{out}}{V_{in}} \\
&= 20 \log_{10} \left[\frac{20.429}{34.64} \right] \\
&= -4.6\,\mathrm{dB}
\end{aligned}
$$

That is a significant drop in output. As to phase shift:

$$
\begin{aligned}
C_w &= 817\,\mathrm{pF} \\
L_w &= 16{\times}10^{-6}\,\mathrm{H} \\
|\mathbb{v}_{w,15Hz}| &= 5\,304\,360\,\mathrm{m\,s^{-1}} \\
|\mathbb{v}_{w,22kHz}| &= 155\,662\,434\,\mathrm{m\,s^{-1}} \\
\Delta t &= \frac{40}{5304360} - \frac{40}{155662434} \\
&= 7.28\,\mathrm{\mu s}
\end{aligned}
$$

There will be a 0.22% shift - a bit more significant than our AWG14 calculation (by 0.02%) but not earth shattering.

Conclusion: Use a thick enough gauge to stay below 5% impedance compared to the speaker impedance.

3.3 Connectors

Having the right wire is important, but equally important is to use good contacts. If the wire does not make proper electrical contact at both terminals (amplifier and speakers), there is a very real chance of losses and distortion to be introduced.

The reason some connectors are gold plated is not, as some may believe, to improve conductivity. In fact, gold is a much worse electrical conductor than copper. Only silver is (barely) better than copper. The only reason it is used instead of copper, is that gold does not corrode or react with oxygen and other elements nearly as much as copper. Therefore, the chances are much better that the surface area will be free from contaminants and make a much better connection. The losses due to the small area of contact is negligible, however losses due to oxides and other surface films forming will be much worse.

As to which connector is best between stripped plain wires, pin connectors, spade connectors, banana connectors or XLR - I would stay away from stripped plain wires just due to the fact that it is easy to make a short circuit and the surface area is copper, which will suffer from oxidization and corrode over time. Both banana and XLR will work fine. Spade connectors should be OK too but I have a preference for banana plugs just due to their simplicity.

Conclusion: Use gold plated, robust spring construction banana plugs. Do not pay a fortune.

3.4 Other

There are many other things you can do to dramatically improve the audio (and visual) performance of your home theatre system beyond speaker wiring, such as:

1. Invest money in good speakers. Not ridiculously priced, but well reviewed, well awarded speakers of a size that will complement your entertainment room's dimensions. Do not spend $10000 on a receiver only to spend $1000 on speakers. There needs to be a balance. Make sure to get at least 5.1 surround for your home theatre. Adding additional surround speakers beyond 5.1 is a plausible investment, but has diminishing returns. 5.1 will rock your world if done right. And yes, that ".1" refers to the subwoofer - make sure to get a good subwoofer. Your front speakers cannot deal with the low frequencies produced by modern movies.

2. Make sure to invest in a decent receiver. Make sure it supports all the codecs you are interested in, that it supports the impedance of the speakers you have chosen and that it produces enough power to properly control your speakers.

3. Get a good television. OLED is currently the best. If you need large size, get a high quality projector. Just make sure you can keep the room completely dark. Do not fret too much about 4K. The problem with 4K, although indeed better in all respects to HD, is that it is not possible to see the difference even in principle from a typical viewing distance assuming a typical screen size. Even an 85 in monster screen at 10 ft from your viewing position and with 20/20 eyesight, it will have marginal benefits for resolution. But be careful to not blindly trust those online graphs you see. Here are two - spot the not:

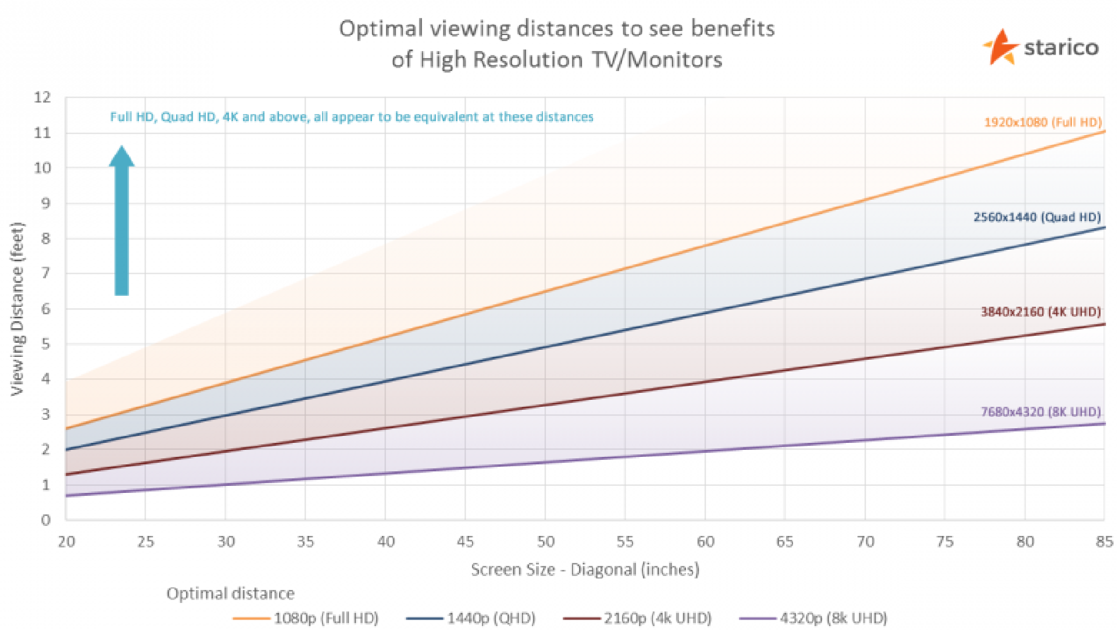

Figure 3.1: Viewing Distance Chart #1

According to one graph, at 10 ft an 85 in screen will need 1440p resolution to resolve all details. Yet the other graph suggests you need 4320p (8K) or even more.

To set the record straight, let's use science. It is commonly accepted that at a distance of 1 ft you need at least 300 dpi to have enough pixel density to not be able to resolve individual pixels (printing industry). This corresponds to an angle of view of approximately 50° (assuming the print has a diagonal similar in size to the distance the print is held for optimal viewing).

To maintain this density relative to viewing distance, at 10 ft a 300 dpi paper will be 111 in wide. Scaling that resolution yields a target resolution of 30 dpi,

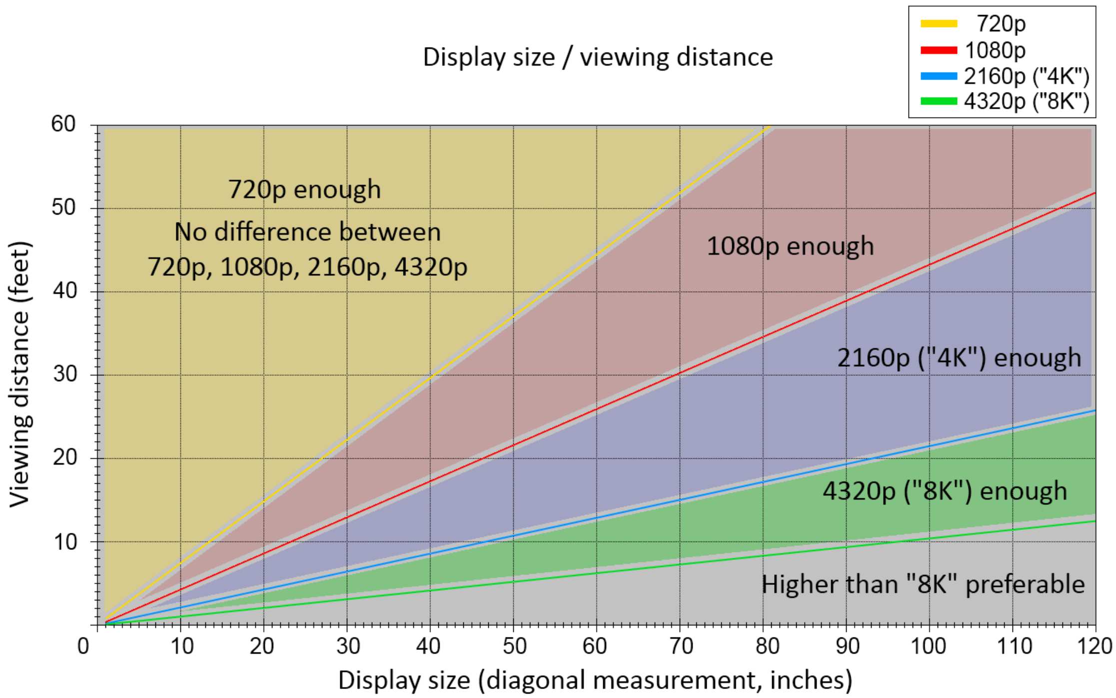

Figure 3.2: Viewing Distance Chart #2

or 1884p (vertically). That is slightly less than 4K, however it is for a 128 in screen (remember, they are measured diagonally). For an 85 in screen that becomes 1250p, or slightly more than HD. Most recordings are upscaled from 2K or even 3K, which means it is very rare to find a 4K recording that truly has a 2160p resolution. And if your screen is 55 in? Then you only need 810p - i.e. less than full HD. It appears Viewing Distance Chart #1 is correct.

HDR (High Dynamic Range) is nice, it does indeed make a difference. However it only becomes visible (to me at least) under ideal viewing conditions - i.e. the room must be very dark and you need a good 4K recording.

4. Acoustics acoustics acoustics. If you have a decent amplifier, TV and speakers the most important thing you can do is to have good acoustics. This includes speaker placement, room acoustics, listening position etc. Changing the toe-in of a speaker can make a much bigger difference than a $300 per foot speaker wire. It is also a heck of a lot cheaper. If you have something like Audyssey - use it. It will determine the configuration, position and types of speakers you

have and adjust output levels and delays based on the distances and sizes.

5. In today's digital world it is much less of an issue to have a high end source. For Blu-Ray or streaming media, as long as it supports the feature set of the disks they all should be similar in performance. Especially if you just perform pass through on audio and video - in that case the source just becomes a hard disk. Do not waste money on expensive streaming boxes or Blu-Ray players unless it is expensive because it is functional - such as large 4K storage space with remote streaming etc.

6. You do not always control the media your entertainment arrives in, but try and find a good recording. Prefer 4K HDR Blu-Ray over HD. Prefer Blu-Ray over streaming, especially if it is from an online source as the compression will most definitely affect quality. In fact, I could not find one Netflix 4K movie online that had any resolution advantage over HD when viewed up close (1 ft). My 4K Blu-Ray collection is another matter altogether. Standing up close to the screen, each pixel is clearly rendering unique content in Lucy (not all 4K recordings are created equal). Online streaming kills resolution. Blu-Ray is compressed much less. As a comparison, a Blu-Ray 4K movie is typically 45GB in length. A 4K movie streamed over Netflix is about 14GB. Where do you think did that other 31GB go? It is not really Netflix's fault as nobody can really stream 45GB per movie - we are not there yet. Just do not be fooled by the marketing claims that 4K streaming is in any way better than HD streaming (which *is* quite good).

Chapter 4

Conclusion

This article intended to show some science behind speaker wires. It is not there to convince you not to buy uber expensive cables. In the end the decision is yours. I merely wanted to make you aware that there is a lot of snake oil, misconceptions, ignorance and down right lies in the industry - both from manufacturers and your trusted audiophile experts at your local shop, but now you know the truth. At least, when spending the price of a small car on cables, know you are doing so in order to waste money and have bragging rights rather than to alter the sonic performance of your system in any perceivable way.

Use common sense when purchasing equipment. Ask questions, and question the responses. If the responses include a lot of technobabble - walk away. Nothing in the audio world should need to be explained in technical detail to convince you to buy it. Listen to it - blindfolded - and make up your own mind. If you cannot hear a difference between a \$5000 system and a \$50000 system, buy the \$5000 system. Use the rest to spend on wine. But make sure you do a double blind, or at the very least single blind test. That means - make sure you honestly do not know which system you are listening to when doing an A/B comparison. This is the only way to not have the placebo effect ruin your decision making abilities.