Semiconductors

Lessons in Electric Circuits
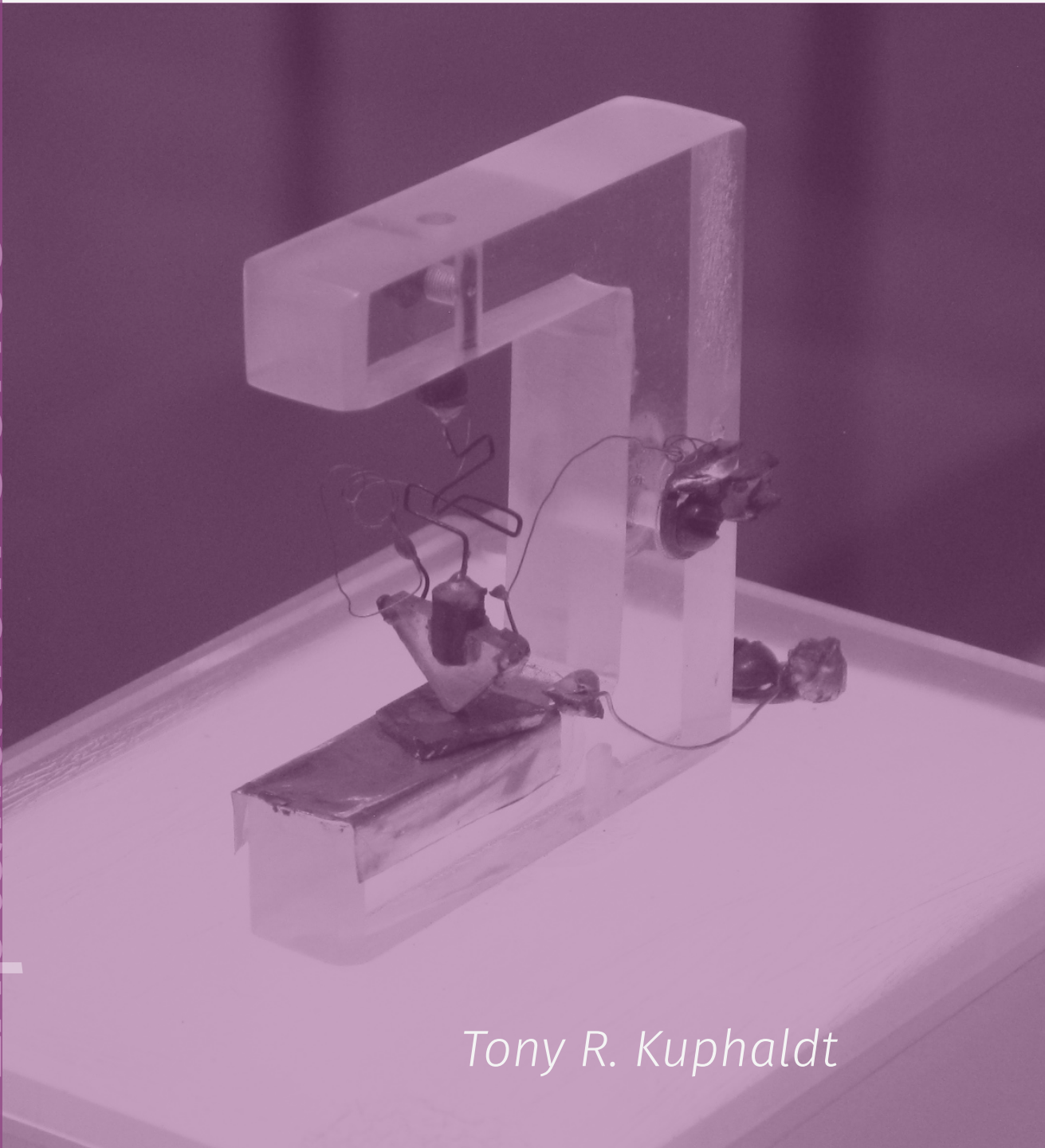
Tony R. Kuphaldt

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About This Book

Purpose

They say that necessity is the mother of invention. At least in the case of this book, that adage is true. As an industrial electronics instructor, I was forced to use a sub-standard textbook during my first year of teaching. My students were daily frustrated with the many typographical errors and obscure explanations in this book, having spent much time at home struggling to comprehend the material within. Worse yet were the many incorrect answers in the back of the book to selected problems. Adding insult to injury was the $100+ price.

Contacting the publisher proved to be an exercise in futility. Even though the particular text I was using had been in print and in popular use for a couple of years, they claimed my complaint was the first they'd ever heard. My request to review the draft for the next edition of their book was met with disinterest on their part, and I resolved to find an alternative text.

Finding a suitable alternative was more difficult than I had imagined. Sure, there were plenty of texts in print, but the really good books seemed a bit too heavy on the math and the less intimidating books omitted a lot of information I felt was important. Some of the best books were out of print, and those that were still being printed were quite expensive.

It was out of frustration that I compiled *Lessons in Electric Circuits* from notes and ideas I had been collecting for years. My primary goal was to put readable, high-quality information into the hands of my students, but a secondary goal was to make the book as affordable as possible. Over the years, I had experienced the benefit of receiving free instruction and encouragement in my pursuit of learning electronics from many people, including several teachers of mine in elementary and high school. Their selfless assistance played a key role in my own studies, paving the way for a rewarding career and fascinating hobby. If only I could extend the gift of their help by giving to other people what they gave to me . . .

So, I decided to make the book freely available. More than that, I decided to make it "open," following the same development model used in the making of free software (most notably the various UNIX utilities released by the Free Software Foundation, and the Linux operating system, whose fame is growing even as I write). The goal was

to copyright the text -- so as to protect my authorship -- but expressly allow anyone to distribute and/or modify the text to suit their own needs with a minimum of legal encumbrance. This willful and formal revoking of standard distribution limitations under copyright is whimsically termed *copyleft*. Anyone can "copyleft" their creative work simply by appending a notice to that effect on their work, but several Licenses already exist, covering the fine legal points in great detail.

The first such License I applied to my work was the GPL -- General Public License -- of the Free Software Foundation (GNU). The GPL, however, is intended to copyleft works of computer software, and although its introductory language is broad enough to cover works of text, its wording is not as clear as it could be for that application. When other, less specific copyleft Licenses began appearing within the free software community, I chose one of them (the Design Science License, or DSL) as the official notice for my project. Once the author of the DSL said it was obsolete, I moved on to Creative Commons (CC BY License).

In "copylefting" this text, I guaranteed that no instructor would be limited by a text insufficient for their needs, as I had been with error-ridden textbooks from major publishers. I'm sure this book in its initial form will not satisfy everyone, but anyone has the freedom to change it, leveraging my efforts to suit variant and individual requirements. For the beginning student of electronics, learn what you can from this book, editing it as you feel necessary if you come across a useful piece of information. Then, if you pass it on to someone else, you will be giving them something better than what you received. For the instructor or electronics professional, feel free to use this as a reference manual, adding or editing to your heart's content. The only "catch" is this: if you plan to distribute your modified version of this text, you must give credit where credit is due (to me, the original author, and anyone else whose modifications are contained in your version), and you must ensure that whoever you give the text to is aware of their freedom to similarly share and edit the text. The next chapter covers this process in more detail.

It must be mentioned that although I strive to maintain technical accuracy in all of this book's content, the subject matter is broad and harbors many potential dangers. Electricity maims and kills without provocation, and deserves the utmost respect. I strongly encourage experimentation on the part of the reader, but only with circuits powered by small batteries where there is no risk of electric shock, fire, explosion, etc. High-power electric circuits should be left to the care of trained professionals! The CC BY License clearly states that neither I nor any contributors to this book bear any liability for what is done with its contents.

The use of SPICE

One of the best ways to learn how things work is to follow the inductive approach: to observe specific instances of things working and derive general conclusions from those observations. In science education, labwork is the traditionally accepted venue for this type of learning, although in many cases labs are designed by educators to reinforce principles previously learned through lecture or textbook reading, rather than to allow the student to learn on their own through a truly exploratory process.

Having taught myself most of the electronics that I know, I appreciate the sense of frustration students may have in teaching themselves from books. Although electronic components are typically inexpensive, not everyone has the means or opportunity to set up a laboratory in their own homes, and when things go wrong there's no one to ask for help. Most textbooks seem to approach the task of education from a deductive perspective: tell the student how things are supposed to work, then apply those principles to specific instances that the student may or may not be able to explore by themselves. The inductive approach, as useful as it is, is hard to find in the pages of a book.

However, textbooks don't have to be this way. I discovered this when I started to learn a computer program called SPICE. It is a text-based piece of software intended to model circuits and provide analyses of voltage, current, frequency, etc. Although nothing is quite as good as building real circuits to gain knowledge in electronics, computer simulation is an excellent alternative. In learning how to use this powerful tool, I made a discovery: SPICE could be used within a textbook to present circuit simulations to allow students to "observe" the phenomena for themselves. This way, the readers could learn the concepts inductively (by interpreting SPICE's output) as well as deductively (by interpreting my explanations). Furthermore, in seeing SPICE used over and over again, they should be able to understand how to use it themselves, providing a perfectly safe means of experimentation on their own computers with circuit simulations of their own design.

Another advantage to including computer analyses in a textbook is the empirical verification it adds to the concepts presented. Without demonstrations, the reader is left to take the author's statements on faith, trusting that what has been written is indeed accurate. The problem with faith, of course, is that it is only as good as the authority in which it is placed and the accuracy of interpretation through which it is understood. Authors, like all human beings, are liable to err and/or communicate poorly. With demonstrations, however, the reader can immediately

see for themselves that what the author describes is indeed true. Demonstrations also serve to clarify the meaning of the text with concrete examples.

SPICE is introduced early in volume I (DC) of this book series, and hopefully in a gentle enough way that it doesn't create confusion. For those wishing to learn more, a chapter in the Reference volume (volume V) contains an overview of SPICE with many example circuits. There may be more flashy (graphic) circuit simulation programs in existence, but SPICE is free, a virtue complementing the charitable philosophy of this book very nicely.

Acknowledgements

First, I wish to thank my wife, whose patience during those many and long evenings (and weekends!) of typing has been extraordinary.

I also wish to thank those whose open-source software development efforts have made this endeavor all the more affordable and pleasurable. The following is a list of various free computer software used to make this book, and the respective programmers:

- *GNU/Linux* Operating System -- Linus Torvalds, Richard Stallman, and a host of others too numerous to mention.

- *Vim* text editor -- Bram Moolenaar and others.

- *Xcircuit* drafting program -- Tim Edwards.

- *SPICE* circuit simulation program -- too many contributors to mention.

- TeX text processing system -- Donald Knuth and others.

- *Texinfo* document formatting system -- Free Software Foundation.

- LaTeX document formatting system -- Leslie Lamport and others.

- *Gimp* image manipulation program -- too many contributors to mention.

Appreciation is also extended to Robert L. Boylestad, whose first edition of *Introductory Circuit Analysis* taught me more about electric circuits than any other book.

Other important texts in my electronics studies include the 1939 edition of *The "Radio" Handbook*, Bernard Grob's second edition of *Introduction to Electronics I*, and Forrest Mims' original *Engineer's Notebook*.

Thanks to the staff of the Bellingham Antique Radio Museum, who were generous enough to let me terrorize their establishment with my camera and flash unit.

I wish to specifically thank Jeffrey Elkner and all those at Yorktown High School for being willing to host my book as part of their Open Book Project, and to make the first effort in contributing to its form and content. Thanks also to David Sweet (website: (`http://www.andamooka.org`)) and Ben Crowell (website: (`http://www.lightandmatter.com`)) for providing encouragement, constructive criticism, and a wider audience for the online version of this book.

Thanks to Michael Stutz for drafting his Design Science License, to Richard Stallman for pioneering the concept of copyleft, and to Creative Commons for the CC BY License.

Last but certainly not least, many thanks to my parents and those teachers of mine who saw in me a desire to learn about electricity, and who kindled that flame into a passion for discovery and intellectual adventure. I honor you by helping others as you have helped me.

Tony Kuphaldt, July 2001

> *"A candle loses nothing of its light when lighting another"*
>
> **Kahlil Gibran** :::

SMI E.0: Introduction

From Electric to Electronic

This third volume of the book series *Lessons In Electric Circuits* makes a departure from the former two in that the transition between *electric* circuits and *electronic* circuits is formally crossed. Electric circuits are connections of conductive wires and other devices whereby the uniform flow of electrons occurs. Electronic circuits add a new dimension to electric circuits in that some means of *control* is exerted over the flow of electrons by another electrical signal, either a voltage or a current.

In and of itself, the control of electron flow is nothing new to the student of electric circuits. Switches control the flow of electrons, as do potentiometers, especially when connected as variable resistors (rheostats). Neither the switch nor the potentiometer should be new to your experience by this point in your study. The threshold marking the transition from electric to electronic, then, is defined by *how* the flow of electrons is controlled rather than whether or not any form of control exists in a circuit. Switches and rheostats control the flow of electrons according to the positioning of a mechanical device, which is actuated by some physical force external to the circuit. In electronics, however, we are dealing with special devices able to control the flow of electrons according to another flow of electrons, or by the application of a static voltage. In other words, in an electronic circuit, *electricity is able to control electricity*.

The historic precursor to the modern electronics era was invented by Thomas Edison in 1880 while developing the electric incandescent lamp. Edison found that a small current passed from the heated lamp filament to a metal plate mounted inside the vacuum envelop. (Figure 1 (a)) Today this is known as the "Edison effect". Note that the battery is only necessary to heat the filament. Electrons would still flow if a non-electrical heat source was used.

By 1904 Marconi Wireless Company adviser John Flemming found that an externally applied current (plate battery) only passed in one direction from filament to plate (Figure 1 (b)), but not the reverse direction (not shown). This invention was the vacuum diode, used to convert alternating currents to DC. The addition of a third electrode by Lee DeForest (Figure 1 (c)) allowed a small signal to control the larger electron flow from filament to plate.
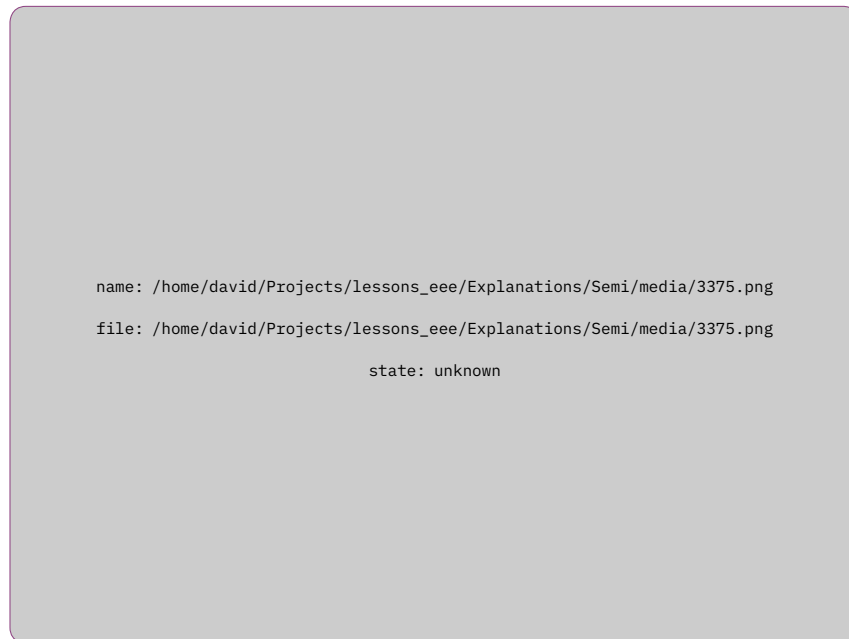
Figure 1 *(a) Edison Effect, (B) Fleming Valve or Vacuum Diode, (C) Deforest Audion Triode Vacuum Tube Amplifier*

Historically, the era of electronics began with the invention of the *Audion tube*, a device controlling the flow of an electron stream through a vacuum by the application of a small voltage between two metal structures within the tube. A more detailed summary of so-called *electron tube* or *vacuum tube* technology is available in the last chapter of this volume for those who are interested.

Electronics technology experienced a revolution in 1948 with the invention of the *transistor*. This tiny device achieved approximately the same effect as the Audion tube, but in a vastly smaller amount of space and with less material. Transistors control the flow of electrons through solid *semiconductor* substances rather than through a vacuum, and so transistor technology is often referred to as *solid-state* electronics.

Active versus Passive Devices

An *active* device is any type of circuit component with the ability to electrically control electron flow (electricity controlling electricity). In order for a circuit to be properly called *electronic*, it must contain at least one active device. Components

incapable of controlling current by means of another electrical signal are called *passive* devices. Resistors, capacitors, inductors, transformers, and even diodes are all considered passive devices. Active devices include, but are not limited to, vacuum tubes, transistors, silicon-controlled rectifiers (SCRs), and TRIACs. A case might be made for the saturable reactor to be defined as an active device, since it is able to control an AC current with a DC current, but I've never heard it referred to as such. The operation of each of these active devices will be explored in later chapters of this volume.

All active devices control the flow of electrons through them. Some active devices allow a voltage to control this current while other active devices allow another current to do the job. Devices utilizing a static voltage as the controlling signal are, not surprisingly, called *voltage-controlled* devices. Devices working on the principle of one current controlling another current are known as *current-controlled* devices. For the record, vacuum tubes are voltage-controlled devices while transistors are made as either voltage-controlled or current controlled types. The first type of transistor successfully demonstrated was a current-controlled device.

Contributors

Contributors to this chapter are listed in chronological order of their contributions, from most recent to first. See Appendix 2 (Contributor List) for dates and contact information.

Colin Barnard (November 2003): Correction regarding Alexander Graham Bell's country of origin (Scotland, not the United States).

SMI E.1: Amplifiers and Active Devices

Amplifiers

The practical benefit of active devices is their *amplifying* ability. Whether the device in question be voltage-controlled or current-controlled, the amount of power required of the controlling signal is typically far less than the amount of power available in the controlled current. In other words, an active device doesn't just allow electricity to control electricity; it allows a *small* amount of electricity to control a *large* amount of electricity.

Because of this disparity between *controlling* and *controlled* powers, active devices may be employed to govern a large amount of power (controlled) by the application of a small amount of power (controlling). This behavior is known as *amplification*.

It is a fundamental rule of physics that energy can neither be created nor destroyed. Stated formally, this rule is known as the Law of Conservation of Energy, and no exceptions to it have been discovered to date. If this Law is true -- and an over-whelming mass of experimental data suggests that it is -- then it is impossible to build a device capable of taking a small amount of energy and magically transforming it into a large amount of energy. All machines, electric and electronic circuits included, have an upper efficiency limit of 100 percent. At best, power out equals power in as in Figure 1.
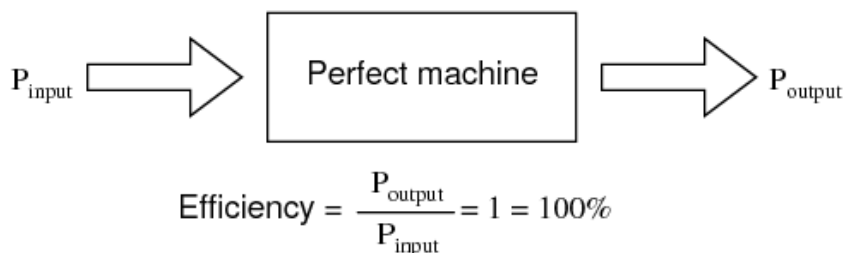

$$\text{Efficiency} = \frac{P_{output}}{P_{input}} = 1 = 100\%$$
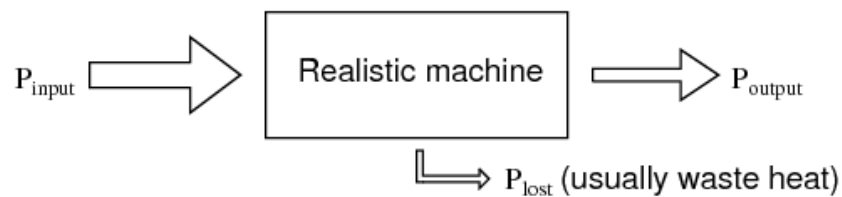
Figure 1   *The Power Output of a Machine Can Approach, But Never Exceed, The Power Input For 100% Efficiency as an Upper Limit*

Usually, machines fail even to meet this limit, losing some of their input energy in the form of heat which is radiated into surrounding space and therefore not part of the output energy stream. (Figure 2)

$$\text{Efficiency} = \frac{P_{output}}{P_{input}} < 1 = \text{less than } 100\%$$

Figure 2 *A Realistic Machine Most Often Loses Some of its Input Energy as Heat in Transforming it Into The Output Energy Stream*

Many people have attempted, without success, to design and build machines that output more power than they take in. Not only would such a *perpetual motion* machine prove that the Law of Conservation of Energy was not a Law after all, but it would usher in a technological revolution such as the world has never seen, for it could power itself in a circular loop and generate excess power for "free". (Figure 3)

$$\text{Efficiency} = \frac{P_{output}}{P_{input}} > 1 = \text{more than } 100\%$$
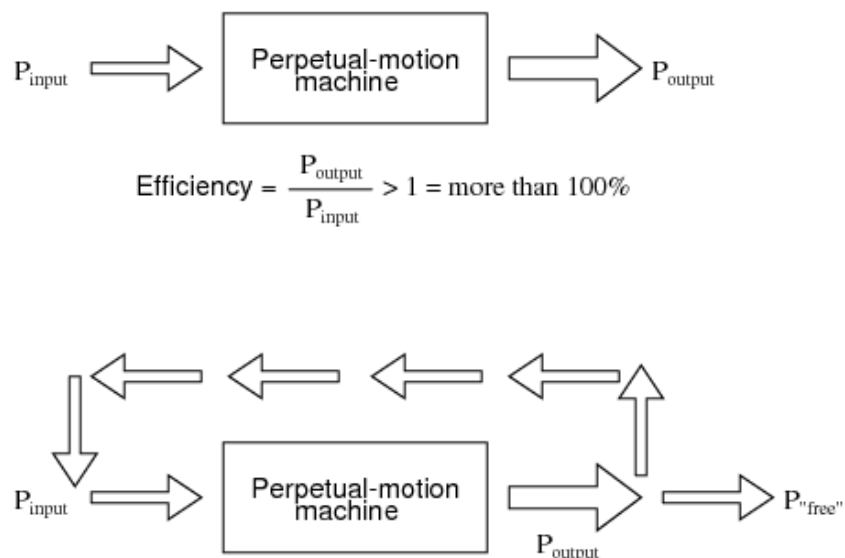

Figure 3 *Hypothetical "Perpetual Motion Machine" Powers Itself?*

Despite much effort and many unscrupulous claims of "free energy" or *over-unity* machines, not one has ever passed the simple test of powering itself with its own energy output and generating energy to spare.

There does exist, however, a class of machines known as *amplifiers*, which are able to take in small-power signals and output signals of much greater power. The key to understanding how amplifiers can exist without violating the Law of Conservation of Energy lies in the behavior of active devices.

Because active devices have the ability to *control* a large amount of electrical power with a small amount of electrical power, they may be arranged in circuit so as to duplicate the form of the input signal power from a larger amount of power supplied by an external power source. The result is a device that appears to magically magnify the power of a small electrical signal (usually an AC voltage waveform) into an identically-shaped waveform of larger magnitude. The Law of Conservation of Energy is not violated because the additional power is supplied by an external source, usually a DC battery or equivalent. The amplifier neither creates nor destroys energy, but merely reshapes it into the waveform desired as shown in Figure 4.
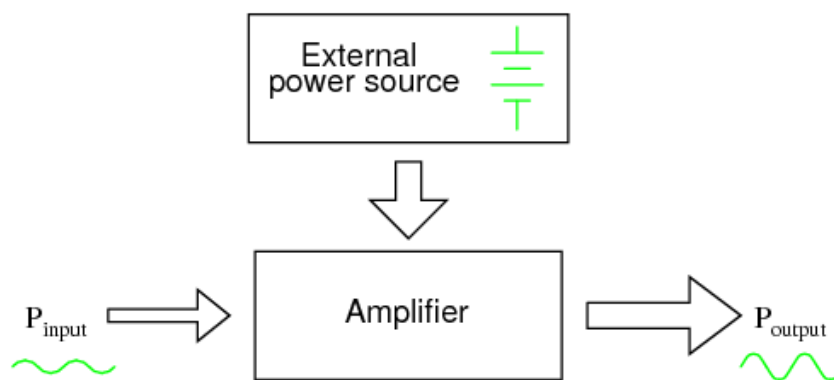

Figure 4   *While an Amplifier can Scale a Small Input Signal to Large Output, its Energy Source is an External Power Supply*

In other words, the current-controlling behavior of active devices is employed to *shape* DC power from the external power source into the same waveform as the input signal, producing an output signal of like shape but different (greater) power magnitude. The transistor or other active device within an amplifier merely forms a larger *copy* of the input signal waveform out of the "raw" DC power provided by a battery or other power source.

Amplifiers, like all machines, are limited in efficiency to a maximum of 100 percent. Usually, electronic amplifiers are far less efficient than that, dissipating considerable amounts of energy in the form of waste heat. Because the efficiency of an amplifier is always 100 percent or less, one can never be made to function as a "perpetual motion" device.

The requirement of an external source of power is common to all types of amplifiers, electrical and non-electrical. A common example of a non-electrical amplification system would be power steering in an automobile, amplifying the power of the driver's arms in turning the steering wheel to move the front wheels of the car. The source of power necessary for the amplification comes from the engine. The active device controlling the driver's "input signal" is a hydraulic valve shuttling fluid power from a pump attached to the engine to a hydraulic piston assisting wheel motion. If the engine stops running, the amplification system fails to amplify the driver's arm power and the car becomes very difficult to turn.

Amplifier gain

Because amplifiers have the ability to increase the magnitude of an input signal, it is useful to be able to rate an amplifier's amplifying ability in terms of an output/input ratio. The technical term for an amplifier's output/input magnitude ratio is *gain*. As a ratio of equal units (power out / power in, voltage out / voltage in, or current out / current in), gain is naturally a unitless measurement. Mathematically, gain is symbolized by the capital letter "A".

For example, if an amplifier takes in an AC voltage signal measuring 2 volts RMS and outputs an AC voltage of 30 volts RMS, it has an AC voltage gain of 30 divided by 2, or 15:

$$A_v = \frac{V_{output}}{V_{input}}$$

$$A_v = \frac{30\,\text{V}}{2\,\text{V}}$$

$$A_v = 15$$

Correspondingly, if we know the gain of an amplifier and the magnitude of the input signal, we can calculate the magnitude of the output. For example, if an amplifier with an AC current gain of 3.5 is given an AC input signal of 28 mA RMS, the output will be 3.5 times 28 mA, or 98 mA:

$$I_{output} = (A_1)\,(I_{input})$$

$$I_{output} = (3.5)\,(28\text{mA})$$

$$I_{output} = 98\,\text{mA}$$

In the last two examples I specifically identified the gains and signal magnitudes in terms of "AC." This was intentional, and illustrates an important concept: electronic amplifiers often respond differently to AC and DC input signals, and may amplify them to different extents. Another way of saying this is that amplifiers often amplify *changes* or *variations* in input signal magnitude (AC) at a different ratio than *steady* input signal magnitudes (DC). The specific reasons for this are too complex to explain at this time, but the fact of the matter is worth mentioning. If gain calculations are to be carried out, it must first be understood what type of signals and gains are being dealt with, AC or DC.

Electrical amplifier gains may be expressed in terms of voltage, current, and/or power, in both AC and DC. A summary of gain definitions is as follows. The triangle-shaped "delta" symbol (Δ) represents *change* in mathematics, so "ΔV_{output} / ΔV_{input}" means "change in output voltage divided by change in input voltage," or more simply, "AC output voltage divided by AC input voltage":

	DC gains	AC gains
Voltage	$A_V = \dfrac{V_{output}}{V_{input}}$	$A_V = \dfrac{\Delta V_{output}}{\Delta V_{input}}$
Current	$A_I = \dfrac{I_{output}}{I_{input}}$	$A_I = \dfrac{\Delta I_{output}}{\Delta I_{input}}$
Power	$A_P = \dfrac{P_{output}}{P_{input}}$	$A_P = \dfrac{(\Delta V_{output})(\Delta I_{output})}{(\Delta V_{input})(\Delta I_{input})}$
		$A_P = (A_V)(A_I)$

Δ = "change in . . ."

Figure 5 Gain Relationships
between Voltage, Current, and Power

If multiple amplifiers are staged, their respective gains form an overall gain equal to the product (multiplication) of the individual gains (Figure 6). If a 1 V signal were applied to the input of the gain of 3 amplifier in Figure 6 a 3 V signal out of the first amplifier would be further amplified by a gain of 5 at the second stage yielding 15 V at the final output.
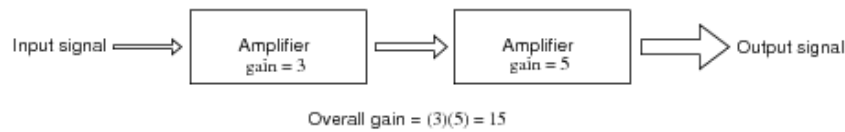
Figure 6   *the Gain Of a Chain Of Cascaded Amplifiers is The Product of The Individual Gains*

Decibels

In its simplest form, an amplifier's *gain* is a ratio of output over input. Like all ratios, this form of gain is unitless. However, there is an actual unit intended to represent gain, and it is called the *bel*.

As a unit, the bel was actually devised as a convenient way to represent power *loss* in telephone system wiring rather than *gain* in amplifiers. The unit's name is derived from Alexander Graham Bell, the famous Scottish inventor whose work was instrumental in developing telephone systems. Originally, the bel represented the amount of signal power loss due to resistance over a standard length of electrical cable. Now, it is defined in terms of the common (base 10) logarithm of a power ratio (output power divided by input power):

$$A_{P(\text{ratio})} = \frac{P_{output}}{P_{input}}$$

$$A_{P(\text{bel})} = \log \frac{P_{output}}{P_{input}}$$

Because the bel is a logarithmic unit, it is nonlinear. To give you an idea of how this works, consider the following table of figures, comparing power losses and gains in bels versus simple ratios:

It was later decided that the bel was too large of a unit to be used directly, and so it became customary to apply the metric prefix *deci* (meaning 1/10) to it, making it *deci*bels, or dB. Now, the expression "dB" is so common that many people do not realize it is a combination of "deci-" and "-bel," or that there even is such a unit as the "bel." To put this into perspective, here is another table contrasting power gain/loss ratios against decibels:

As a logarithmic unit, this mode of power gain expression covers a wide range of ratios with a minimal span in figures. It is reasonable to ask, "why did anyone feel

Table: Gain / loss in bels

Loss/gain as a ratio $\dfrac{P_{output}}{P_{input}}$	Loss/gain in bels $\log \dfrac{P_{output}}{P_{input}}$	Loss/gain as a ratio $\dfrac{P_{output}}{P_{input}}$	Loss/gain in bels $\log \dfrac{P_{output}}{P_{input}}$
1000	3 B	0.1	-1 B
100	2 B	0.01	-2 B
10	1 B	0.001	-3 B
$\dfrac{1}{\text{(no loss or gain)}}$	0 B	0.0001	-4 B

Figure 7   Examples of Gains and Losses in bels

Table: Gain / loss in decibels

Loss/gain as a ratio $\dfrac{P_{output}}{P_{input}}$	Loss/gain in decibels $10 \log \dfrac{P_{output}}{P_{input}}$	Loss/gain as a ratio $\dfrac{P_{output}}{P_{input}}$	Loss/gain in decibels $10 \log \dfrac{P_{output}}{P_{input}}$
1000	30 dB	0.1	-10 dB
100	20 dB	0.01	-20 dB
10	10 dB	0.001	-30 dB
$\dfrac{1}{\text{(no loss or gain)}}$	0 dB	0.0001	-40 dB

Figure 8   Examples of Gains and Losses in decibels

the need to invent a *logarithmic* unit for electrical signal power loss in a telephone system?" The answer is related to the dynamics of human hearing, the perceptive intensity of which is logarithmic in nature.

Human hearing is highly nonlinear: in order to double the perceived intensity of a sound, the actual sound power must be multiplied by a factor of ten. Relating telephone signal power loss in terms of the logarithmic "bel" scale makes perfect sense in this context: a power loss of 1 bel translates to a perceived sound loss of 50 percent, or 1/2. A power gain of 1 bel translates to a doubling in the perceived intensity of the sound.

An almost perfect analogy to the bel scale is the Richter scale used to describe earthquake intensity: a 6.0 Richter earthquake is 10 times more powerful than a 5.0 Richter earthquake; a 7.0 Richter earthquake 100 times more powerful than a 5.0 Richter earthquake; a 4.0 Richter earthquake is 1/10 as powerful as a 5.0 Richter earthquake, and so on. The measurement scale for chemical pH is likewise logarithmic, a difference of 1 on the scale is equivalent to a tenfold difference in hydrogen ion concentration of a chemical solution. An advantage of using a logarithmic measurement scale is the tremendous range of expression afforded by a relatively small span of numerical values, and it is this advantage which secures the use of Richter numbers for earthquakes and pH for hydrogen ion activity.

Another reason for the adoption of the bel as a unit for gain is for simple expression of system gains and losses. Consider the last system example (Figure 6) where two amplifiers were connected tandem to amplify a signal. The respective gain for each amplifier was expressed as a ratio, and the overall gain for the system was the product (multiplication) of those two ratios:

$$Overall\,gain = (3)(5) = 15$$

If these figures represented *power* gains, we could directly apply the unit of bels to the task of representing the gain of each amplifier, and of the system altogether. (Figure 9)
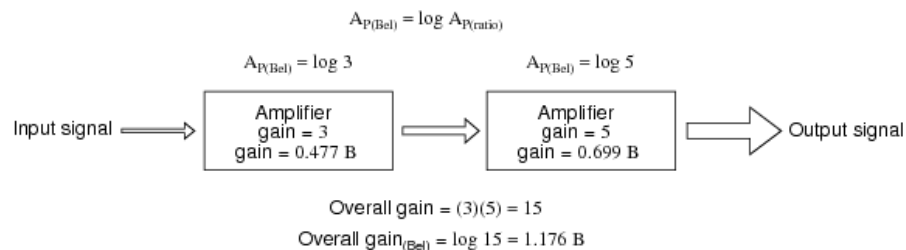

Figure 9 *Power Gain In bels Is Additive: 0.477 B + 0.699 B = 1.176 B.*

Close inspection of these gain figures in the unit of "bel" yields a discovery: they're additive. Ratio gain figures are multiplicative for staged amplifiers, but gains expressed in bels *add* rather than *multiply* to equal the overall system gain. The first amplifier with its power gain of 0.477 B adds to the second amplifier's power gain of 0.699 B to make a system with an overall power gain of 1.176 B.

Recalculating for decibels rather than bels, we notice the same phenomenon (Figure 10).
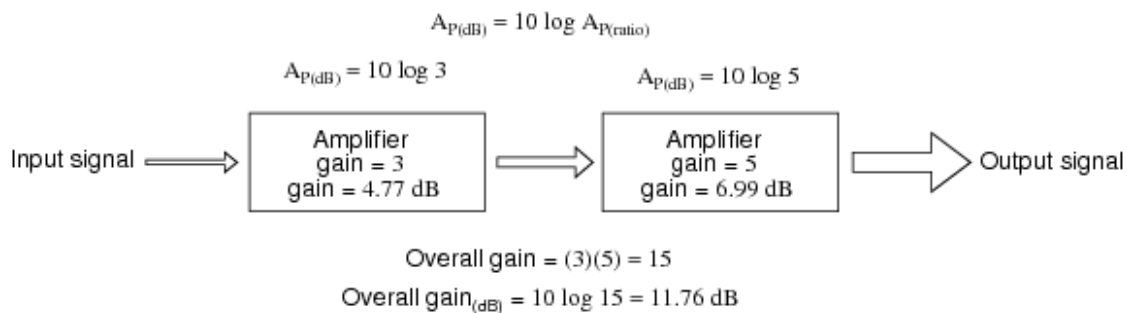
$$A_{P(dB)} = 10 \log A_{P(ratio)}$$

$$A_{P(dB)} = 10 \log 3 \qquad\qquad A_{P(dB)} = 10 \log 5$$

Input signal ⟹ | Amplifier
gain = 3
gain = 4.77 dB | ⟹ | Amplifier
gain = 5
gain = 6.99 dB | ⟹ Output signal

Overall gain = (3)(5) = 15

Overall gain$_{(dB)}$ = 10 log 15 = 11.76 dB

Figure 10 *Gain of Amplifier Stages in decibels is Additive: 4.77 Db + 6.99 Db = 11.76 dB*

To those already familiar with the arithmetic properties of logarithms, this is no surprise. It is an elementary rule of algebra that the antilogarithm of the sum of two numbers' logarithm values equals the product of the two original numbers. In other words, if we take two numbers and determine the logarithm of each, then add those two logarithm figures together, then determine the "antilogarithm" of that sum (elevate the base number of the logarithm -- in this case, 10 -- to the power of that sum), the result will be the same as if we had simply multiplied the two original numbers together. This algebraic rule forms the heart of a device called a *slide rule*, an analog computer which could, among other things, determine the products and quotients of numbers by addition (adding together physical lengths marked on sliding wood, metal, or plastic scales). Given a table of logarithm figures, the same mathematical trick could be used to perform otherwise complex multiplications and divisions by only having to do additions and subtractions, respectively. With the advent of high-speed, handheld, digital calculator devices, this elegant calculation technique virtually disappeared from popular use. However, it is still important to understand when working with measurement scales that are logarithmic in nature, such as the bel (decibel) and Richter scales.

When converting a power gain from units of bels or decibels to a unitless ratio, the mathematical inverse function of common logarithms is used: powers of 10, or the *antilog*.

If

$$A_{P(\text{bel})} = \log A_{P(\text{ratio})}$$

Then

$$A_{P(\text{ratio})} = 10^{A_{P(\text{bel})}}$$

Converting decibels into unitless ratios for power gain is much the same, only a division factor of 10 is included in the exponent term:

If

$$A_{P(\text{dB})} = 10 \log \left(A_{P(\text{ratio})} \right)$$

Then

$$A_{P(\text{ratio})} = 10^{\frac{A_{P(\text{dB})}}{10}}$$

Example: Power into an amplifier is 1 Watt, the power out is 10 Watts. Find the power gain in dB.

$$A_{P(\text{dB})} = 10 \log_{10} \frac{P_O}{P_I} = 10 \log_{10} \frac{10}{1} = 10 \log_{10} (10) = 10 \, (1) = 10 \, dB$$

Example: Find the power gain ratio $A_{P(\text{ratio})} = \left(\frac{P_O}{P_I} \right)$ for a 20 dB Power gain.

$$A_{P(\text{dB})} = 20 = 10 \, \log_{10} \, A_{P(\text{ratio})}$$

$$\frac{20}{10} = \log_{10} \, A_{P(\text{ratio})}$$

$$10^{\frac{20}{10}} = 10^{\log_{10} (A_{P(\text{ratio})})}$$

$$100 = A_{P(\text{ratio})} = \left(\frac{20}{10} \right)$$

Because the bel is fundamentally a unit of *power* gain or loss in a system, voltage or current gains and losses don't convert to bels or dB in quite the same way. When using bels or decibels to express a gain other than power, be it voltage or current, we must perform the calculation in terms of how much power gain there would be for that amount of voltage or current gain. For a constant load impedance, a voltage or current gain of 2 equates to a power gain of 4 (2^2); a voltage or current gain of 3 equates to a power gain of 9 (3^2). If we multiply either voltage or current by a given factor, then the power gain incurred by that multiplication will be the square of that factor. This relates back to the forms of Joule's Law where power was calculated from either voltage or current, and resistance:

$$P = \frac{E^2}{R}$$

$$P = I^2 R$$

Power is proportional to the *square*
of either voltage or current

Figure 11   Joule's Law

Thus, when translating a voltage or current gain *ratio* into a respective gain in terms of the bel unit, we must include this exponent in the equation(s):

$$A_{P(Bel)} = \log A_{P(ratio)}$$

$$A_{V(Bel)} = \log A_{V(ratio)}^2 \quad \text{\textit{Exponent required}}$$

$$A_{I(Bel)} = \log A_{I(ratio)}^2$$

Figure 12   Logarithms
and Ratios as bels

The same exponent requirement holds true when expressing voltage or current gains in terms of decibels:

$$A_{P(dB)} = 10 \log A_{P(ratio)}$$

$$A_{V(dB)} = 10 \log A_{V(ratio)}^2 \quad \text{\textit{Exponent required}}$$

$$A_{I(dB)} = 10 \log A_{I(ratio)}^2$$

Figure 13   Logarithms
and Ratios as decibels

However, thanks to another interesting property of logarithms, we can simplify these equations to eliminate the exponent by including the "2" as a *multiplying factor* for the logarithm function. In other words, instead of taking the logarithm of the *square* of the voltage or current gain, we just multiply the voltage or current gain's logarithm figure by 2 and the final result in bels or decibels will be the same:

The process of converting voltage or current gains from bels or decibels into unitless ratios is much the same as it is for power gains:

Here are the equations used for converting voltage or current gains in decibels into unitless ratios:

For bels:

$$A_{V(Bel)} = \log A_{V(ratio)}^2 \qquad\qquad A_{I(Bel)} = \log A_{I(ratio)}^2$$
... *is the same as* ...   ... *is the same as* ...
$$A_{V(Bel)} = 2 \log A_{V(ratio)} \qquad\qquad A_{I(Bel)} = 2 \log A_{I(ratio)}$$

For decibels:

$$A_{V(dB)} = 10 \log A_{V(ratio)}^2 \qquad\qquad A_{I(dB)} = 10 \log A_{I(ratio)}^2$$
... *is the same as* ...   ... *is the same as* ...
$$A_{V(dB)} = 20 \log A_{V(ratio)} \qquad\qquad A_{I(dB)} = 20 \log A_{I(ratio)}$$

Figure 14   Multiplication of Logarithms

If:

$$A_{V(Bel)} = 2 \log A_{V(ratio)} \qquad\qquad A_{I(Bel)} = 2 \log A_{I(ratio)}$$

Then:

$$A_{V(ratio)} = 10^{\frac{A_{V(Bel)}}{2}} \qquad\qquad A_{I(ratio)} = 10^{\frac{A_{I(Bel)}}{2}}$$

Figure 15   Application to Power Gains

While the bel is a unit naturally scaled for power, another logarithmic unit has been invented to directly express voltage or current gains/losses, and it is based on the *natural* logarithm rather than the *common* logarithm as bels and decibels are. Called the *neper*, its unit symbol is "N_p; though, lower-case"n" may be encountered.

For better or for worse, neither the neper nor its attenuated cousin, the *decineper*, is popularly used as a unit in American engineering applications.

Example: The voltage into a 600 Ω audio line amplifier is 10 mV, the voltage across a 600 Ω load is 1 V. Find the power gain in dB.

$$A_{(dB)} = 20 \ \log_{10} \left(\frac{V_O}{V_I}\right) = 20 \ \log_{10} \left(\frac{1}{0.01}\right) = 20 \ \log_{10}(100) = 20\,(2) = 40 \ dB$$

Example: Find the voltage gain ratio $A_{V(ratio)} = \left(\frac{V_O}{V_I}\right)$ for a 20 dB gain amplifier having a 50 Ω input and out impedance.

$$A_{V(dB)} = 20 \ \log_{10} A_{V(ratio)}$$

$$20 = 20 \ \log_{10} A_{V(ratio)}$$

If:

$$A_{V(dB)} = 20 \log A_{V(ratio)} \qquad A_{I(dB)} = 20 \log A_{I(ratio)}$$

Then:

$$A_{V(ratio)} = 10^{\frac{A_{V(dB)}}{20}} \qquad A_{I(ratio)} = 10^{\frac{A_{I(dB)}}{20}}$$

Figure 16 Application to Voltage or Current Gains

$$A_{V(ratio)} = \frac{V_{output}}{V_{input}} \qquad A_{I(ratio)} = \frac{I_{output}}{I_{input}}$$

$$A_{V(neper)} = \ln A_{V(ratio)} \qquad A_{I(neper)} = \ln A_{I(ratio)}$$

Figure 17 Definition of the neper

$$\frac{20}{20} = \log_{10} A_{V(ratio)}$$

$$10^{\frac{20}{20}} = 10^{\log_{10}\left(A_{V(ratio)}\right)}$$

$$10 = A_{V(ratio)} = \left(\frac{V_O}{V_I}\right)$$

Review

- Gains and losses may be expressed in terms of a unitless ratio, or in the unit of bels (B) or decibels (dB). A decibel is literally a *deci*-bel: one-tenth of a bel.

- The bel is fundamentally a unit for expressing *power* gain or loss. To convert a power ratio to either bels or decibels, use one of these equations:

$$A_{P(bel)} = \log A_{P(ratio)}$$

$$A_{P(dB)} = 10 \log A_{P(ratio)}$$

- When using the unit of the bel or decibel to express a *voltage* or *current* ratio, it must be cast in terms of an equivalent *power* ratio. Practically, this means the use of different equations, with a multiplication factor of 2 for the logarithm value corresponding to an exponent of 2 for the voltage or current gain ratio:

$$A_{V\text{(bel)}} = 2\log A_{V\text{(ratio)}}$$

$$A_{I\text{(bel)}} = 2\log A_{I\text{(ratio)}}$$

$$A_{V\text{(dB)}} = 20\log A_{V\text{(ratio)}}$$

$$A_{I\text{(dB)}} = 20\log A_{I\text{(ratio)}}$$

- To convert a decibel gain into a unitless ratio gain, use one of these equations:

$$A_{V\text{(ratio)}} = 10^{\frac{A_{V\text{(dB)}}}{20}}$$

$$A_{I\text{(ratio)}} = 10^{\frac{A_{I\text{(dB)}}}{20}}$$

$$A_{P\text{(ratio)}} = 10^{\frac{A_{P\text{(dB)}}}{20}}$$

- A gain (amplification) is expressed as a positive bel or decibel figure. A loss (attenuation) is expressed as a negative bel or decibel figure. Unity gain (no gain or loss; ratio = 1) is expressed as zero bels or zero decibels.

- When calculating overall gain for an amplifier system composed of multiple ampli-fier stages, individual gain ratios are *multiplied* to find the overall gain ratio. Bel or decibel figures for each amplifier stage, on the other hand, are *added* together to determine overall gain.

Absolute dB scales

It is also possible to use the decibel as a unit of absolute power, in addition to using it as an expression of power gain or loss. A common example of this is the use of decibels as a measurement of sound pressure intensity. In cases like these, the measurement is made in reference to some standardized power level defined as 0 dB. For measurements of sound pressure, 0 dB is loosely defined as the lower threshold of human hearing, objectively quantified as 1 picowatt of sound power per square meter of area.

A sound measuring 40 dB on the decibel sound scale would be 10^4 times greater than the threshold of hearing. A 100 dB sound would be 10^{10} (ten billion) times greater than the threshold of hearing.

Because the human ear is not equally sensitive to all frequencies of sound, variations of the decibel sound-power scale have been developed to represent physiologically equivalent sound intensities at different frequencies. Some sound intensity instruments were equipped with filter networks to give disproportionate indications across the frequency scale, the intent of which to better represent the effects of sound on the human body. Three filtered scales became commonly known as the "A," "B," and "C" weighted scales. Decibel sound intensity indications measured through these respective filtering networks were given in units of dBA, dBB, and dBC. Today, the "A-weighted scale" is most commonly used for expressing the equivalent physiological impact on the human body, and is especially useful for rating dangerously loud noise sources.

Another standard-referenced system of power measurement in the unit of decibels has been established for use in telecommunications systems. This is called the *dBm* scale (Figure 18). The reference point, 0 dBm, is defined as 1 milliwatt of electrical power dissipated by a 600 Ω load. According to this scale, 10 dBm is equal to 10 times the reference power, or 10 milliwatts; 20 dBm is equal to 100 times the reference power, or 100 milliwatts. Some AC voltmeters come equipped with a dBm range or scale (sometimes labeled "DB") intended for use in measuring AC signal power across a 600 Ω load. 0 dBm on this scale is, of course, elevated above zero because it represents something greater than 0 (actually, it represents 0.7746 volts across a 600 Ω load, voltage being equal to the square root of power times resistance; the square root of 0.001 multiplied by 600). When viewed on the face of an analog meter movement, this dBm scale appears compressed on the left side and expanded on the right in a manner not unlike a resistance scale, owing to its logarithmic nature.

Radio frequency power measurements for low level signals encountered in radio receivers use dBm measurements referenced to a 50 Ω load. Signal generators for the evaluation of radio receivers may output an adjustable dBm rated signal. The signal level is selected by a device called an attenuator, described in the next section.

An adaptation of the dBm scale for audio signal strength is used in studio recording and broadcast engineering for standardizing volume levels, and is called the *VU* scale. VU meters are frequently seen on electronic recording instruments to indicate whether or not the recorded signal exceeds the maximum signal level limit of the device, where significant distortion will occur. This "volume indicator" scale is calibrated in according to the dBm scale, but does not directly indicate dBm for any signal other than steady sine-wave tones. The proper unit of measurement for a VU meter is *volume units.*

Table: Absolute power levels in dBm (decibel milliwatt)

Power in watts	Power in milliwatts	Power in dBm	Power in milliwatts	Power in dBm
1	1000	30 dB	1	0 dB
0.1	100	20 dB	0.1	-10 dB
0.01	10	10 dB	0.01	-20 dB
0.004	4	6 dB	0.001	-30 dB
0.002	2	3 dB	0.0001	-40 dB

Figure 18   Absolute Power Levels in dBm (decibels referenced to 1 milliwatt)

When relatively large signals are dealt with, and an absolute dB scale would be useful for representing signal level, specialized decibel scales are sometimes used with reference points greater than the 1 mW used in dBm. Such is the case for the *dBW* scale, with a reference point of 0 dBW established at 1 Watt. Another absolute measure of power called the *dBk* scale references 0 dBk at 1 kW, or 1000 Watts.

Review

- The unit of the bel or decibel may also be used to represent an absolute measurement of power rather than just a relative gain or loss. For sound power measurements, 0 dB is defined as a standardized reference point of power equal to 1 picowatt per square meter. Another dB scale suited for sound intensity measurements is normalized to the same physiological effects as a 1000 Hz tone, and is called the *dBA* scale. In this system, 0 dBA is defined as any frequency sound having the same physiological equivalence as a 1 picowatt-per-square-meter tone at 1000 Hz.
- An electrical dB scale with an absolute reference point has been made for use in telecommunications systems. Called the *dBm* scale, its reference point of 0 dBm is defined as 1 milliwatt of AC signal power dissipated by a 600 Ω load.

- A *VU* meter reads audio signal level according to the dBm for sine-wave signals. Because its response to signals other than steady sine waves is not the same as true dBm, its unit of measurement is *volume units*.
- dB scales with greater absolute reference points than the dBm scale have been invented for high-power signals. The *dBW* scale has its reference point of 0 dBW defined as 1 Watt of power. The *dBk* scale sets 1 kW (1000 Watts) as the zero-point reference.

Attenuators

Attenuators are passive devices. It is convenient to discuss them along with decibels. Attenuators weaken or *attenuate* the high level output of a signal generator, for example, to provide a lower level signal for something like the antenna input of a sensitive radio receiver. (Figure 19) The attenuator could be built into the signal generator, or be a stand-alone device. It could provide a fixed or adjustable amount of attenuation. An attenuator section can also provide isolation between a source and a troublesome load.
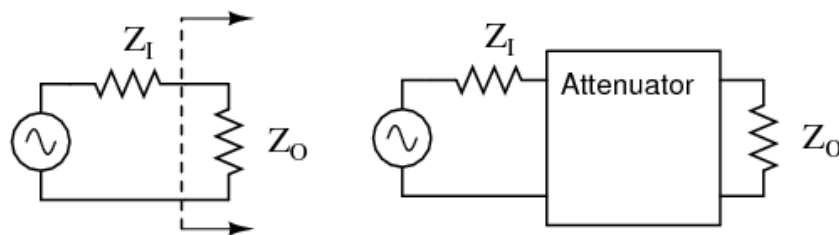

Figure 19   Constant impedance attenuator is matched to source impedance Z_I and load impedance Z_O. For radio frequency equipment Z is 50 Ω

In the case of a stand-alone attenuator, it must be placed in series between the signal source and the load by breaking open the signal path as shown in Figure 19. In addition, it must match both the source impedance $\mathbf{Z_I}$ and the load impedance $\mathbf{Z_O}$, while providing a specified amount of attenuation. In this section we will only consider the special, and most common, case where the source and load impedances are equal. Not considered in this section, unequal source and load impedances may be matched by an attenuator section. However, the formulation is more complex.
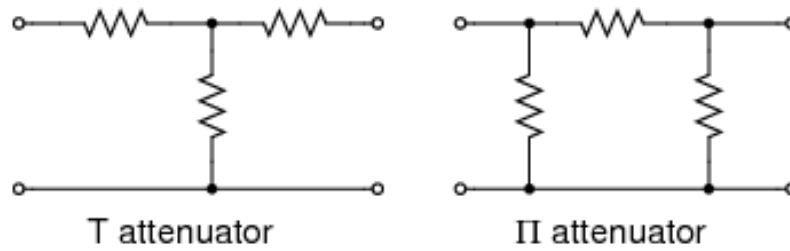
T attenuator   Π attenuator

Figure 20   T section and Π section attenuators are common forms

Common configurations are the **T** and **Π** networks shown in Figure 20 Multiple attenuator sections may be cascaded when even weaker signals are needed as in Figure 28.

Decibels

Voltage ratios, as used in the design of attenuators are often expressed in terms of decibels. The voltage ratio (K below) must be derived from the attenuation in decibels. Power ratios expressed as decibels are additive. For example, a 10 dB attenuator followed by a 6 dB attenuator provides 16dB of attenuation overall

$$10 \text{ dB} + 6 \text{ dB} = 16 \text{ dB}$$

Changing sound levels are perceptible roughly proportional to the logarithm of the power ratio $\left(\frac{P_I}{P_O}\right)$

$$\text{sound level} = \log_{10}\left(\frac{P_I}{P_O}\right)$$

A change of 1 dB in sound level is barely perceptible to a listener, while 2 db is readily perceptible. An attenuation of 3 dB corresponds to cutting power in half, while a gain of 3 db corresponds to a doubling of the power level. A gain of -3 dB is the same as an attenuation of +3 dB, corresponding to half the original power level.

The power change in decibels in terms of power ratio is

$$\text{dB} = 10 \log_{10}\left(\frac{P_I}{P_O}\right)$$

Assuming that the load R_I at P_I is the same as the load resistor R_O at P_O (i.e. $R_I = R_O$), the decibels may be derived from the voltage ratio $\left(\frac{V_I}{V_O}\right)$ or current ratio $\left(\frac{I_I}{I_O}\right)$ as

$$P_O = V_O I_O = \frac{V_O^2}{R} = I_O^2 R$$

$$P_I = V_I I_I = \frac{V_I^2}{R} = I_I^2 R$$

$$\text{dB} = 10 \log_{10}\left(\frac{P_I}{P_O}\right) = 10 \log_{10}\left(\frac{V_I^2}{V_O^2}\right) = 20 \log_{10}\left(\frac{V_I}{V_O}\right)$$

$$\text{dB} = 10 \log_{10}\left(\frac{P_I}{P_O}\right) = 10 \log_{10}\left(\frac{I_I^2}{I_O^2}\right) = 20 \log_{10}\left(\frac{I_I}{I_O}\right)$$

The two most often used forms of the decibel equation are

$$\text{dB} = 10 \log_{10}\left(\frac{P_I}{P_O}\right)$$

or

$$\text{dB} = 20 \log_{10}\left(\frac{V_I}{V_O}\right)$$

We will use the latter form, since we need the voltage ratio. Once again, the voltage ratio form of equation is only applicable where the two corresponding resistors are equal. That is, the source and load resistance need to be equal.

Example: Power into an attenuator is 10 Watts, the power out is 1 Watt. Find the attenuation in dB.

$$\text{dB} = 10 \log_{10}\left(\frac{P_I}{P_O}\right) = 10 \log_{10}\left(\frac{10}{1}\right) = 10\,(1) = 10 \text{ dB}$$

Example: Find the voltage attenuation ratio $(K = (V_I / V_O))$ for a 10 dB attenuator.

$$\text{dB} = 10 = 20 \log_{10}\left(\frac{V_I}{V_O}\right)$$

$$\frac{10}{20} = \log_{10}\left(\frac{V_I}{V_O}\right)$$

$$10^{\frac{10}{20}} = 10^{\log_{10}\left(\frac{V_I}{V_O}\right)}$$

$$3.16 = \left(\frac{V_I}{V_O}\right) = A_{P(\text{ratio})}$$

Example: Power into an attenuator is 100 milliwatts, the power out is 1 milliwatt. Find the attenuation in dB.

$$dB = 10\log_{10}\left(\frac{P_I}{P_O}\right) = 10\log_{10}\left(\frac{100}{1}\right) = 10\log_{10}(100) = 10(2) = 20 \text{ dB}$$

Example: Find the voltage attenuation ratio $K = \left(\frac{V_I}{V_O}\right)$ for a 20 dB attenuator.

$$dB = 20 = 20\log_{10}\left(\frac{V_I}{V_O}\right)$$

$$10^{\frac{20}{20}} = 10^{\log_{10}\left(\frac{V_I}{V_O}\right)}$$

$$10 = \left(\frac{V_I}{V_O}\right) = K$$

T-section Attenuator

The T and Π attenuators must be connected to a **Z** source and **Z** load impedance. The **Z**-(arrows) pointing away from the attenuator in the figure below indicate this. The **Z**-(arrows) pointing toward the attenuator indicates that the impedance seen looking into the attenuator with a load Z on the opposite end is Z, Z=50 Ω for our case. This impedance is a constant (50 Ω) with respect to attenuation-- impedance does not change when attenuation is changed.

The table in Figure 21 lists resistor values for the **T** and **Π** attenuators to match a 50 Ω source/ load, as is the usual requirement in radio frequency work.

Telephone utility and other audio work often requires matching to 600 Ω. Multiply all **R** values by the ratio (600/50) to correct for 600 Ω matching. Multiplying by 75/50 would convert table values to match a 75 Ω source and load.

The amount of attenuation is customarily specified in dB (decibels). Though, we need the voltage (or current) ratio **K** to find the resistor values from equations. See the **dB/20** term in the power of **10** term for computing the voltage ratio **K** from dB, above.
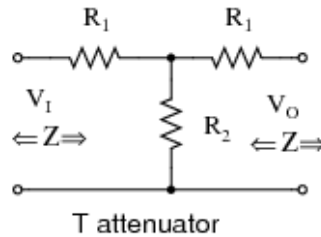
dB = attenuation in decibels

Z = source/load impedance (resistive)

K > 1

$$K = \frac{V_I}{V_O} = 10^{\,dB/20}$$

$$R_1 = Z\left(\frac{K-1}{K+1}\right)$$

$$R_2 = Z\left(\frac{2K}{K^2-1}\right)$$

T attenuator

Resistors for T-section			
Z = 50			
Attenuation			
dB	K=Vi/Vo	R1	R2
1.0	1.12	2.88	433.34
2.0	1.26	5.73	215.24
3.0	1.41	8.55	141.93
4.0	1.58	11.31	104.83
6.0	2.00	16.61	66.93
10.0	3.16	25.97	35.14
20.0	10.00	40.91	10.10

Figure 21   Formulas for T-section attenuator resistors, given K, the voltage attenuation ratio, and $Z_I = Z_O = 50\ \Omega$

The **T** (and below **Π**) configurations are most commonly used as they provide bidirectional matching. That is, the attenuator input and output may be swapped end for end and still match the source and load impedances while supplying the same attenuation.

Disconnecting the source and looking in to the right at **V_I**, we need to see a series parallel combination of **R_1**, **R_2**, **R_1**, and **Z** looking like an equivalent resistance of **Z_{IN}**, the same as the source/load impedance Z: (a load of Z is connected to the output.)

$$Z_{IN} = R_1 + \left(R_2 \parallel \left(R_1 + Z\right)\right)$$

For example, substitute the 10 dB values from the 50 Ω attenuator table for **R_1** and **R_2** as shown in Figure 22.

$$Z_{IN} = 25.97 + (35.14 \parallel (25.97 + 50))$$

$$Z_{IN} = 25.97 + (35.14 \parallel 75.97)$$

$$Z_{IN} = 25.97 + 24.03 = 50$$

This shows us that we see 50 Ω looking right into the example attenuator (Figure 22) with a 50 Ω load.

Replacing the source generator, disconnecting load **Z** at **V_O**, and looking in to the left, should give us the same equation as above for the impedance at **V_O**, due to symmetry. Moreover, the three resistors must be values which supply the required attenuation from input to output. This is accomplished by the equations for **R_1** and **R_2** above as applied to the **T**-attenuator below.
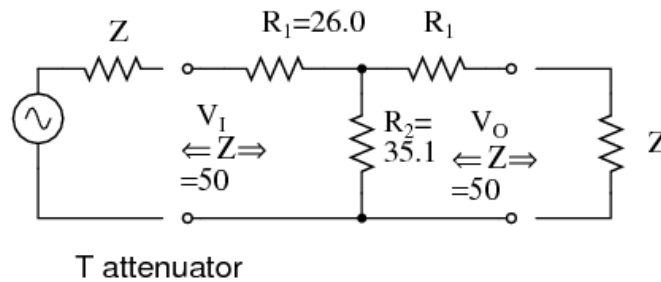
T attenuator

10 dB attenuators for matching input/output to Z= 50 Ω.

Figure 22   10 dB T-Section Attenuator for
Insertion Between a 50 Ω Source and Load

Π-section Attenuator

The table in Figure 23 lists resistor values for the **Π** attenuator matching a 50 Ω source/ load at some common attenuation levels. The resistors corresponding to other attenuation levels may be calculated from the equations.

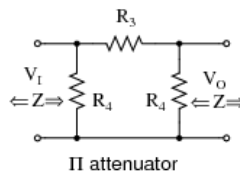**Figure 23**   Formulas for Π-section Attenuator Resistors, given *K*, the Voltage Attenuation Ratio, and $Z_I = Z_O = 50$ Ω

The above apply to the π-attenuator below.

What resistor values would be required for both the **Π** attenuators for 10 dB of attenuation matching a 50 Ω source and load?

The **10 dB** corresponds to a voltage attenuation ratio of **K=3.16** in the next to last line of the above table. Transfer the resistor values in that line to the resistors on the schematic diagram in Figure 24.
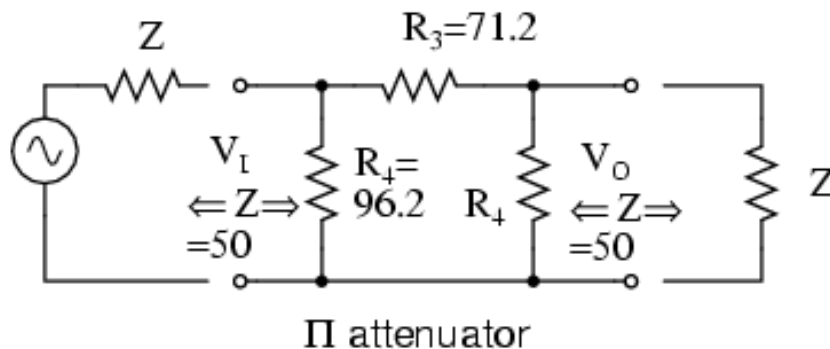
Figure 24   10 dB Π-section Attenuator
Example for Matching a 50 Ω Source and Load

L-Section Attenuator

The table in Figure 25 lists resistor values for the **L** attenuators to match a 50 Ω source / load. The table in Figure 26 lists resistor values for an alternate form. Note that the resistor values are not the same.

dB = attenuation in decibels
Z = source/load impedance (resistive)
K > 1

$$K = \frac{V_I}{V_O} = 10^{dB/20}$$

$$R_5 = Z\left(\frac{K-1}{K}\right)$$

$$R_6 = \frac{Z}{(K-1)}$$
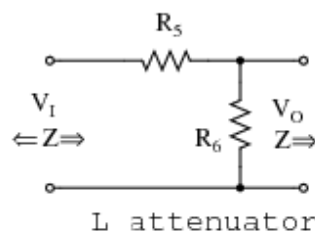
L attenuator

Resistors for L-section			
Z=,50.00			
Attenuation L			
dB	K=Vi/Vo	R5	R6
1.0	1.12	5.44	409.77
2.0	1.26	10.28	193.11
3.0	1.41	14.60	121.20
4.0	1.58	18.45	85.49
6.0	2.00	24.94	50.24
10.0	3.16	34.19	23.12
20.0	10.00	45.00	5.56

Figure 25   _L-Section Attenuator Table for 50 Ω Source and Load Impedance

The above apply to the **L** attenuator below.

Bridged T Attenuator

The table in Figure 27 lists resistor values for the bridged **T** attenuators to match a 50 Ω source and load. The bridged-T attenuator is not often used. Why not?
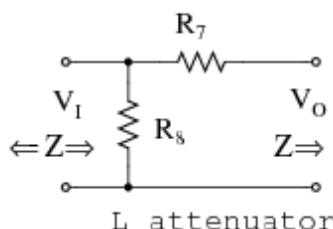
dB = attenuation in decibels

Z = source/load impedance (resistive)

K > 1

$$K = \frac{V_I}{V_O} = 10^{dB/20}$$

$$R_7 = Z(K-1)$$

$$R_8 = Z\left(\frac{K}{K-1}\right)$$

L attenuator

Resistors for L-section			
Z=50.00			
Attenuation			
dB	K=Vi/Vo	R7	R8
1.0	1.12	6.10	459.77
2.0	1.26	12.95	243.11
3.0	1.41	20.63	171.20
4.0	1.58	29.24	135.49
6.0	2.00	49.76	100.24
10.0	3.16	108.11	73.12
20.0	10.00	450.00	55.56

Figure 26   _Alternate Form L-Section Attenuator Table for 50 Ω Source and Load Impedance
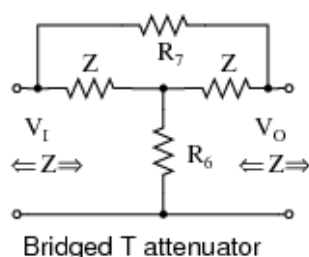
dB = attenuation in decibels

Z = source/load impedance (resistive)

K > 1

$$K = \frac{V_I}{V_O} = 10^{dB/20}$$

$$R_6 = \frac{Z}{(K-1)}$$

$$R_7 = Z(K-1)$$

Bridged T attenuator

Resistors for bridged T			
Z=50.00			
Attenuation			
dB	K=Vi/Vo	R7	R6
1.0	1.12	6.10	409.77
2.0	1.26	12.95	193.11
3.0	1.41	20.63	121.20
4.0	1.58	29.24	85.49
6.0	2.00	49.76	50.24
10.0	3.16	108.11	23.12
20.0	10.00	450.00	5.56

Figure 27   _Formulas and Abbreviated Table for Bridged-T Attenuator Section, Z = 50 Ω

Cascaded Sections

Attenuator sections can be cascaded as in Figure 28 for more attenuation than may be available from a single section. For example two 10 db attenuators may be cascaded to provide 20 dB of attenuation, the dB values being additive. The voltage attenuation ratio **K** or **V$_I$/V$_O$** for a 10 dB attenuator section is 3.16. The voltage attenuation ratio for the two cascaded sections is the product of the two **K**s or 3.16x3.16=10 for the two cascaded sections.

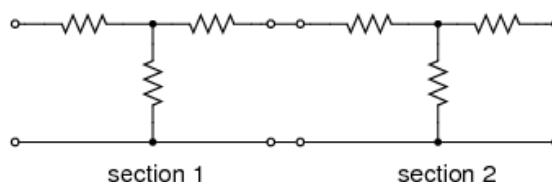section 1   section 2

Figure 28   Cascaded Attenuator Sections: dB Attenuation is Additive

Variable attenuation can be provided in discrete steps by a switched attenuator. The example Figure 29, shown in the 0 dB position, is capable of 0 through 7 dB of attenuation by additive switching of none, one or more sections.
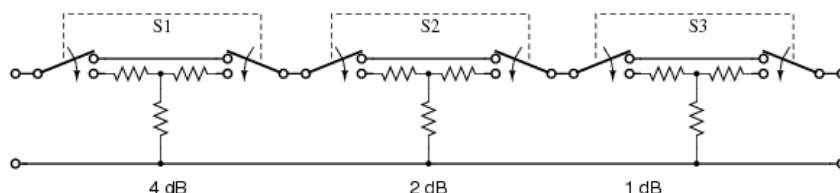

Figure 29   Switched Attenuator:
Attenuation is Variable in Discrete Steps

The typical multi section attenuator has more sections than the above figure shows. The addition of a 3 or 8 dB section above enables the unit to cover to 10 dB and beyond. Lower signal levels are achieved by the addition of 10 dB and 20 dB sections, or a binary multiple 16 dB section.

RF Attenuators

For radio frequency (RF) work (<1000 Mhz), the individual sections must be mounted in shielded compartments to thwart capacitive coupling if lower signal levels are to be achieved at the highest frequencies. The individual sections of the switched attenuators in the previous section are mounted in shielded sections. Additional measures may be taken to extend the frequency range to beyond 1000 Mhz. This involves construction from special shaped lead-less resistive elements.

A coaxial T-section attenuator consisting of resistive rods and a resistive disk is shown in Figure 30. This construction is usable to a few gigahertz. The coaxial Π version would have one resistive rod between two resistive disks in the coaxial line as in Figure 31.

RF connectors, not shown, are attached to the ends of the above T and Π attenuators. The connectors allow individual attenuators to be cascaded, in addition to connecting between a source and load. For example, a 10 dB attenuator may be placed between a troublesome signal source and an expensive spectrum analyzer input. Even though we may not need the attenuation, the expensive test equipment is protected from the source by attenuating any overvoltage.

metalic conductor

resistive disc
resistive rod
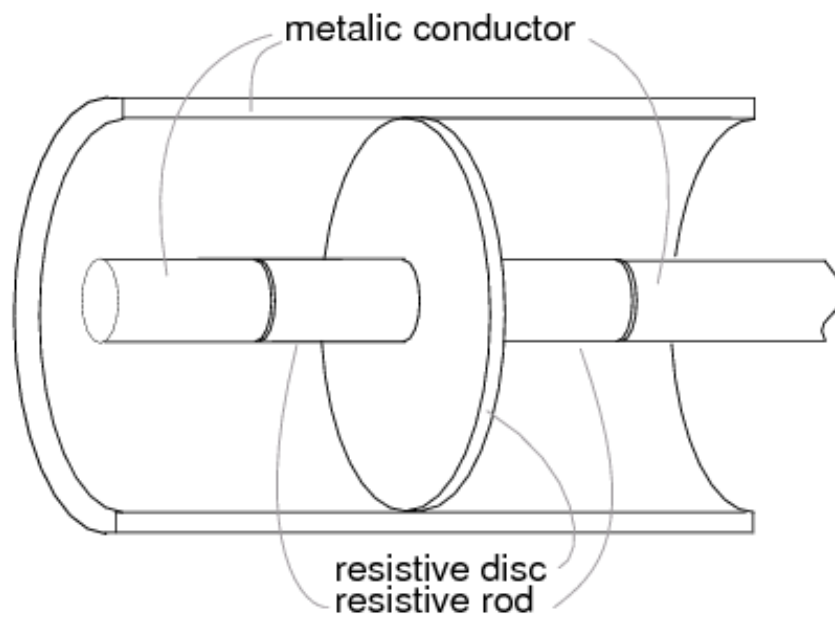
Coaxial T-attenuator for radio frequency work

Figure 30   Coaxial T-Attenuator for Radio Frequency Work

metalic conductor

resistive rod
resistive disc
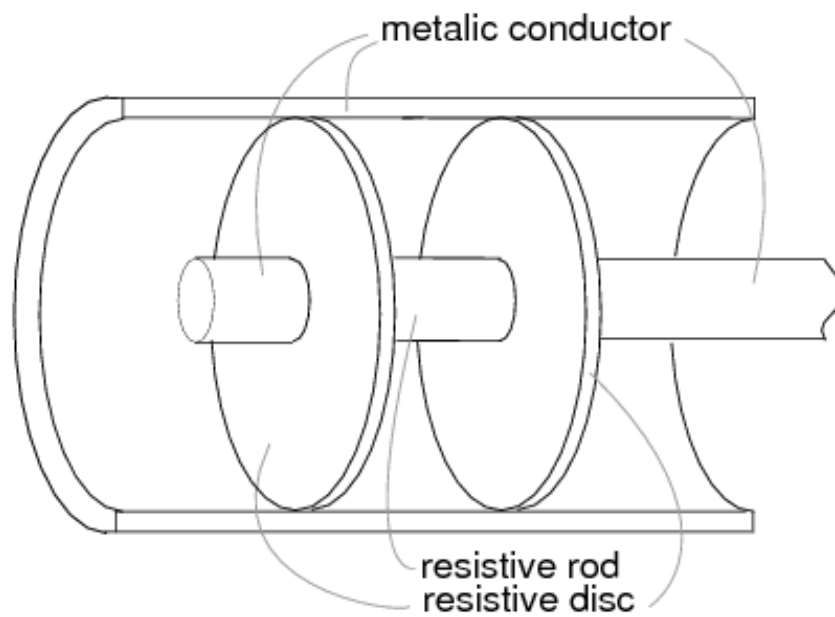
Coaxial Π-attenuator for radio frequency work

Figure 31   Coaxial Π-Attenuator for Radio Frequency Work

Summary: Attenuators

- An *attenuator* reduces an input signal to a lower level.

- The amount of attenuation is specified in *decibels* (dB). Decibel values are additive for cascaded attenuator sections.

- dB from power ratio

$$\text{dB} = 10 \log_{10} \left(\frac{P_I}{P_O} \right)$$

- dB from voltage ratio

$$\text{dB} = 20 \log_{10} \left(\frac{V_I}{V_O} \right)$$

- *T* and *Π* section attenuators are the most common circuit configurations.

Contributors

Contributors to this chapter are listed in chronological order of their contributions, from most recent to first. See Appendix 2 (Contributor List) for dates and contact information.

Colin Barnard (November 2003): Correction regarding Alexander Graham Bell's country of origin (Scotland, not the United States).

Contributor List

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Credits

All entries arranged in alphabetical order of surname. Major contributions are listed by individual name with some detail on the nature of the contribution(s), date, contact info, etc. Minor contributions (typo corrections, etc.) are listed by name only for reasons of brevity. Please understand that when I classify a contribution as "minor," it is in no way inferior to the effort or value of a "major" contribution, just smaller in the sense of less text changed. Any and all contributions are gratefully accepted. I am indebted to all those who have given freely of their own knowledge, time, and resources to make this a better book!

John Anhalt

- **Date(s) of contribution(s):** December 2008
- **Nature of contribution:** Updated lead-acid cell chemistry, Ch 11
- **Contact at:** jpa@anhalt.org

Benjamin Crowell, Ph.D.

- **Date(s) of contribution(s):** January 2001
- **Nature of contribution:** Suggestions on improving technical accuracy of electric field and charge explanations in the first two chapters.
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Dennis Crunkilton

- **Date(s) of contribution(s):** January 2006 to present
- **Nature of contribution:** Mini table of contents, all chapters except appedicies; html, latex, ps, pdf; See Devel/tutorial.html; 01/2006.
- DC network analysis ch, Mesh current section, Mesh current by inspection, new material.i DC network analysis ch, Node voltage method, new section.
- Ch3, Added AFCI paragraphs after GFCI, 10/09/2007.
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- **Nature of contribution:** Helped create the "table" concept for use in analysis of series and parallel circuits.

Davy Van Nieuwenborgh

- **Date(s) of contribution(s):** October 2006
- **Nature of contribution:** DC network analysis ch, Mesh current section, supplied solution to mesh problem, pointed out error in text.
- **Contact at:** `Theoretical Computer Science laboratory, Department of Computer Science, Vrije Universiteit Brussel.`

Ray A. Rayburn

- **Date(s) of contribution(s):** September 2009
- **Nature of contribution:** Nonapplicability of Maximum Power Transfer Theorem to Hi-Fi audio amplifier.
- **Contact at:** `http://forum.allaboutcircuits.com/member.php?u=54720`

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- **Nature of contribution:** Provided capacitor photographs for chapter 13.

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- **Date(s) of contribution(s):** November 2009
- **Nature of contribution:** Chapter 8, troublehooting tip end of Kelvin section.

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Typo Corrections and other "Minor" Contributions

- *The students of Bellingham Technical College's Instrumentation program*.

- **anonymous** (July 2007) Ch 1, remove :registers. Ch 5, s/figures something/figures is something/. Ch 6 s/The current/The current. (September 2007) Ch 5, 8, 9, 10, 11, 12, 13, 15. Numerous typos, clarifications.

- **Tony Armstrong** (January 2003) Suggested diagram correction in "Series and Parallel Combination Circuits" chapter.

- **James Boorn** (January 2001) Clarification on SPICE simulation.

- **Dejan Budimir** (January 2003) Clarification of Mesh Current method explanation.

- **Sridhar Chitta**, Assoc. Professor, Dept. of Instrumentation and Control Engg., Vignan Institute of Technology and Science, Deshmukhi Village, Pochampally Mandal, Nalgonda Distt, Andhra Pradesh, India (December 2005) Chapter 13: CAPACITORS, Clarification: s/note the direction of current/note the direction of electron current/, 2-places

- **Colin Creitz** (May 2007) Chapters: several, s/it's/its.

- **Larry Cramblett** (September 2004) Typographical error correction in "Nonlinear conduction" section.

- **Brad Drum** (May 2006) Error correction in "Superconductivity" section, Chapter 12: PHYSICS OF CONDUCTORS AND INSULATORS. Degrees are not used as a modifier with kelvin(s), 3 changes.

- **Jeff DeFreitas** (March 2006)Improve appearance: replace "/" and"/" Chapters: A1, A2. Type errors Chapter 3: /am injurious spark/an injurious spark/, /in the even/inthe event/

- **Sean Donner** (December 2004) Typographical error correction in "Voltage and current" section, Chapter 1: BASIC CONCEPTS OF ELECTRICITY,(by a the/ by the) (current of current/ of current).

(Januar 2005), Typographical error correction in "Fuses" section, Chapter 12: THE PHYSICS OF CONDUCTORS AND INSULATORS (Neither fuses nor circuit breakers were not designed to open / Neither fuses nor circuit breakers were designed to open).

(January 2005), Typographical error correction in "Factors Affecting Capacitance" section, Chapter 13: CAPACITORS, (greater plate area gives greater capacitance; less plate area gives less capacitance / greater plate area gives greater capacitance; less plate area gives less capacitance); "Factors Affecting Capacitance" section, (thin layer if insulation/thin layer of insulation).

(January 2005), Typographical error correction in "Practical Considerations" section, Chapter 15: INDUCTORS, (there is not such thing / there is no such thing).

(January 2005), Typographical error correction in "Voltage and current calculations" section, Chapter 16: RC AND L/R TIME CONSTANTS (voltage in current / voltage and current).

- **Manuel Duarte** (August 2006): Ch: DC Metering Circuits ammeter images: 00163.eps, 00164.eps; Ch: RC and L/R Time Constants, simplified ln() equation images 10263.eps, 10264.eps, 10266.eps, 10276.eps.

- **Aaron Forster** (February 2003) Typographical error correction in "Physics of Conductors and Insulators" chapter.

- **Bill Heath** (September-December 2002) Correction on illustration of atomic structure, and corrections of several typographical errors.

- **Stefan Kluehspies** (June 2003): Corrected spelling error in Andrew Tannenbaum's name.

- **David M. St. Pierre** (November 2007): Corrected spelling error in Andrew Tanenbaum's name (from the title page of his book).

- **Geoffrey Lessel**,Thompsons Station, TN (June 2005): Corrected typo error in Ch 1 "If this charge (static electricity) is stationary, and you won't realize--remove If; Ch 2 "Ohm's Law also make intuitive sense if you apply if to the water-and-pipe analogy." s/if/it; Chapter 2 "Ohm's Law is not very useful for analyzing the behavior of components like these where resistance is varies with voltage and current." remove "is"; Ch 3 "which halts fibrillation and and gives the heart a

chance to recover." double "and"; Ch 3 "To be safest, you should follow this procedure is checking, using, and then checking your meter.... s/is/of.

- **LouTheBlueGuru**, allaboutcircuits.com, July 2005 Typographical errors, in Ch 6 "the current through R1 is half:" s/half/twice; "current through R1 is still exactly twice that of R2" s/R3/R2

- **Norm Meyrowitz** , nkm, allaboutcircuits.com, July 2005 Typographical errors, in Ch 2.3 "where we don't know both voltage and resistance:" s/resistance/current

- **Don Stalkowski** (June 2002) Technical help with PostScript-to-PDF file format conversion.

- **Joseph Teichman** (June 2002) Suggestion and technical help regarding use of PNG images instead of JPEG.

- **Derek Terveer** (June 2006) Typographical errors, several in Ch 1,2,3.

- **Geoffrey Lessel** (June 2005) Typographical error, s/It discovered/It was discovered/ in Ch 1.

- **Austin@allaboutcircuits.com** (July 2007) Ch 2, units of mass, pound vs kilogram, near "units of pound" s/pound/kilogram/.

- **CATV@allaboutcircuits.com** (April 2007) Telephone ring voltage error, Ch 3.

- **line@allaboutcircuits.com** (June 2005) Typographical error correction in Volumes 1,2,3,5, various chapters ,(:s/visa-versa/vice versa/).

- **rob843@allaboutcircuits.com** (April 2007) Telephone ring voltage error, Ch 3.

- **bigtwenty@allaboutcircuits.com** (July 2007) Ch 4 near "different metric prefix", s/right to left/left to right/.

- **jut@allaboutcircuits.com** (September 2007) Ch 13 near s/if were we to/if we were to/, s/a capacitors/a capacitor.

- **rxtxau@allaboutcircuits.com** (October 2007) Ch 3, suggested, GFCI terminology, non-US usage.

- **Stacy Mckenna Seip** (November 2007) Ch 3 s/on hand/one hand, Ch 4 s/weight/weigh, Ch 8 s/weight/weigh, s/left their/left there, Ch 9 s/cannot spare/cannot afford/, Ch1 Clarification, static electricity.

- **Cory Benjamin** (November 2007) Ch 3 s/on hand/one hand.

- **Larry Weber** (Feb 2008) Ch 3 s/on hand/one hand.

- **trunks14@allaboutrcircuits.com** (Feb 2008) Ch 15 s/of of/of .

- **Greg Herrington** (Feb 2008) Ch 1, Clarification: no neutron in hydrogen atom.

- **mark44** (Feb 2008) Ch 1, s/naturaly/naturally/

- **Unregistered@allaboutcircuits.com** (February 2008) Ch 1, s/smokelsee/smokeless , s/ecconomic/economic/ .

- **Timothy Unregistered@allaboutcircuits.com** (Feb 2008) Changed default roman font to newcent.

- **Imranullah Syed** (Feb 2008) Suggested centering of uncaptioned schematics.

- **davidr@insyst_ltd.com** (april 2008) Ch 5, s/results/result 2plcs.

- **Professor Thom@allaboutcircuits.com** (Oct 2008) Ch 6, s/g/c near Ecd and near 00435.png, 2plcs.

- **John Schwab** (Dec 2008) Ch 1, Static Electricity, near Charles Coulomb: rearrangement of text segments.

- **Olivier Derewonko** (Dec 2008) Ch 4 s/orientation a voltage/orientation of a/. Ch2 s/flow though/flow through/. Ch Safe meter usage, REVIEW, s/,/./ . Ch5, s/is it/it is/.

- **dor@allaboutcircuits.com** (June 2009) Ch 1, s/nusiance/nuisance.

- **rspuzio@allaboutcircuits.com** (September 2009) Ch 8, s/logarithmic/nonlinear , 6-plcs.

- **David Lewis@allaboutcircuits.com** (September 2009) Ch 1, hide paragraph: Physical dimension also impacts conductivity. . . etc.

- **Walter Odington@allaboutcircuits.com** (January 2010) Ch 3, s/hydration another/hydration is another/ .

- **tone_b@allaboutcircuits.com** (January 2010) Ch 6 , s/must were/were/ .

- **Unregistered Guest@allaboutcircuits.com** (July 2010) Ch 1 , s/is is/it is/ .

- **Unregistered Guest@allaboutcircuits.com** (July 2010) Ch 5 , added I2 to image 00090.png .

- **Unregistered Guest@allaboutcircuits.com** (August 2010) Ch 1 , s/was one the/was one of the/ .

- **D. Crunkilton** (June 2011) hi.latex, header file; updated link to openbookproject.net .

- **Bob Arthur** (Jan 2012) images: 00046.eps, 00047.eps,00048.eps 00362.eps, graph line visibility fixed.

- **vspriyan@allaboutcircuits.com** (Jan 2013) Ch 10, Near: voltages divided by their s/currents/resistances/ .

- **Eugene Smirnoff** (Jan 2013) Ch1, s/an hypothetical/a hypothetical/ . Ch 2 s/An historic/A historic/ .

- **Gulliveig@allaboutcircuits.com** (Jan 2014) Ch4, s/significant digits/mantissa, s/1000/999/ .

- **slidercrank@allaboutcircuits.com** (Feb 2014) Ch6, s/both positive/both be positive/ .

- **Skfir@allaboutcircuits.com** (August 2015) Ch10, s/suppling/supplying/ .

- **John Wang** (Sept 2017) Ch2, s/points 1 and 4/points 1 and 6/, s/points 2 and 3/3 and 4/ .

- **Stewart Todd Morgan** (Feb 2020) Ch3, s+http://web.mit.edu/safety+https://ehs.mit.edu/workpla safety-program/electr

- **DC** (Sept 2017) Ch12, Chi3; Reformated various tables to html/latex.

- **DC** (Nov 2021) ChA1, ChA2, ChA3; Replaced Design Science with Creative Commons CC BY license

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Colophon

Built in 1947 at the Bell Labs in the United States, this image shows the first working transistor. The point-contact transistor effect takes place in the germanium surface below the triangle tip. One wire connects to the germanium plate, forming the *base*. Two other wires connect via the triangle to two closely spaced narrow gold foils (<0.1mm at surface at the lower tip) to the germanium surface (forming the *emitter* and *collector*) .

The rapid miniaturisation of the transitor led to observation by Gordon Moore (the co-founder of Fairchild Semiconductor and Intel) in 1965 that the number of transistors in an integrated circuit doubles about every two years. Knows as "Moore's Law" this emperical observation held with remarkable consistency from the 1960s to around 2020. In this time the feature size of transistors drop from milimetres (as shown) to nanometres, with individual 'gates' composed of just a few atoms.

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