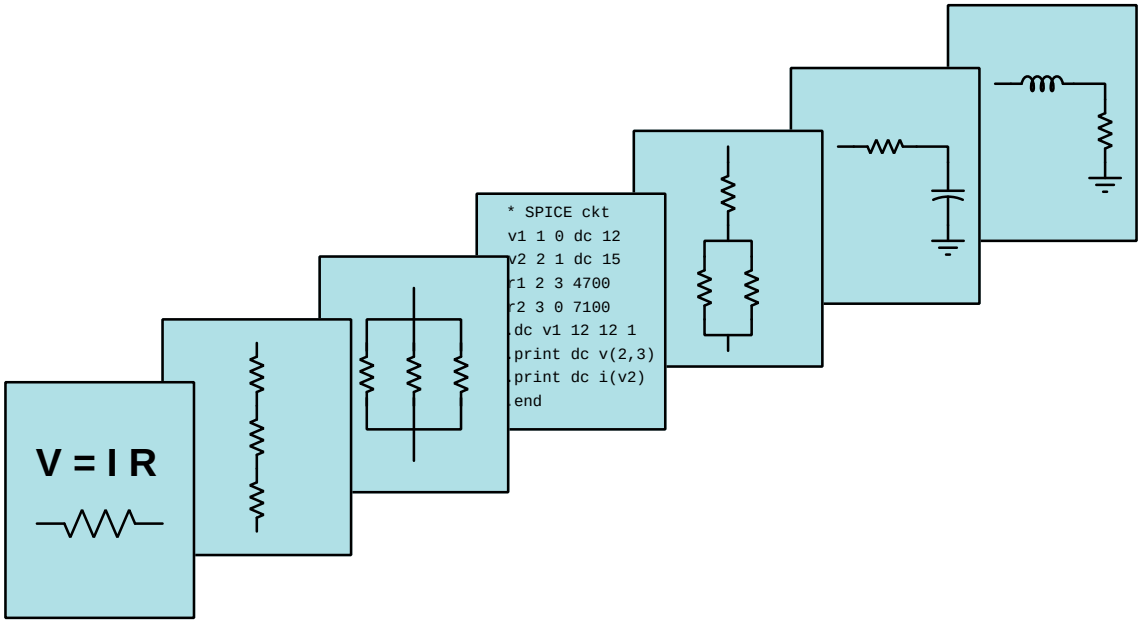
Modular Electronics Learning (ModEL) project



Optical Communication

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Chapter 1

Introduction

1.1 Recommendations for students

Communication of data by means of light pulses traveling through optically clear fibers is a relatively new technology, but it has utterly revolutionized telecommunications. Optical fibers have exceptionally high bandwidth, relatively low signal loss, zero "crosstalk" with adjacent fibers, and are immune to electrical interference, high voltage differences, and other problems plaguing metallic conductor cables. This module explores the basic concepts of optical fiber and its testing.

Important concepts related to fiber optics include **serial data** communication, **bandwidth**, **noise**, **refraction**, **Snell's Law**, **total internal reflection**, optical **modes**, **wavelength**, **irradiance**, **dispersion**, **transmission lines**, **bandwidth-length** ratings, **acceptance testing**, **decibels**, and **reflectometry**.

Here are some good questions to ask of yourself while studying this subject:

- How might an experiment be designed and conducted to assess a fiber optic cable's minimum safe bend radius? What hypothesis (i.e. prediction) might you pose for that experiment, and what result(s) would either support or disprove that hypothesis?
- What are some of the advantages optical fiber enjoys over electrical signal cables?
- What are some of the disadvantages suffered by optical fiber, compared to electrical signal cables?
- How does Snell's Law relate to light?
- How is a typical optical fiber constructed?
- How does a beam of light remain inside an optical fiber?
- What are some of the standard optical fiber diameters?
- What distinguishes multi-mode fiber from single-mode fiber?

- How may optical fibers be spliced together?
- What will happen if optical fiber is bent too sharply?
- What are some of the dangers of working with optical fiber, as well as the corresponding precautionary measures?
- What are "decibels" used to measure?
- How does the total decibel figure for power loss of a long cable relate to the decibel values for each of cable's sections and connectors?
- What does it mean if an optical fiber has a bandwidth-length rating of 750 MHz-km?
- What does "dispersion" refer to with optical signals, and how does it practically impact the use of optical fiber for data communication?
- How does an OTDR test the integrity of an optical fiber?

1.2 Challenging concepts related to fiber optics

The following list cites concepts related to this module's topic that are easily misunderstood, along with suggestions for properly understanding them:

- **Snell's Law** – the relationship between incident and refracted light beam angles based on the speeds of light through two adjacent materials is one that many students find confusing, but is easier to grasp if you perform a set of "thought experiments" with a given pair of materials and different incident beam angles. You'll find, for example, that when the incident beam strikes the interface perpendicularly it doesn't matter what the two speeds of light are because the exiting beam doesn't refract at all (but rather emerges perpendicular to that same interface as well).

1.3 Recommendations for instructors

This section lists realistic student learning outcomes supported by the content of the module as well as suggested means of assessing (measuring) student learning. The outcomes state what learners should be able to do, and the assessments are specific challenges to prove students have learned.

- **Outcome** – Demonstrate effective technical reading and writing

  Assessment – Students present their outlines of this module's instructional chapters (e.g. Case Tutorial, Tutorial, Historical References, etc.) ideally as an entry to a larger Journal document chronicling their learning. These outlines should exhibit good-faith effort at summarizing major concepts explained in the text.

  Assessment – Students present their "Conceptual Toolbox" Theory Journal entries listing important concepts applied in the Tutorial text(s). A "Conceptual Toolbox" serves as inspiration when solving problems, each concept suggesting a potential problem-solving action. Challenge students to collaboratively generate a Conceptual Toolbox for the day's topic during the class session and then use it when solving problems together, thus fostering the habit of reasoning from principles rather than recalling procedures!

- **Outcome** – Calculate power losses through optical fiber and fiber connectors

  Assessment – Calculate expected power losses along a run of optical fiber based on fiber and connector performance specifications; e.g. pose problems in the form of the "Optical power test" Quantitative Reasoning question.

  Assessment – Determine likely locations of fiber or connector faults based on optical power measurements; e.g. pose problems in the form of the "Optical power test" Quantitative Reasoning question.

- **Outcome** – Diagnose a faulted optical line

  Assessment – Properly interpret an OTDR display on a faulted line; e.g. pose problems in the form of the "Comparing OTDR traces" Diagnostic Reasoning question.

- **Outcome** – Independent research

  Assessment – Locate datasheets on communications-grade optical fiber and properly interpret some of the information contained in those documents including optical power loss per kilometer, minimum bend radius, cost, etc.

Chapter 2

Tutorial

Light has long[1] been used as a long-range signaling medium. While communication by light through open air is still possible using modern technology, it is far more practical in most cases to channel the light signals through a special strand of optically transparent material called an *optical fiber*. When packaged in a protective sheath, it is known as a fiber optic cable.

The transmission of light through a "light pipe" was demonstrated as early as 1842 by Daniel Colladon and Jacques Babinet in Paris, using a running stream of water to guide a beam of light. Many modern houses in the United States are equipped with light-pipes[2] directing natural sunlight into rooms for illumination, without the use of "skylight" ceiling windows. Modern fiber optic cables apply similar optical principles to very small-diameter fibers of transparent material (usually ultra-pure glass), able to convey optical energy and optically-encoded information.

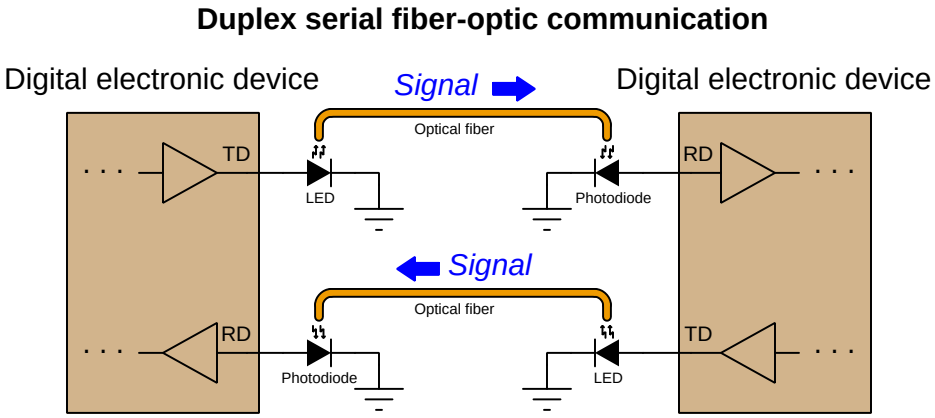
[1] Smoke signals are an ancient form of light-based communication!

[2] These are thin plastic or sheet metal tubes with mirrored internal surfaces, extending from a collector dome (made of glass or plastic) outside the dwelling to a diffusion lens inside the dwelling.

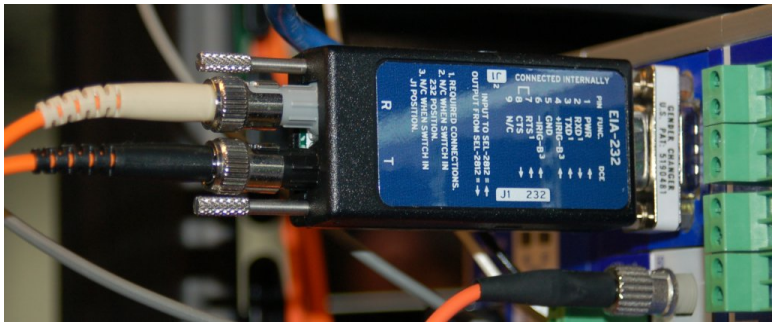
2.1 Fiber optic data communication

Simply put, an optical fiber is a "pipe" through which light flows. This is, of course, merely an analogy for how an optical fiber works, but it conveys the basic idea. The interface between a piece of electronic equipment and an optical fiber consists of an optical *source* (typically an LED or a semiconductor laser) to generate light signals from electrical signals, and an optical *detector* (typically a photodiode or phototransistor) to generate electrical signals from received light signals.

The predominant use of optical fiber in modern industry is as a data communication medium between digital electronic devices, replacing copper-wire signal and network cabling. An illustration showing two digital electronic devices communicating over a pair of optical fibers appears here, each fiber "conducting" pulses of light (representing serial digital data) from an LED source to a photodiode detector:

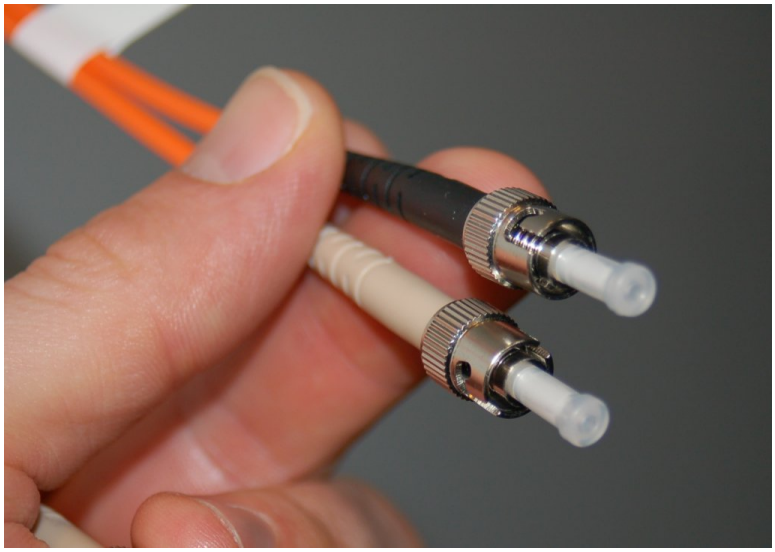


The following photograph shows a serial converter (the black rectangular plastic box with a blue label) used to convert optical data pulses entering and exiting through orange-jacketed optical cables (on the left) into EIA/TIA-232 compliant electrical signals through a DB-9 connector (on the right) and vice-versa, allowing the electronic serial data device on the right-hand side of the photograph to communicate via fiber optic cabling:



Note how the two optical fiber ports on the converter body are labeled "R" and "T" for *Receive* and *Transmit*, respectively. Serial devices with built-in electronic/optical converters will similarly label their optical ports.

For this device, connection to each of the optical fibers is made using an "ST" style connector, with a quarter-turn locking ring holding each one in place (much like the quarter-turn barrel body of a "BNC" style electrical connector except considerably smaller in size). The next photograph shows a pair of optical fibers terminated with ST-style connectors. White plastic caps cover the connector tips, keeping the glass fiber ends protected from dust and abrasion:



As a data pathway, optical fiber enjoys certain advantages over electrical cable, including:

- Much greater bandwidth (data-carrying capacity), estimated to be in the teraHertz range
- Much less equivalent signal power loss per unit cable length (less than 1 dB per kilometer compared with 25 dB per kilometer for coaxial cable)
- Complete immunity to external "noise" sources
- No radiation of energy or data from the cable, thus will not create interference nor be liable to eavesdropping
- No electrical conductivity, allowing safe routing of cables near high voltage conductors
- Total galvanic isolation (i.e. no electrically conductive connection) between data devices, allowing safe and reliable operation at different electrical potentials
- Safe for use in areas with explosive vapors, dust, and/or fibers

These advantages deserve some elaboration. The superior bandwidth of fiber-optic cable is so dramatic that the present-day (2020) limitation on data transfer rates for most fiber-optic installations is the electronic devices at each end, and not the optical fiber itself! This, combined with the low inherent power loss of optical fiber, makes it an ideal medium for long-range data communication such as telephone and internet. Thousands of kilometers of optical fiber cable have

been buried in underground trenches, laid down on sea floors, strung as overhead lines, and used as "patch" cables in room-scale applications since the advent of affordable optical cabling in the 1980's. The "tech boom" of the 1990's saw an impressive amount of trans-continental and inter-continental optical fiber installation, paving the way for the global expansion of internet services into the 21st century. The limitations of electronics at each end of these long fibers means we have not yet begun to tap their full data-carrying capacity, either. Conveying data in photonic – as opposed to electronic – form means there is absolutely no such thing as capacitive or inductive coupling with external systems as there is with conductive wire cable, which not only means optical fiber communication is immune to external interference but also that the optical signals cannot create interference for any other system. Since optical fibers are customarily manufactured from glass which is electrically non-conductive, it is possible to route optical fibers alongside high-voltage power lines, and also connecting together devices at vastly different electrical potentials from each other, with no risk of bridging those differing potentials. Finally, the low power levels associated with optical fiber signals also makes this technology completely safe in areas where explosive compounds in the atmosphere might otherwise be ignited by faults in electrical communications cable.

Data-carrying capacity of any given optical fiber is commonly rated by *bandwidth-length*, which is the product of maximum signal frequency (bandwidth) in Hertz and length in kilometers. For example, an optical fiber with a bandwidth-length of 500 MHz-km could reliably conduct a 500 MHz pulse signal over a distance of 1 kilometer, or a 250 MHz signal over 2 kilometers, or a 100 MHz signal over 5 kilometers, etc. Some optical fibers built for long-distance transmission offer bandwidth-length ratings on the order of 10^{13} Hz-km!

Optical fibers suffer from some unique limitations when compared against electrical cable, including:

- Need to avoid tight bend radii for optical cables
- Connections need to be extremely clean
- Specialized tools and skills necessary for installation and maintenance
- Expensive testing equipment

While electrical "transmission line" signal cables must also avoid sharp bends and other discontinuities caused by cramped installations, this need is especially pronounced for optical fiber (for reasons which will be explained later in this section). Since fiber-to-fiber connections consist of glass pressed against glass, the presence of even microscopic contaminants such as dust particles may damage fiber optic connectors if they aren't cleaned[3] prior to insertion. Cutting, preparing, and terminating optical fiber cables requires its own set of specialized tools and skills, and is not without unique hazards[4]. Lastly, the test equipment necessary to check the integrity of an optical pathway is similarly specialized and typically quite expensive.

[3] Technicians working with optical fiber typically carry pressurized cans of dust-blowing air or other gas to clean connectors and sockets prior to joining the two.

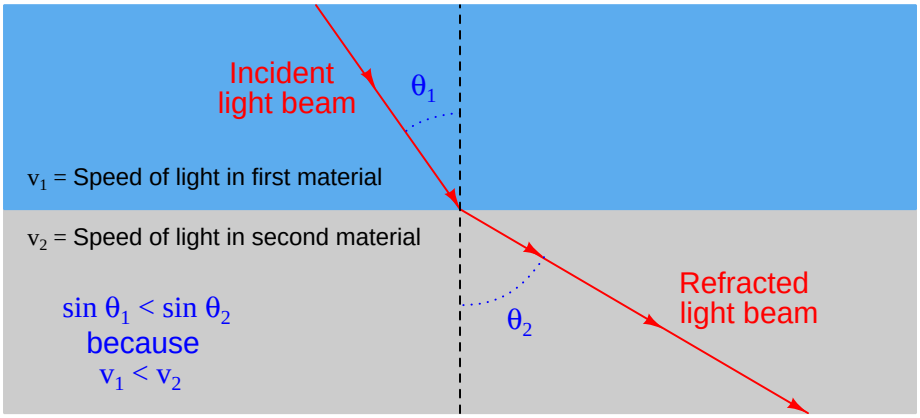
[4] Chief of which is the potential to get optical fibers embedded in the body, where such transparent "slivers" are nearly impossible to find and extract.

2.2 Fiber optic cable construction

Communication-grade optical fibers are manufactured from fused silica (SiO_2) glass of exceptional purity[5]. A single strand of optical fiber made from this glass called the "core" serves as a waveguide for the light. The core is surrounded by another layer of glass called the "cladding" which has a different index of refraction[6] necessary to "channel" the majority of the optical energy through the core and inhibit "leakage" of optical power from the cable. Additional layers of plastic and other materials around the core/cladding center provide coloring (for fiber identification in multi-fiber cables), protection against abrasion, and tensile strength so the cable will not suffer damage when pulled through conduit.

The purpose of building a fiber optic cable with a core and a cladding having different refractive indices (i.e. different speeds of light) is to exploit a phenomenon called *total internal reflection*, whereby rays of light reflect off the interface between core and cladding to prevent its unintentional escape from the core at any point along the length of the fiber.

When light crosses an interface between two materials having different speeds, the light beam will become *refracted* as a function of those two speeds as described by *Snell's Law*:



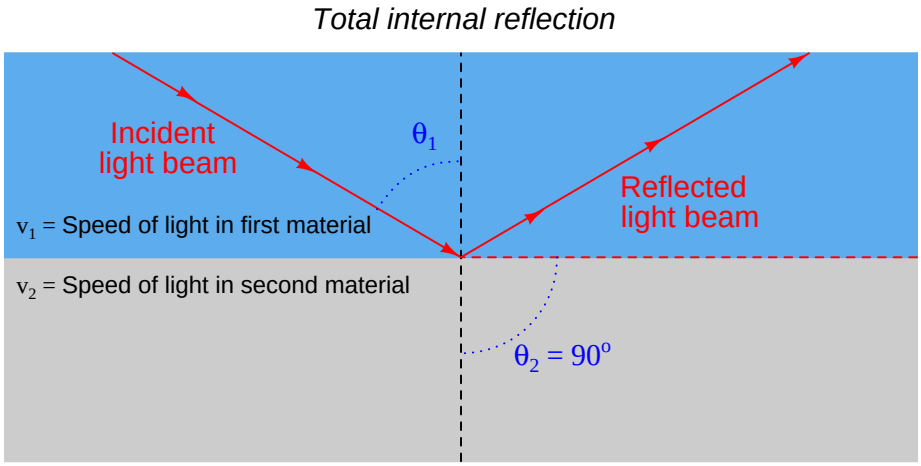
Snell's Law relates the sine of the incident angle to the sine of the refracted angle as a ratio to each material's speed of light, the material possessing the greatest speed of light (i.e. the lowest refractive index value) exhibiting the greatest angle as measured from perpendicular to the interface:

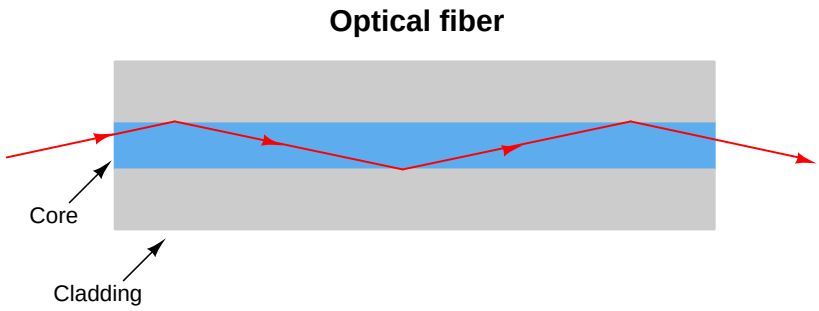
$$\frac{\sin\theta_1}{v_1} = \frac{\sin\theta_2}{v_2}$$

[5]Impurities such as metals and water are held to values less than 1 part per *billion* (ppb) in modern optical fiber-grade glass.

[6]The "index of refraction" (n) for any substance is the ratio of the speed of light through a vacuum (c) compared to the speed of light through that substance (v): $n = \frac{c}{v}$. For all substances this value will be greater than one (i.e. the speed of light will always be greatest through a vacuum, at 299792458 meters per second or 186282.4 miles per second). Thus, the refractive index for an optically transparent substance is analogous to the reciprocal of the *velocity factor* of an electrical transmission line, where the permittivity and permeability of the cable materials act to slow down the propagation of electric and magnetic fields through the cable. Interestingly, the velocity factors of optical fibers and of copper-conductor transmission lines are quite comparable. The superior data rate ("speed") of optical fiber compared to copper cable is actually its higher *bandwidth* (maximum signal frequency), not a higher *velocity* of propagation.

According to Snell's Law, there will be a critical angle at which the incident light ray will refract to being parallel to the interface. Beyond this critical angle, the light ray ideally reflects off the interface and never enters the second material at all. This is the condition of *total internal reflection*, and it is what we desire in an optical fiber where the core is the first material and the cladding is the second material:





Both the core and cladding of an optical fiber are manufactured from the same base material of ultra-pure fused silica, but "doped" with specific impurities designed to alter the refractive index of each one (raising the refractive index of the core to decrease its optical velocity and lowering the refractive index of the cladding to increase its optical velocity).

The diameter of core and cladding vary with the type of optical fiber, but several standard sizes have emerged in the industry, each one specified by the diameter of the core followed by the diameter of the cladding expressed in *microns* (millionths of a meter). A common optical fiber standard in the United States is 62.5/125 (62.5 micron core diameter, 125 micron cladding diameter), and 50/125 in Europe. Some less common standard core/cladding diameters[7] include 85/125 and 100/140.

[7] All of these sizes refer to *glass* fibers. Plastic-based optical fibers are also manufactured, with much larger core diameters to offset the much greater optical losses through plastic compared to through ultra-pure glass. A typical plastic optical fiber (POF) standard is specified at a core diameter of 980 microns and a cladding diameter of 1000

To give some perspective on the physical size of an optical fiber core, the following photograph shows the end-view of an "ST" style fiber optic connector for a 50/125 micron cable, held by my hand. A green LED light source is shining into the other end of this cable, the tiny green dot visible at the center of the ST connector revealing the diameter of the 50 micron core:

Other layers of material must be placed over the core and cladding to form a practical optical fiber. The first is a layer of plastic coating typically 250 microns (0.25 mm) in diameter to cover the glass cladding. This three-layer construction of glass core, glass cladding, and plastic coating is known in the industry as *Primary Coated Optical Fiber*, or *PCOF*. Over this is another protective plastic layer called a *buffer*, which may either be tightly bound to a single clad fiber (called "tight buffer") as a second plastic coating applied over the first usually with a diameter of 900 microns (0.9 mm), or a hollow plastic tube containing multiple PCOFs (called "loose buffer"). Tightly-buffered optical fiber is also known as *Secondary Coated Optical Fiber* or *SCOF*, and is generally found in single-fiber assemblies. Loosely-buffered optical fiber is used in multi-fiber cables, where the buffer tubes are often filled with a viscous gel to further protect the fibers from vibration, physical shock, and water intrusion.

microns (1 millimeter)!

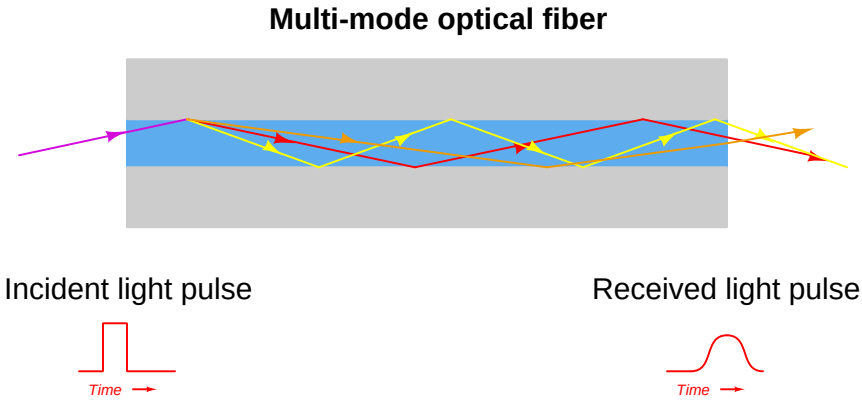
Buffered fibers are still too fragile on their own for practical applications, necessitating even more layers of protection. Indoor-application optical cables have fiberglass or Kevlar strands wrapped around the tightly-buffered fiber (SCOF) providing additional tensile strength, and a protective PVC plastic outer-layer jacket to protect against abrasion. Single-fiber "patch" cables used to connect one piece of optical equipment to another within the same rack or cabinet are of this construction. Cables intended for outdoor, aerial, direct burial, and undersea applications usually take the form of loosely-buffered fibers packaged within an extremely rugged encasement with metal strands for tensile strength and multiple outer layers for abrasion and environmental resistance.

2.3 Multi-mode and single-mode optical fibers

In any sort of waveguide – optical, electrical, or even acoustical (sound) – the signal energy may be able to propagate down the waveguide in different orientations. This is true for optical fibers where the core diameter is relatively large[8] compared to the wavelength of the light: there will be many alternative pathways for light to travel along the length of a fiber's core. Optical fibers with core diameters of 50 microns or more are referred to as *multi-mode* fibers, because multiple independent pathways, or "modes", of light are possible within the core's width.

If an optical fiber's core is manufactured to be small enough, relative to the wavelength of the light used, the fiber will only support one "mode" or pathway down its core. Such fiber is called *single-mode*. Single-mode fiber cores typically range from 4 to 10 microns in diameter, with 8 micron being typical.

The purpose of single-mode optical fiber is to avoid a problem called *modal dispersion* which is the primary phenomenon limiting the speeds at which data may be communicated through a fiber. When multiple "modes" of light propagate down the length of an optical fiber, they don't all have the same length. That is to say, some modes actually take a straighter (and more direct) path down the fiber's core than others. The reason this is a problem is that this phenomenon corrupts the integrity of high-speed (i.e. short-period) pulses. An exaggerated illustration of this problem appears here, showing the relative path lengths of three different light rays, each one entering the fiber core at a slightly different angle. The light ray closest to parallel with the core's centerline finds the shortest "mode" to the fiber's end, and arrives in the least amount of time:



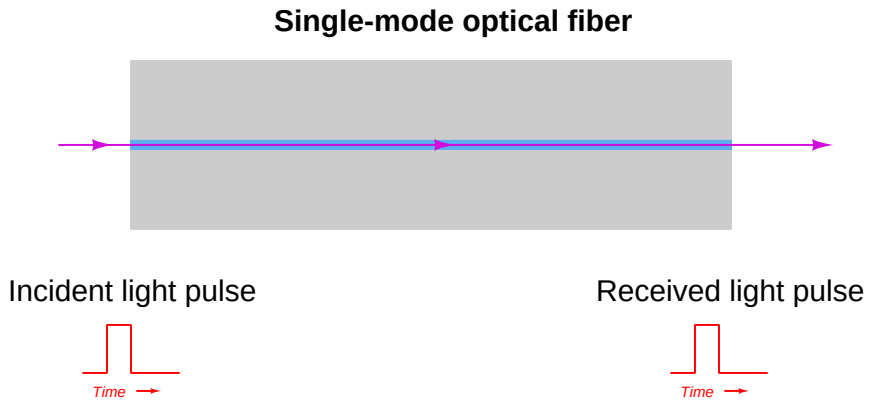
With different "modes" of light arriving at different times from the same incident pulse, the received light pulse at the exiting end of the fiber will no longer possess a crisp "square-wave" shape. Instead, the pulse will be "smeared" over time, occupying a larger time span. This poses a bandwidth limit on the fiber, as there will be some maximum pulse frequency at which adjacent pulses will begin to merge together and become indistinguishable. The longer the length of optical fiber, the more pronounced this dispersion will be. This problem is most evident in applications where the fiber length is very long (hundreds of kilometers) and the data rate is very high (hundreds

[8] A common core size for "multi-mode" optical fiber is 50 microns, or 50 micro-meters. If a wavelength of 1310 nanometers (1.31 microns) is used, the core's diameter will be $\frac{50}{1.31}$ or over 38 times the wavelength.

of megaHertz). Thus, it is a significant problem for long-distance data trunk cables such as those used for transcontinental and intercontinental internet traffic.

This is why optical fiber data ratings are expressed in terms of *bandwidth-length*, typically in the compound unit of Hertz-kilometers. An optical fiber with a bandwidth-length product of 120 GHz-km, for example, is able to convey a crisp pulse signal having a frequency of 120 gigaHertz for a distance of 1 kilometer, but that same frequency over a longer distance would result in dispersion significantly affecting the shape of the received pulses at the far end of the fiber. Shortening the length of the optical fiber means less total pathway over which the light modes may disperse, which in turn directly increases the possible pulse signal frequency that may be successfully conveyed by that fiber, so a 120 GHz-km fiber just 0.1 kilometer in length could[9] convey a signal frequency as high as 1200 GHz.

Single-mode optical fiber mitigates the modal dispersion problem by restricting[10] the possible number of light-ray modes within the fiber core to just one. When there is only one mode (pathway) for light to travel, there will be exactly one distance for light to travel from one end of the fiber to the other. Therefore, all portions of the incident light pulse should experience the same travel time, and the light pulse arrives at the far end of the cable suffers no modal dispersion:



Other dispersive effects still exist, and so even with single-mode optical fiber there will be *some* pulse-stretching limiting its bandwidth-length product.

A compromise solution to the problem of modal dispersion in multi-mode fibers is to manufacture the core glass with a *graded* index of refraction rather than a homogeneous index of refraction. This means the concentration of doping material in the glass varies from the center of the core to the outer diameter of the core where it interfaces with the cladding. The result of this graded dispersion

[9] Only if the transmitting and receiving electronic hardware is capable of handling such high frequencies, of course! In most cases the raw fiber data capacity far exceeds the switching bandwidth of the transmitting and receiving electronic systems, making the fiber's ultimate data capacity irrelevant.

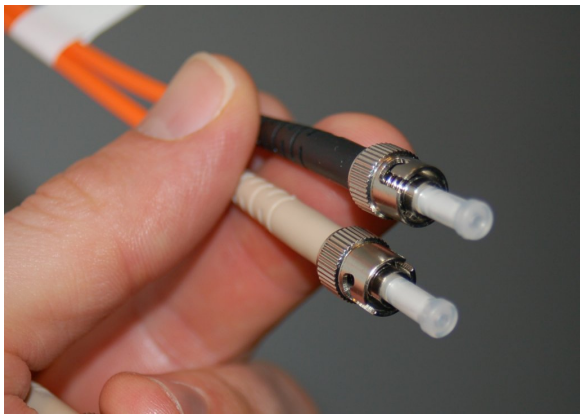
[10] The most straight-forward way to make an optical fiber single-mode is to manufacture it with a skinnier core. However, this is also possible to achieve by increasing the wavelength of the light used! Remember that what makes a single-mode optical fiber only have one mode is the diameter of its core *relative to the wavelength of the light*. For any optical fiber there is a *cutoff wavelength* above which it will operate as single-mode and below which it will operate as multi-mode. However, there are practical limits to how long of a wavelength we can make the light before we run into other problems, and so single-mode optical fiber is made for standard light wavelengths by manufacturing the cable with an exceptionally small core diameter.

is that modes traveling closest to the core's centerline will experience a slower speed of light (i.e. greater index of refraction) than modes near the edge of the core, which means the difference in travel time from one mode to the next will be less pronounced than within normal "step-index" fibers. Of course, this also means graded-index optical fiber is more costly to manufacture than step-index optical fiber.

With single-mode optical fiber maintaining signal integrity far better over long distances than multi-mode fiber, one might wonder why we use multi-mode fiber at all. The simple reason is that multi-mode fiber is far more forgiving with regard to fiber-to-fiber alignment when two optical fibers are joined end-to-end to form a splice. Simply put, the smaller core diameter of single-mode fiber offers less margin for alignment error at each and every fiber-to-fiber junction. Precisely aligning two 5-micron fiber cores is a much more challenging task than precisely aligning two 50-micron cores because the same amount of physical misalignment (offset) will have a far greater impact on light loss for the smaller-core fiber. Multi-mode optical fibers are therefore the better solution for applications where fiber connections must be handled by end-users of the technology (e.g. fibers plugging into a personal computer).

2.4 Fiber optic connectors and routing

One style of single-fiber connector is the so-called "ST" style, using a quarter-turn locking barrel to secure the connector into its matching socket. Other optical fiber connector styles exist, but they all share common features of locking mechanisms, mechanical strain relief for the fiber, and ??? to ensure precise alignment of mating fiber ends:



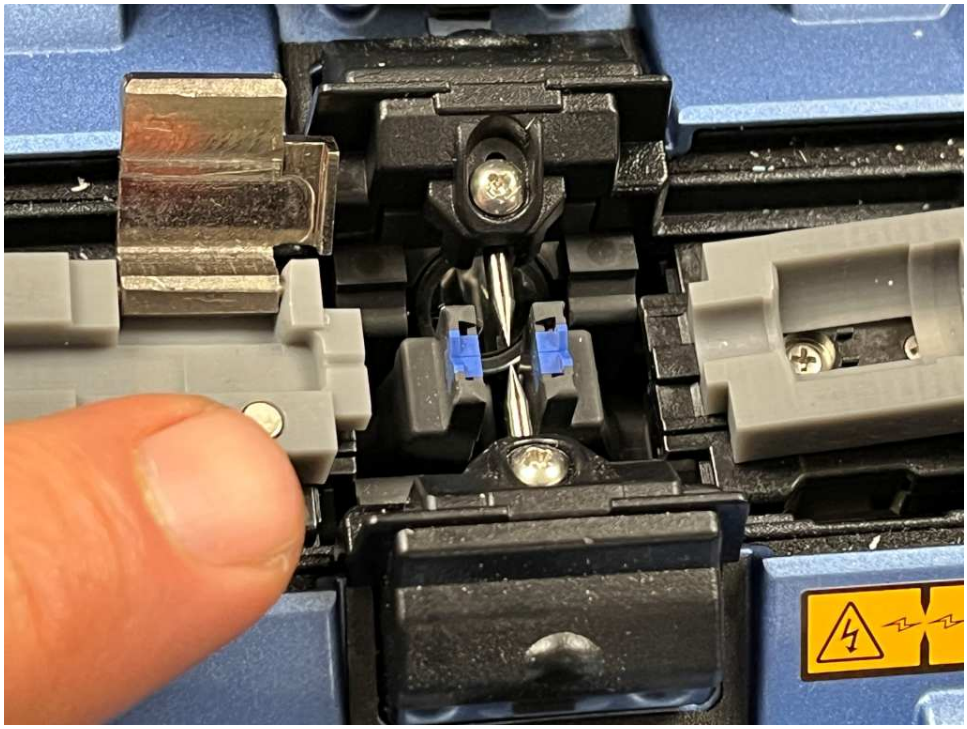
Communication patch cables such as the one shown above come in *pairs* of fibers, one for receiving and one for transmitting. Note how the plastic strain-relief grips between the metal barrel of each connector and each orange-jacketed cable are color-coded (one white, one black) for easy identification at each end of the cable.

Given that communication patch cables typically have two fibers (one for each direction of data flow), connector styles have emerged to accommodate fiber pairs. One such style is the so-called "SC" connector, with a pair of side-by-side plugs accommodating twin optical fibers.

Terminating a bare cable of fibers with individual connectors requires the technician to unbundle the individual fibers, strip the jacketing off of each one to reveal the core and cladding, cleave each glass fiber to give it a flat end, and finally attach each bare fiber to its respective connector. Termination broadly takes two forms, either *mechanical* or *fusion*. Mechanical termination typically use either a "hot-melt" or a chemical epoxy system of attachment, where the glue adheres to the strain-relief fibers of the cable for tensile strength, while the central glass fiber protrudes through a small hole in the center of the connector tip. This protruding glass fiber must be carefully cut and polished to produce a flat end suitable for engagement with another optical fiber aligned to its center. Fusion splicing involves using a high-temperature electric arc to literally "fuse" the end of one optical fiber to the end of another, creating a seamless glass interface between one of the cable's individual fibers and the pre-attached fiber stub supplied with a manufactured connector.

Fusion splicing, once limited to the splicing of long-haul, single-mode optical fibers where signal integrity is paramount, is now commonplace for all kinds of optical fibers thanks to the advent of portable, battery-powered fusion splicer tools such as the Fujikura model 70S splicer shown below:

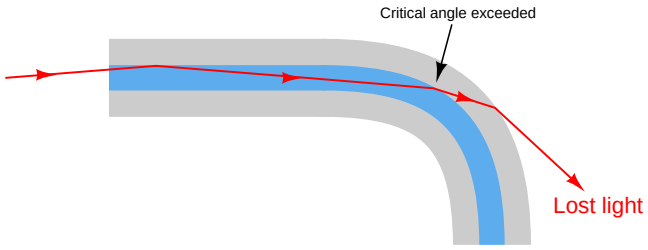
A close-up of this tool shows two pointed metal electrodes, in between which the electric arc forms to fuse the two fiber ends together. This tool has the ability to measure the alignment between fibers to automatically ensure maximum overlap between the fiber cores and therefore maximum transmission of light between them:



The two light-grey-colored plastic assemblies flanking the electrode assembly are called *sheath clamps*, designed to provide strain relief and mechanical stability for the two optical fibers during the alignment and fusing stages. The two smaller, blue-colored plastic pieces closer to the electrodes are called *V-grooves*, designed to guide the bare fiber ends into a condition of close alignment with each other before and during the arc phase when the two glass fibers weld together. After fusing, the splice has a modest amount of tensile strength because it is essentially a continuous length of glass. A splice-protecting *sleeve* is then heat-shrunk over the fused fiber junction to provide abrasion resistance similar to that of the original fiber's buffer tubes and cable jacketing.

Optical fibers may be spliced mid-way in a cable run, although this practice should be avoided whenever possible. If the fibers are multi-mode, the splicing may be done using "butt" connectors but the power losses may be unacceptable. Alternatively, stripped fibers may be inserted into both ends of a small-diameter tube filled with gel having the same index of refraction as the core glass, to "conduct" light with as little loss as possible from one fiber core to the other. This gel-tube technique is not recommended because the gel's optical characteristics tend to change as it ages, eventually leading to increased power loss and ultimate failure.

When laying optical fiber in wire trays, pulling through rigid conduit, or arranging it in connection panels, an important physical consideration is to maintain a minimum bend radius[11] at all points along the fiber's length. This is important because sharp bends will cause light to "leak" out of the fiber core and into the cladding where it may then escape the cable altogether. A sharp bend in an optical fiber will cause the angle between the light ray and the core/cladding interface to reach the critical point where total internal reflection no longer occurs:



The light leakage from an optical fiber may be dramatic if the bend is sharp enough. On an indoor cable, using visible laser light, you can actually see the light "leak" through to the PVC outer coating on the outside of the cable! Interestingly, this "leaking" phenomenon worsens with increasing light wavelength. Short-wavelength light does not tend to diffract into the cladding as readily as long-wavelength light.

Junction boxes and connection panels where excess lengths of fiber optic cabling may be coiled will typically provide plastic forms over which those loops of cable may be bent, the radius of that plastic form exceeding the manufacturer's specification for minimum bend radius.

A common way in which the minimum bend radius requirement is violated is when a cable tie is used to anchor a fiber optic cable to some sturdy surface such as a wiretray or a cabinet post. The sharp bend created by the tension of a tightened cable tie on the fiber optic cable will easily exceed the minimum bend radius for that cable, creating light leakage and subsequent performance problems. Therefore, a good installation practice for fiber optic cables is to always leave cable ties loose enough that they do not tightly grip the cable.

[11] Typically a few inches for multi-mode fiber.

2.5 Fiber optic safety

There are multiple safety concerns when working with optical fibers, both when installing them and when doing maintenance-type work. Installation hazards center around dangers of the glass fiber itself, while maintenance hazards center around the light sources used to "power" the optical fibers.

Installation of fiber optic cable requires that individual glass fibers be separated from each other in a multi-fiber cable and each one terminated with a connector, and this requires at some point that the technician strip each fiber down to its glass core and cladding. Both the core and the cladding are extremely small in diameter, and are made of ultra-pure glass. If a piece of core/cladding breaks off the fiber and penetrates the skin, the resulting "sliver" will be nearly invisible due to its exceptional transparency. Its outer surface is also very smooth, making extraction difficult. Unextracted pieces of an optical fiber, if left in the body, can actually migrate through the victim's flesh and become buried even deeper to the point where they can cause serious health problems.

Technicians working with optical fiber typically lay a length of adhesive tape, sticky-side up, on whatever workbench or table they are using to prepare the cable, as a tool to catch any loose fiber ends they cut off. At the conclusion of the job, this length of tape is carefully rolled up and then disposed of in the same manner that "sharps" may be disposed of in a medical environment.

Maintenance technicians working with functioning fiber optic systems need to be careful when disconnecting "hot" fibers, due to the intensity of the light used in some systems. This is especially true of long-distance telecommunication fibers using laser sources rather than regular LEDs, which may have power levels reaching a half Watt or so. One-half of a Watt doesn't sound like very much power, but when you consider this power level is concentrated over a circular area with a diameter less than 10 microns (for single-mode fiber), the Watt-per-square-meter *irradiance* value is actually large enough to cause significant temperature increases wherever the light beam happens to fall. In fact, you can actually damage a fiber-optic connector on such a system by disconnecting the fiber with the fiber "powered", the laser light being intense enough to burn and pit the aluminum ferrule of the connector!

Even standard LED light sources may pose a hazard if a technician directly views the end of the cable with his or her eyes, due to the focused nature of the light beam. The retina of your eye is extremely sensitive to light, and may easily be damaged by viewing such an intensely focused beam coming out of an optical fiber, where the entire LED's light output is channeled into a core just a fraction of a millimeter in diameter. The optical hazard is even greater when infra-red light sources are used, because there is no visible indication of the light's presence. A technician won't even be able to see the light coming out, yet it could still be intense enough to damage their retina(s).

Laser-sourced fibers should never be unplugged from the equipment. One should treat a laser-sourced fiber with the same respect as a "live" electrical circuit, and use the same lockout/tagout procedures to ensure personnel safety. In systems using visible light wavelengths, a safe way to view the light coming out the end of an optical fiber is to point the fiber end at a piece of paper and look for the colored dot falling on the paper. The paper's rough surface scatters the light so that it is no longer a focused beam.

The only time it is truly safe to view the end of an optical fiber to check for light is when the light source is something diffuse such as natural sunlight or a flashlight. It is common for technicians to use a flashlight to identify fibers from one end of a multi-fiber cable to the other, one technician shining the flashlight at the end of one fiber while another technician views all the fibers at the other

end of the cable to see which one is lit.

Some optical communications equipment come equipped with a feature called an *Open Fiber Control* (OFC) safety system, which turns off all light sources on a channel whenever an interruption of light is detected at the receiver port. Since most duplex (two-way) optical fiber channels consist of two fibers (one for each direction of light), a break in any one fiber will darken one receiver, which then commands the transmitter port on that equipment to darken as well to prevent anyone getting injured from the light. It also completely disrupts communication in that channel, requiring a re-initialization of the channel after the fiber is plugged back in.

2.6 Fiber optic cable testing

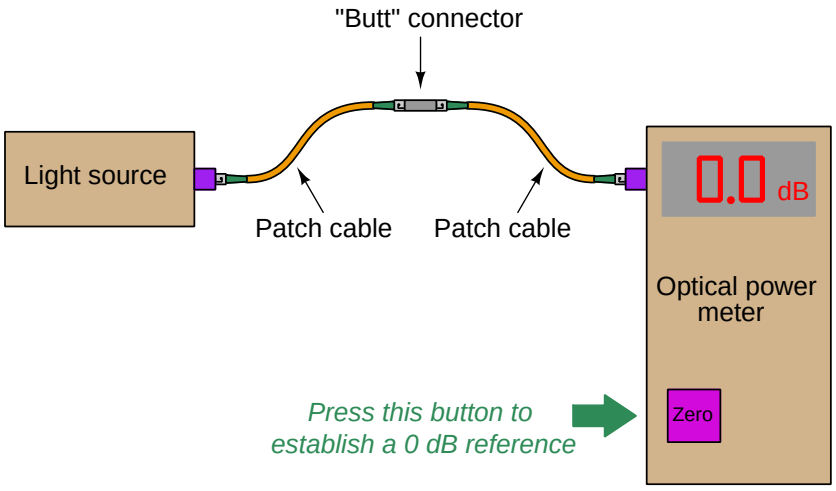
Optical fibers, like electrical communications cable, may need to be tested to measure certain performance characteristics. Such testing is commonplace for new installations of fiber optic cabling to ensure all installed cable lengths and connectors are functioning properly. Repeated tests over time, compared with the initial installation test, quantifies any degradation of cables or connectors. Another common testing procedure, called *acceptance testing*, tests the optical cable while it is still on the spool prior to installation.

Two basic types of optical fiber tests are presented here: one where the power level of light is measured at the far end of the fiber from a source of known optical power, and another where a pulse of light is sent down a fiber and the light received at the same end of the fiber is analyzed. The former test is simply a measurement of optical power, while the latter test is a sophisticated analysis of light over very brief periods of time (time domain reflectometry).

2.6.1 Optical power loss testing

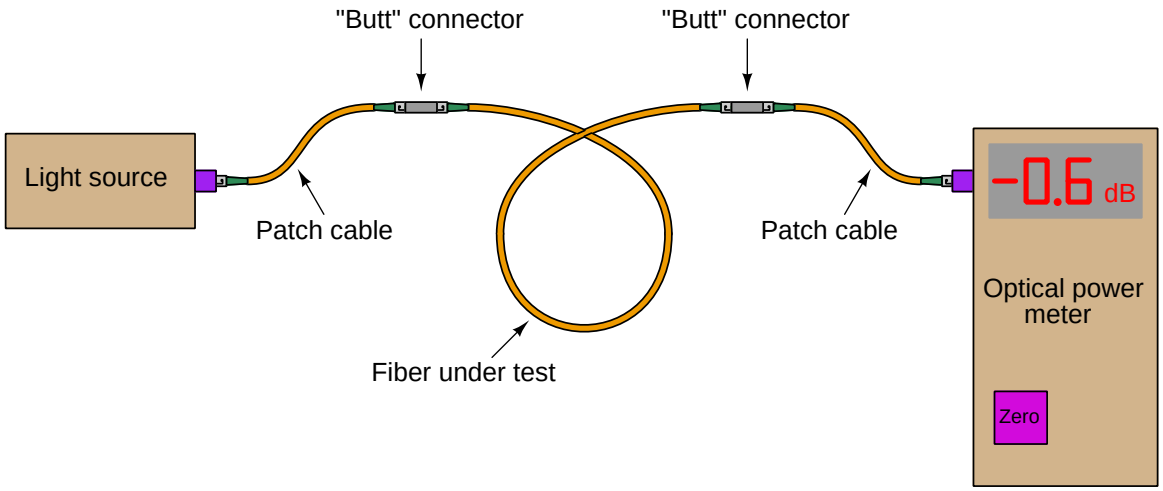
Perhaps the simplest quantitative test of an optical fiber consists of shining a light source of known optical power at one end of a fiber and monitoring the amount of optical power received at the other end of the fiber. This type of test is typically performed with two pieces of equipment: the source and the power meter.

First, the optical power meter and light source are short-coupled together using a pair of patch cables and a single "butt" connector:



Once light is received by the optical power meter, the technician presses the "zero" button to set the baseline or reference point for all future power measurements. Although some light will be lost in the two patch cables and connector, this amount of loss will also be present in the final test and so it must be ignored.

After "zeroing" the optical power meter, the actual fiber to be tested is connected between the light source and the power meter. Any *additional* light lost within the tested fiber[12] will register at the power meter as a negative decibel figure:



Recall that the definition of a "decibel" is 10 times the common logarithm of the power ratio between output and input for any system:

$$\text{dB} = 10 \log \left(\frac{P_{out}}{P_{in}} \right)$$

Thus, the power loss of -0.6 dB shown in the illustration represents 87.1% of the optical source power received by the optical power meter. Decibels are very commonly used as an expression of power gain and loss in communication system testing, because dB figures directly add when components are connected in series with each other. For example, if we knew that a certain type of "butt" connector for optical fiber exhibited a typical power loss of -1.2 dB and that three of these connectors would be used to join a single run of fiber, we would know to expect a total connector loss of -3.6 dB (i.e. 3×-1.2 dB).

[12] Not just light lost along the length of the fiber, but also at each connector on the fiber, since placing the test fiber within the optical path between the light source and optical power meter necessarily introduces another pair of connectors where light may be lost.

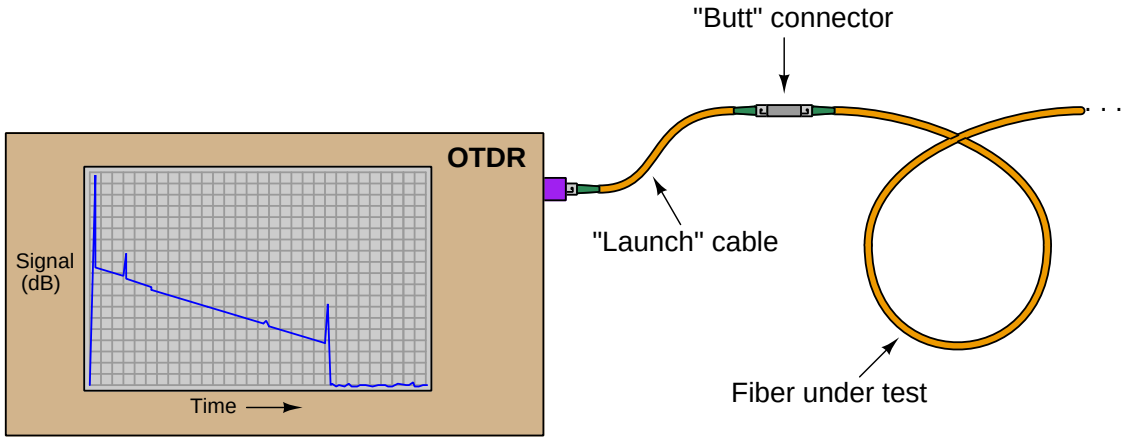
Excessive optical power losses may be caused by a number of different factors, including:

- Poor alignment between fibers in a connector
  - → Connector flaw causing fibers to be mis-aligned (e.g. angular misalignment)
  - → Fiber flaw causing mis-alignment in a good connector (e.g. cores not concentric)
- Mismatched fiber sizes (e.g. 62.5 micron core sending light into a 50 micron core)
- Oil or debris on the end of a connector
- Rough (improperly polished) end on one or more fibers
- Minimum bend radius violated at any point along the fiber's length
- Cracked fiber core

Unfortunately, a power meter test will not indicate what kind of flaw is causing excessive power loss, nor where that flaw might be located. If the cable in question has removable connectors midway in its length, the power meter and/or source may be relocated to test portions of the cable to determine which section contributes more to the power loss, but an end-to-end power test cannot pinpoint the location or the type of fault.

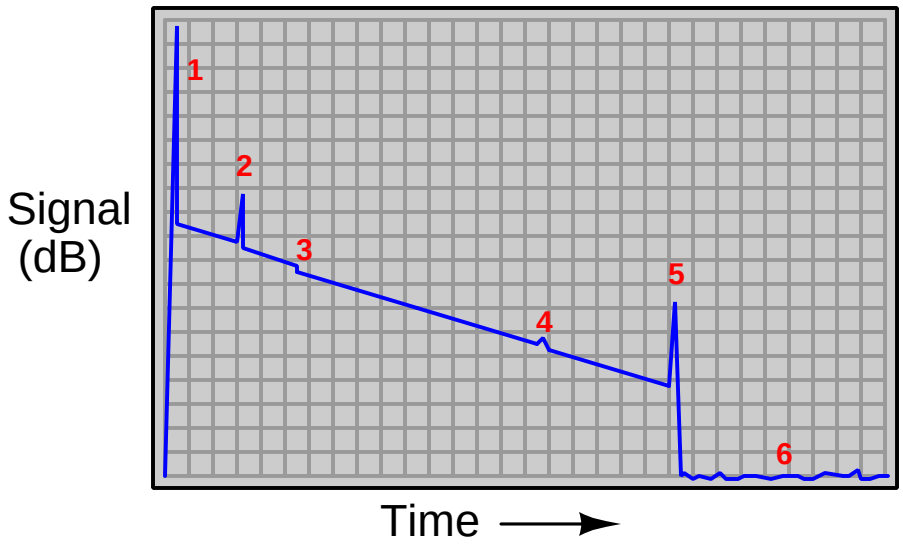
2.6.2 OTDR testing

An *Optical Time-Domain Reflectometer* or *OTDR* is a sophisticated test instrument used to probe the characteristics of long optical fibers. They work by injecting a very brief pulse of light into one end of a long optical fiber, then monitoring any light received at that same end of the fiber. As the light pulse travels down the length of the fiber, it continuously loses some of its magnitude due to scattering in the glass. Some of this scattered light returns back to the source-end of the fiber, presenting a sort of "continuous echo" of the moving pulse. This continuous echo is analogous to the noise heard from an object moving away from the listener. As the light pulse encounters flaws and other discontinuities in the fiber and/or connectors along its length, the echoed signal changes in magnitude. This received signal is displayed as a time-domain plot on the OTDR viewing screen, and will look something like this:



The "trace" shown on the display screen of an OTDR is a plot of the received optical signal strength over time. A large "spike" at the left-hand side of this trace marks the incident pulse of light injected into the optical fiber by the OTDR from the traveling pulse as it propagates down the length of the fiber. All signals after that (to the right of that initial "spike") represent light received from that same end of the optical fiber. In a completely uniform fiber the resulting "echo" would trace a downward-sloping straight line as the traveling light pulse gradually weakens. In an imperfect fiber, any discontinuities such as splices, connector joints, sharp bends, cracks, etc. will cause the traveling light pulse to lose more photons than usual at the location of the discontinuity: sometimes returning a strong echo back toward the OTDR and other times not. A discontinuity such as a mis-aligned fiber connector will tend to return a strong echo as part of the traveling light pulse reflects off the mis-aligned connector end and returns to the OTDR. A discontinuity such as a mal-formed fusion splice merely scatters a greater-than-normal amount of light out through the fiber's cladding, in which case there is no echo "pulse" received by the OTDR but rather just a further weakening of the echo signal.

The OTDR trace shown in the previous illustration demands further explanation. Shown here is a magnified view of it, complete with numbers to identify each noteworthy event:



Legend:

1. Incident pulse output by the OTDR, and injected into the launch fiber
2. Reflection off the face of the near-end connection between the launch fiber and the fiber under test
3. Loss of light due to a non-reflective discontinuity (e.g. sharp bend, splice)
4. Loss of light due to a reflective discontinuity (e.g. mis-aligned connector)
5. Reflection off the face of the far-end connection at the end of the fiber under test
6. The "noise floor"

As you can see, an OTDR trace provides much more information about the performance of an optical fiber than a simple power test. Each flaw in the cable or its associated connectors appears as a deviation from the normal downward-sloped line of the trace, the location in time revealing the distance between the OTDR and the flaw. Thus, an OTDR not only indicates the nature of each flaw, and the amount of optical power lost at each flaw, but also the *location*[13] of each flaw along the fiber's length. One important caveat exists for this distance calculation, and that is the fact that the length of a fiber in a multi-fiber cable will always be somewhat longer than the length of the cable itself, since individual fibers inside a cable are often "wound" in a spiral configuration or otherwise deviating from the straight centerline of the cable. "Loose tube" cables, for example, often exhibit fiber lengths 5% to 10% greater than the physical length of the cable itself.

[13] Since distance along any path is simply the product of speed and time ($x = vt$), and the speed of light through an optical fiber is a well-defined quantity ($v = \frac{c}{n}$ where n is the core's index of refraction), the distance between the OTDR and the flaw is trivial to calculate.

Chapter 3

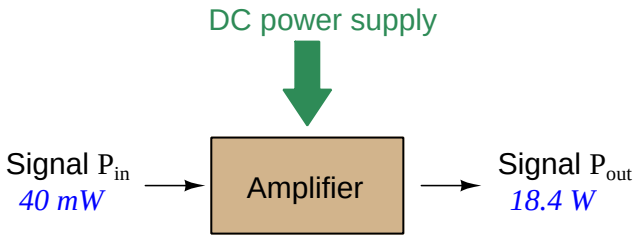
Derivations and Technical References

This chapter is where you will find mathematical derivations too detailed to include in the tutorial, and/or tables and other technical reference material.

3.1 Decibels

One of the mathematical tools popularly used to gauge increases and decreases of electrical power is the *common logarithm*, expressed as a measurement unit called the *decibel*. The basic idea of decibels is to express a ratio of two electrical power quantities in logarithmic terms. Every time you see the unit of "decibel" you can think: *this is an expression of how much greater (or how much smaller) one power is to another*. The only question is which two powers are being compared.

Electronic amplifiers are a type of electrical system where comparisons of power are useful. Students of electronics learn to compare the output power of an amplifier against the input power as a unitless ratio, called a *gain*. Take for example an electronic amplifier with a signal input of 40 milliWatts and a signal output of 18.4 Watts:



$$\text{Gain} = \frac{P_{out}}{P_{in}} = \frac{18.4\ W}{40\ mW} = 460$$

An alternative way to express the gain of this amplifier is to do so using the unit of the *Bel*, defined as the common logarithm of the gain ratio:

$$\log\left(\frac{P_{out}}{P_{in}}\right) = \log\left(\frac{18.4\ \text{W}}{40\ \text{mW}}\right) = 2.66276\ \text{B}$$

When you see an amplifier gain expressed in the unit of "Bel", it's really just a way of saying "The output signal coming from this amplifier is x powers of ten greater than the input signal." An amplifier exhibiting a gain of 1 Bel outputs 10 times as much power as the input signal. An amplifier with a gain of 2 Bels boosts the input signal by a factor of 100. The amplifier shown above, with a gain of 2.66276 Bels, boosts the input signal 460-fold.

At some point in technological history it was decided that the "Bel" (B) was too large and cumbersome, and so it became common to express powers in fractions of a Bel instead: the *deci*Bel (1 dB = $\frac{1}{10}$ of a Bel). Therefore, this is the form of formula you will commonly see for expressing electrical signal power gains or losses:

$$\text{dB} = 10 \log\left(\frac{P_{out}}{P_{in}}\right)$$

The gain of our hypothetical electronic amplifier, therefore, would be more commonly expressed as 26.6276 dB rather than 2.66276 B, although either expression is technically valid[1].

[1] It is interesting to note that although the "Bel" is a metric unit, it is seldom if ever used without the metric prefix

An operation students often struggle with is converting a decibel figure back into a ratio, since the concept of logarithms seems to be universally perplexing. Here I will demonstrate how to algebraically manipulate the decibel formula to solve for the power ratio given a dB figure.

First, we will begin with the decibel formula as given, solving for a value in decibels given a power ratio:

$$\text{dB} = 10 \log(\text{Ratio})$$

If we wish to solve for the ratio, we must "undo" all the mathematical operations surrounding that variable. One way to determine how to do this is to reverse the order of operations we would follow if we knew the ratio and were solving for the dB value. After calculating the ratio, we would then take the logarithm of that value, and then multiply that logarithm by 10: start with the ratio, then take the logarithm, then multiply last. To un-do these operations and solve for the ratio, we must un-do each of these operations in reverse order. First, we must un-do the multiplication (by dividing by 10):

$$\frac{\text{dB}}{10} = \frac{10 \log(\text{Ratio})}{10}$$

$$\frac{\text{dB}}{10} = \log(\text{Ratio})$$

Next, we must un-do the logarithm function by applying its mathematical inverse to both sides of the formula – making each expression a power of 10:

$$10^{\frac{\text{dB}}{10}} = 10^{\log(\text{Ratio})}$$

$$10^{\frac{\text{dB}}{10}} = \text{Ratio}$$

To test our algebra, we can take the previous decibel value for our hypothetical amplifier and see if this new formula yields the original gain ratio:

$$\text{Ratio} = 10^{\frac{26.6276 \text{ dB}}{10}}$$

$$\text{Ratio} = 10^{2.66276 \text{ B}}$$

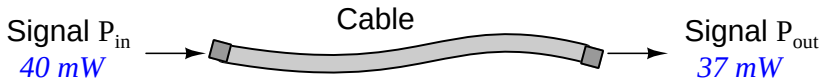
$$\text{Ratio} = 460$$

Sure enough, we arrive at the correct gain ratio of 460, starting with the decibel gain figure of 26.6276 dB.

"deci" ($\frac{1}{10}$). One could express powers in microbels, megabels, or any other metric prefix desired, but it is never done in industry: only the decibel is used.

We may also use decibels to express power *losses* in addition to power *gains*. There are many practical applications of this in signaling systems, both electronic and optical. One such application is *filtering*, where a "filter" circuit screens out certain components of the signal while letting others pass through (e.g. the bass or treble control for an audio system). Another application is *attenuation*, where the entirety of a signal is reduced in magnitude (e.g. the volume control for an audio system).

We will explore yet another application of signal power reduction as a case study for decibels: *cable loss*. Cables designed to convey signals over long distances are not perfect conduits of energy, as some of the signal's energy is inevitably lost along the way. This is true for different types of signals, electrical and optical being two popular examples. In the following illustration we see a signal cable losing power along its length[2], such that the power out is less than the power in:



$$\text{Gain} = \frac{P_{out}}{P_{in}} = \frac{37\ mW}{40\ mW} = 0.925$$

$$10 \log \left(\frac{P_{out}}{P_{in}} \right) = 10 \log \left(\frac{37 \text{ mW}}{40 \text{ mW}} \right) = -0.3386 \text{ dB}$$

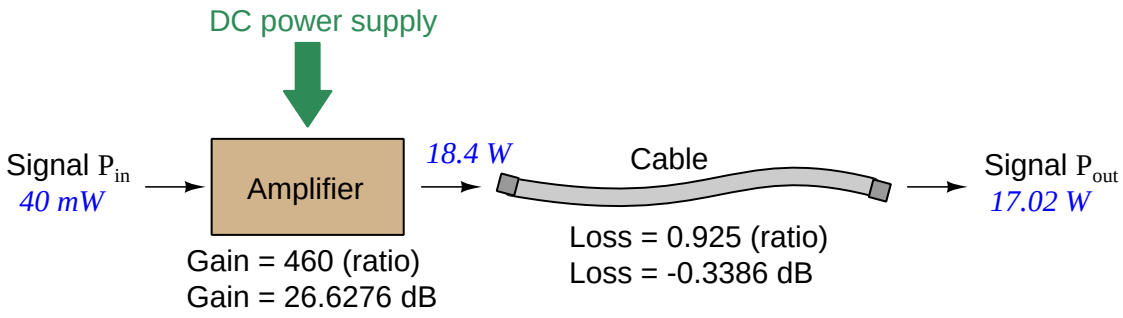
Contrasting this result against the previous result (with the amplifier) we see a very important property of decibel figures: any power *gain* is expressed as a *positive* decibel value, while any power *loss* is expressed as a *negative* decibel value. Any component outputting the exact same power as it takes in will exhibit a "gain" value of 0 dB (equivalent to a gain *ratio* of 1).

Remember that Bels and decibels are nothing more than logarithmic expressions of "greater than" and "less than". Positive values represent powers that are *greater* while negative values represent powers that are *lesser*. Zero Bel or decibel values represent *no change* (neither gain nor loss) in power.

A couple of simple decibel values are useful to remember for approximations, where you need to quickly estimate decibel values from power ratios (or vice-versa). Each addition or subtraction of 10 dB exactly represents a 10-fold multiplication or division of power ratio: e.g. +20 dB represents a power ratio gain of $10 \times 10 = 100$, whereas −30 dB represents a power ratio reduction of $\frac{1}{10} \times \frac{1}{10} \times \frac{1}{10} = \frac{1}{1000}$. Each addition or subtraction of 3 dB approximately represents a 2-fold multiplication or division or power ratio: e.g. +6 dB is approximately equal to a power ratio gain of $2 \times 2 = 4$, whereas −12 dB is approximately equal to a power ratio reduction of $\frac{1}{2} \times \frac{1}{2} \times \frac{1}{2} \times \frac{1}{2} = \frac{1}{16}$. We may combine ± 10 dB and ± 3 dB increments to come up with ratios that are products of 10 and 2: e.g. +26 dB is approximately equal to a power ratio gain of $10 \times 10 \times 2 \times 2 = 400$.

[2]For high-frequency signals such as those used in radio communications, the dominant mode of energy dissipation is *dielectric heating*, where the AC electric field between the cable conductors excites the molecules of the conductor insulation. This energy loss manifests as heat, which explains why there is less signal energy present at the load end of the cable than is input at the source end of the cable. For DC and low-frequency AC circuits the dominant mode of energy dissipation is cable conductor resistance, which is typically very small.

Observe what happens if we combine a "gain" component with a "loss" component and calculate the overall power out versus power in:



The overall gain of this amplifier and cable system expressed as a ratio is equal to the *product* of the individual component gain/loss ratios. That is, the gain ratio of the amplifier *multiplied* by the loss ratio of the cable yields the overall power ratio for the system:

$$\text{Overall gain} = \frac{17.02 \text{ W}}{40 \text{ mW}} = (460)(0.925) = 425.5$$

The overall gain may be alternatively expressed as a decibel figure, in which case it is equal to the *sum* of the individual component decibel values. That is, the decibel gain of the amplifier *added* to the decibel loss of the cable yields the overall decibel figure for the system:

$$\text{Overall gain} = 10 \log \left(\frac{17.02 \text{ W}}{40 \text{ mW}} \right) = 26.6276 \text{ dB} + (-0.3386 \text{ dB}) = 26.2890 \text{ dB}$$

It is often useful to be able to estimate decibel values from power ratios and vice-versa. If we take the gain ratio of this amplifier and cable system (425.5) and round it down to 400, we may easily express this gain ratio as an expanded product of 10 and 2:

$$425.5 \approx 400 = (10) \times (10) \times (2) \times (2)$$

Knowing that every 10-fold multiplication of power ratio is an addition of +10 dB, and that every 2-fold multiplication of power is an addition of +3 dB, we may express the expanded product as a sum of decibel values:

$$(10) \times (10) \times (2) \times (2) = (10 \text{ dB}) + (10 \text{ dB}) + (3 \text{ dB}) + (3 \text{ dB}) = 26 \text{ dB}$$

Therefore, our power ratio of 425.5 is approximately equal to +26 decibels.

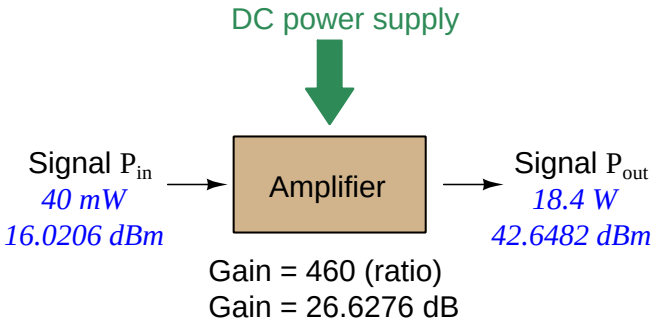
Decibels always represent comparisons of power, but that comparison need not always be P_{out}/P_{in} for a system component. We may also use decibels to express an amount of power compared to some standard reference. If, for example, we wished to express the input power to our hypothetical amplifier (40 milliWatts) using decibels, we could do so by comparing 40 mW against a standard "reference" power of exactly 1 milliWatt. The resulting decibel figure would be written as "dBm" in honor of the 1 *m*illiWatt reference:

$$P_{in} = 10 \log \left(\frac{40 \text{ mW}}{1 \text{ mW}} \right) = 16.0206 \text{ dBm}$$

The unit of "dBm" literally means the amount of dB "greater than" 1 milliWatt. In this case, our input signal of 40 milliWatts is 16.0206 dB greater than a standard reference power of exactly 1 milliWatt. The output power of that amplifier (18.4 Watts) may be expressed in dBm as well:

$$P_{out} = 10 \log \left(\frac{18.4 \text{ W}}{1 \text{ mW}} \right) = 42.6482 \text{ dBm}$$

A signal power of 18.4 Watts is 42.6482 dB greater than a standard reference power of exactly 1 milliWatt, and so it has a decibel value of 42.6482 dBm.



Notice how the output and input powers expressed in dBm relate to the power gain of the amplifier. Taking the input power and simply *adding* the amplifier's gain factor yields the amplifier's output power in dBm:

$$P_{in}(\text{dB}) + P_{gain}(\text{dB}) = P_{out}(\text{dB})$$

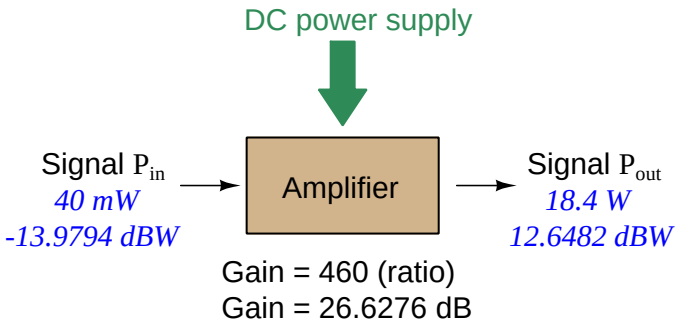
$$16.0206 \text{ dBm} + 26.6276 \text{ dB} = 42.6482 \text{ dBm}$$

An electronic signal that begins 16.0206 dB greater than 1 milliWatt, when boosted by an amplifier gain of 26.6276 dB, will become 42.6482 dB greater than the original reference power of 1 milliWatt.

We may alternatively express all powers in this hypothetical amplifier in reference to a 1-Watt standard power, with the resulting power expressed in units of "dBW" (decibels greater than 1 Watt):

$$P_{in} = 10 \log \left(\frac{40 \text{ mW}}{1 \text{ W}} \right) = -13.9794 \text{ dBW}$$

$$P_{out} = 10 \log \left(\frac{18.4 \text{ W}}{1 \text{ W}} \right) = 12.6482 \text{ dBW}$$



Note how the input power of 40 milliWatts equates to a negative dBW figure because 40 milliWatts is *less* than the 1 Watt reference, and how the output power of 18.4 Watts equates to a positive dBW figure because 18.4 Watts is *more* than the 1 Watt reference. A positive dB figure means "more than" while a negative dB figure means "less than."

Note also how the output and input powers expressed in dBW still relate to the power gain of the amplifier by simple addition, just as they did when previously expressed in units of dBm. Taking the input power in units of dBW and simply *adding* the amplifier's gain factor yields the amplifier's output power in dBW:

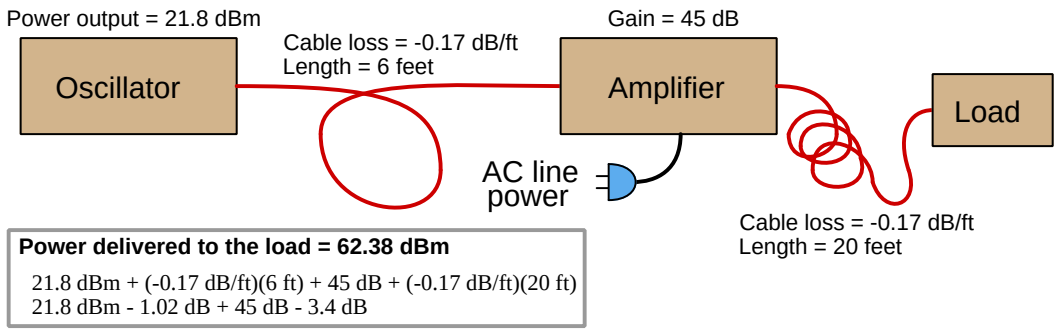
$$P_{in}(\text{dB}) + P_{gain}(\text{dB}) = P_{out}(\text{dB})$$

$$-13.9794 \text{ dBW} + 26.6276 \text{ dB} = 12.6482 \text{ dBW}$$

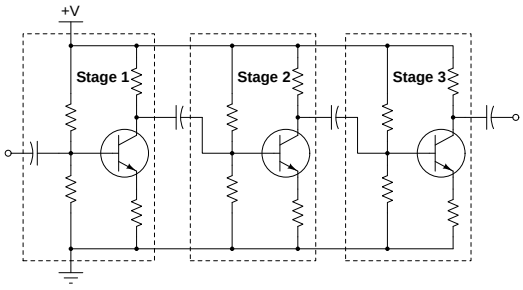
An electronic signal that begins 13.9794 dB less than 1 Watt, when boosted by an amplifier gain of 26.6276 dB, will become 12.6482 dB greater than the original reference power of 1 Watt.

This is one of the major benefits of using decibels to express powers: we may very easily calculate power gains and losses by summing a string of dB figures, each dB figure representing the power gain or power loss of a different system component. Normally, any compounding of *ratios* involves multiplication and/or division of those ratios, but with decibels we may simply add and subtract. One of the interesting mathematical properties of logarithms is that they "transform[3]" one type of problem into a simpler type: in this case, a problem of multiplying ratios into a (simpler) problem of adding decibel figures.

For example, we may express the power dissipated along a cable in terms of decibels per foot; the longer the cable, of course, the more power will be lost this way, all other factors being equal. For example, a radio-frequency signal cable having a loss figure of −0.15 decibels per foot at a signal frequency of 2.4 GHz will suffer −15 dB over 100 feet, and −150 dB over 1000 feet. To illustrate how decibels may be used to calculate power delivered to a load in such a system, accounting for various gains and losses along the way using decibel figures:



A similar application of decibels is found in multi-stage amplifier circuits, where one stage amplifies a signal to be fed into a successive stage to be amplified more. The power gains of these stages, each expressed as a ratio, *multiply* to make the over-all amplifier's power gain (ratio). The power gains of those same stages, each expressed as a decibel figure, *add* to make the over-all amplifier's power gain (dB):



[3]In fact, logarithms are one of the simplest examples of a *transform function*, converting one type of mathematical problem into another type. Other examples of mathematical transform functions used in engineering include the *Fourier transform* (converting a time-domain function into a frequency-domain function) and the *Laplace transform* (converting a differential equation into an algebraic equation).

Another common application of decibels is to express ratios of voltage and/or current rather than power. However, since the unit of the Bel has been defined as an expression of a *power* ratio, we cannot simply substitute V or I for P in any of the formulae we've seen so far.

Suppose an amplifier has a voltage gain of 2 (i.e. V_{out} is twice as large as V_{in}), and we would like to express this gain in decibels. Since decibels are intended to express power gain and not voltage gain, we must figure out how much power gain is equivalent to a voltage gain of two. Obviously, voltage and power are fundamentally different quantities, but if we imagine ourselves connecting a fixed load resistance to the input signal, and then to the output signal, we will realize that load's power dissipation will be more than double when energized by a voltage twice as large. Joule's Law is helpful to determine the exact ratio of power dissipation:

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

Doubling voltage for any given load resistance results in power *quadrupling* because power is proportional to the square of the voltage applied to a fixed resistance. Using this as the basis for applying decibels to a voltage ratio. Knowing that Joule's Law also declares power is proportional to the square of the current applied to a fixed resistance ($P = I^2R$) means this same mathematical relationship will apply to current gains and reductions as well as voltage gains and reductions:

$$\text{dB} = 10 \log \left(\frac{P_{out}}{P_{in}} \right) = 10 \log \left(\frac{V_{out}}{V_{in}} \right)^2 = 10 \log \left(\frac{I_{out}}{I_{in}} \right)^2$$

An algebraic identity of logarithms is that the logarithm of any quantity raised to a power is equal to that power multiplied by the logarithm of the quantity. Expressed in general terms:

$$\log x^y = y \log x$$

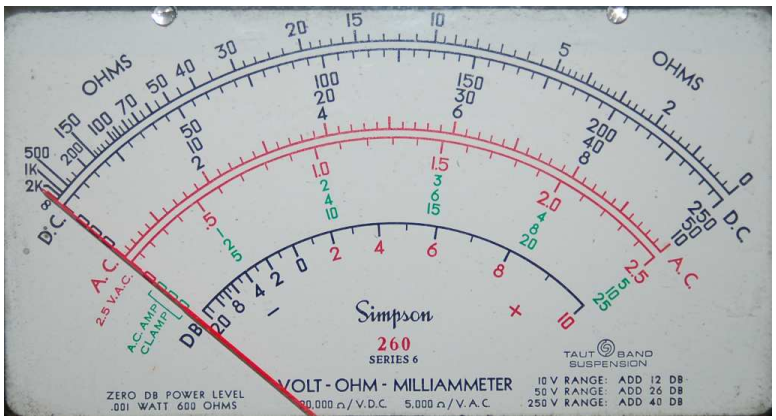
Therefore, we may simplify the decibel formula for voltage gain by removing the "2" power and making it a multiplier:

$$10 \log \left(\frac{V_{out}}{V_{in}} \right)^2 = (2)(10) \log \left(\frac{V_{out}}{V_{in}} \right) = 20 \log \left(\frac{V_{out}}{V_{in}} \right)$$

$$10 \log \left(\frac{I_{out}}{I_{in}} \right)^2 = (2)(10) \log \left(\frac{I_{out}}{I_{in}} \right) = 20 \log \left(\frac{I_{out}}{I_{in}} \right)$$

Thus, we may use decibels to express voltage or current ratios if we simply substitute 20 instead of 10 as the multiplier.

We can see the practicality of using decibels to represent something other than electrical *power* by examining this analog meter face, belonging to a Simpson model 260 VOM (Volt-Ohm-Milliammeter). Note the bottom scale on this meter's face, calibrated in decibels (DB):



Pay attention to the note on decibels written in the lower-left corner of the meter face, where 0 dB is defined as 0.001 Watt dissipated by 600 Ohms. The fact that 0 dB is defined as 1 milliWatt means it should (properly) be labeled dBm rather than dB[4]. A load resistance value is necessary as part of this definition for dB because this meter cannot measure power directly but must infer signal power from measurements of AC *voltage*. Without a specific load resistance, there is no clear relation between voltage and power. 600 Ohms is an old telecommunications standard for audio-frequency AC signals, and continues to be used today for voltage-based decibel measurements of audio-frequency AC signals.

The meter as shown is connected to nothing at all, and so registers 0 Volts AC. This, of course, corresponds to zero power, and it has no corresponding decibel value because the logarithm of zero is mathematically *undefined*[5]. Practically, it means $-\infty$ dB, which is why the needle at the 0 Volt position "falls off" the left-hand end of the dB scale.

Close inspection of the dB scale on this meter face reveals another interesting property of decibels, and that is the *nonlinear* nature of the dB scale. This contrasts starkly against all the voltage and current scales on this meter face which are linear. This nonlinearity is a fundamental property of decibels because it is based on the *logarithm* function which is nonlinear.

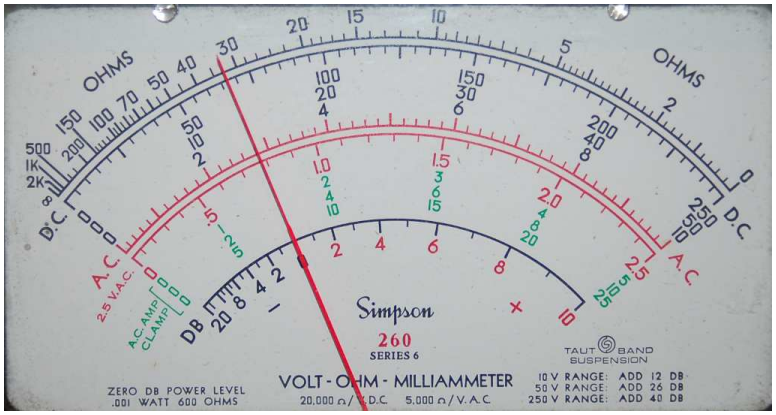
[4] Such mis-labeling is not that uncommon in the profession, the expectation being that the technician or engineer working with the instrument ought to be familiar enough with the concept of decibels to know when dB really means dBm, or dBW, etc.

[5] Your electronic calculator will complain if you attempt to take the logarithm of zero!

Now, we will explore what is necessary to make this meter register 0 dBm (i.e. 1 milliWatt) with an applied AC voltage. 1 milliWatt of power dissipated by 600 Ohms is equivalent to:

$$V = \sqrt{PR} = \sqrt{(0.001)(600)} = 0.7746 \text{ Volts}$$

Setting the VOM to the 2.5 VAC range and applying just enough AC voltage to bring the needle to the 0 dB mark allows us to verify that this is indeed equivalent to just under 0.8 Volts (read on the 2.5 VAC scale):



In the lower-right corner of the meter face we see some notes regarding correction values for decibel measurements when using different AC voltage ranges. The dB scale is read directly when the meter is set on the 2.5 VAC range. When set on the 10 VAC range (i.e. a range *four times* as great), the meter's needle will experience a deflection one-fourth as much as when set to the 2.5 VAC range, and therefore it will point to a lesser (or even negative) value on the dB scale. Converting a voltage ratio of 0.25 into a decibel figure shows us how much less the needle will register on the dB scale when the voltage range is quadrupled:

$$20 \log \left(\frac{2.5}{10} \right) = -12.04 \text{ dB}$$

Therefore, when using the 10 VAC range instead of the 2.5 VAC range, one must add 12 dB to the reading. Likewise, we may prove each of the printed correction factors for the alternative voltage-measurement ranges listed (50 Volt AC range and 250 Volt AC range):

$$20 \log \left(\frac{2.5}{50} \right) = -26.02 \text{ dB}$$

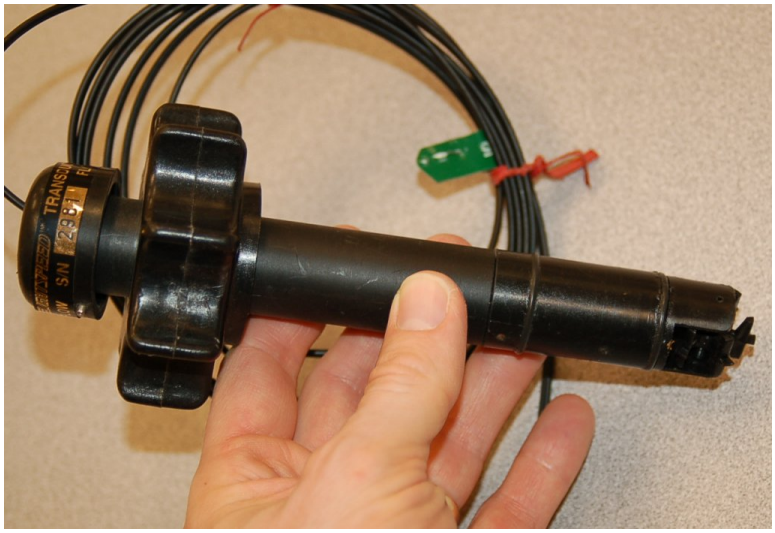
$$20 \log \left(\frac{2.5}{250} \right) = -40.0 \text{ dB}$$

3.2 Fiber optic sensing applications

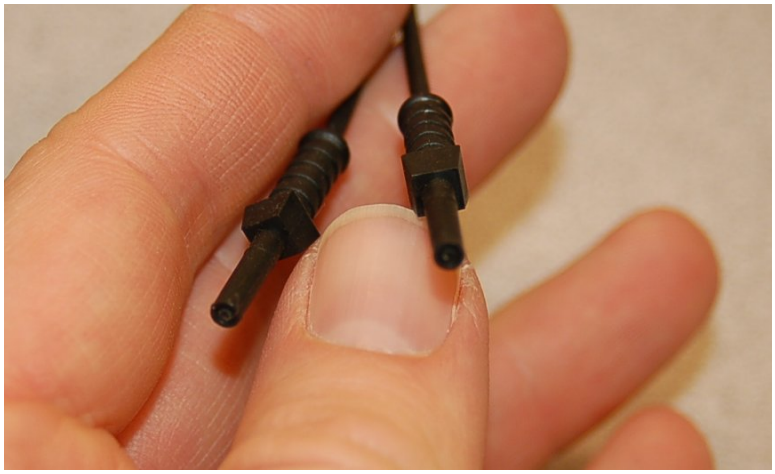
Optical fibers find applications beyond electronic data cable replacement, though, which means they will be a growing presence in the field of industrial instrumentation above and beyond their use as serial data communication cables. Some industrial process transmitters use optical fibers to send and receive light between the transmitter electronics and an optically-based primary sensing element. This may be as simple as a non-contact proximity switch using light to sense the presence of an object within a gap between the two fibers' ends, or as sophisticated as a chemical analyzer relying on the absorption of specific light wavelengths to detect the presence of a chemical substance in a solution.

3.2.1 Turbine flowmeter sensing

One example of a specialized application for optical fibers is shown in this photograph of a paddlewheel-style liquid flowmeter using a pair of optical fibers to convey light to and from the paddlewheel assembly, where the spinning paddlewheel serves to "chop" the light beam and thereby represent liquid flow rate as a frequency of pulsing light:

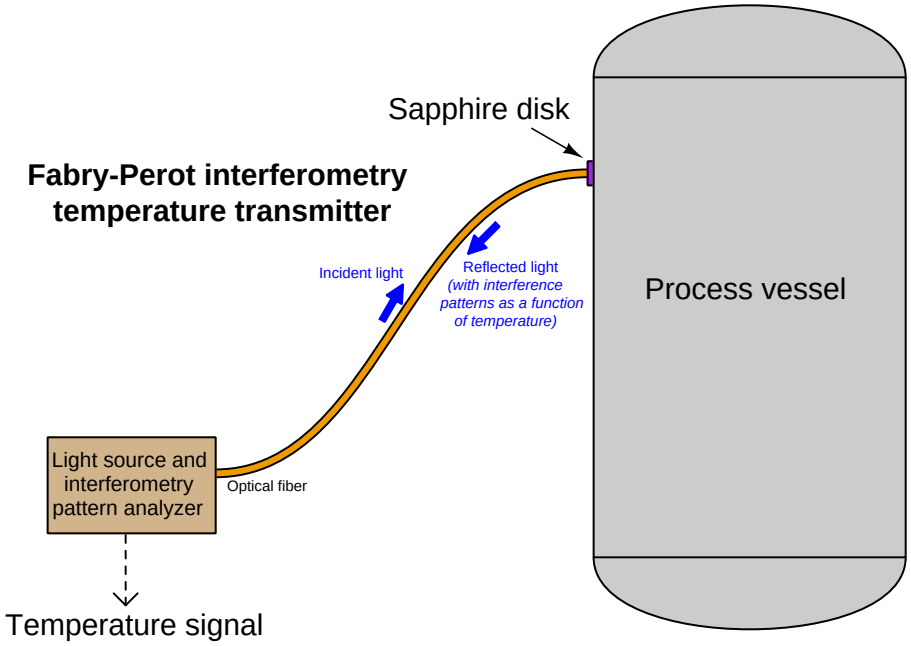


An end-view of the two optical fibers is shown in the next photograph. When installed as a working system, these two fibers will plug into a flow transmitter device sending a continuous beam of light through one fiber and sensing the pulsed light signal coming back from the paddlewheel through the other fiber:



3.2.2 Fabry-Perot interferometry temperature measurement

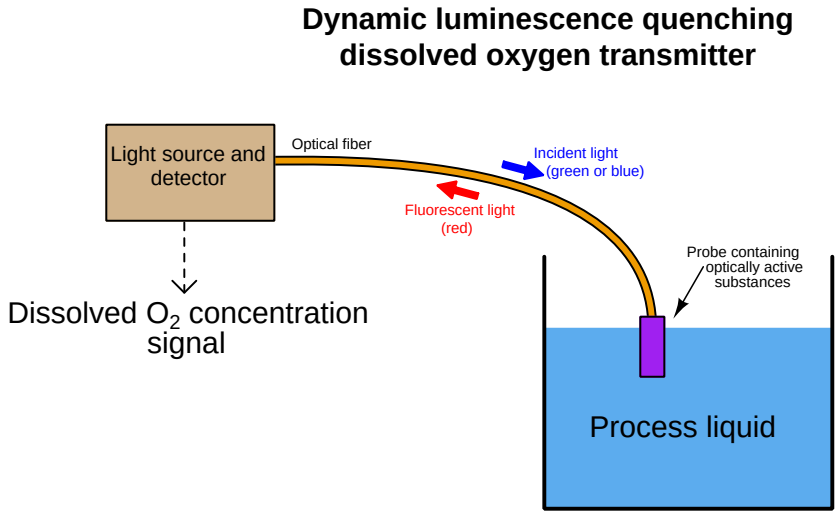
Another example of a specialized application for optical fibers is measurement of high temperatures using the *Fabry-Perot interferometry* method. This technology utilizes a small, thin disk of sapphire as a temperature sensor. The thickness of this disk as well as the speed of light through the sapphire are both temperature-dependent, which means a photon[6] of light shot at the face of the disk will reflect off the back face of the disk and return to the source at different times depending on the temperature of the disk. In a Fabry-Perot interferometer instrument, the "optical thickness" of the sapphire disk is measured by sending a continuous beam of white light to the disk and receiving the reflected light from the disk through a single optical fiber, the optical interference resulting from the incident and reflected light beams representing the disk's temperature. This novel method of temperature measurement shows promise for certain challenging industrial process applications such as high-temperature measurement inside slagging coal gasifiers used to efficiently extract energy and chemical feedstocks from coal:



[6] A "photon" is a quantity of light energy represented as a particle, along the same scale as an electron. It isn't entirely fair to characterize light as either consisting of waves or as consisting of particles, because light tends to manifest properties of both. Actually, this may be said of any sub-atomic particle (such as an electron) as well: under certain conditions these particles act like clumps of matter, and under different conditions they tend to act as waves of electromagnetic energy. This particle-wave duality lies at the heart of quantum physics, and continues to be something of a philosophical mystery simply because the behavior defies the macroscopic constructs we are accustomed to using when modeling the natural world.

3.2.3 Dissolved oxygen measurement

Yet another example of a specialized application for optical fibers is the measurement of dissolved oxygen in aqueous solutions using the *dynamic luminescence quenching* or *fluorescence quenching* method. This technology uses a thin layer of solid material containing molecules known to fluoresce[7] with red light when exposed to visible light of a shorter wavelength (typically green or blue). Oxygen molecules present in the liquid solution tend to bond with the fluorescing molecules in the sensor and inhibit that fluorescence, thus providing a means of measuring oxygen concentration near the sensor: the less O_2 dissolved in solution, the stronger the fluorescence (i.e. more red light received, for a longer duration); the more O_2, the less fluorescence. Optical fibers convey both the incident (green or blue) and returned (red) light between the wet sensing element and the interpreting electronics.



In both the Fabry-Perot interferometry and the fluorescence quenching sensors, the function of the fiber optic cable is to physically separate the sensing element from the sophisticated and fragile electronic transmitter needed to interpret the optical signal as a process variable measurement.

[7] Fluorescence is the phenomenon of a substance emitting a long-wavelength (low-energy) photon when "excited" by a short-wavelength (high-energy) photon. Perhaps the most familiar example of fluorescence is when certain materials emit visible light when exposed to ultraviolet light which is invisible to the human eye. The example of fluorescence discussed here with dissolved oxygen sensing happens to use two different colors (wavelengths) of visible light, but the basic principle is the same.

3.2.4 Arc flash detection

There is at least one application where the optical fiber itself *is* the sensing element: arc flash detection within high-voltage switchgear cabinets. "Arc flash" is the phenomenon of intense heat and light developed at a high-current electrical arc, especially a phase-to-phase arc between electric power conductors where there is little circuit resistance to limit fault current. High-voltage switchgear is constructed in such a way as to extinguish the arc normally developed at the contacts during each "opening" cycle, but certain faults within a piece of switchgear may inhibit this extinguishing function. In such cases the potential for equipment damage and threat to human health and life is severe.

If a bare (unjacketed) optical fiber is properly arranged within a piece of switchgear, an arc flash event will inject enough light through the fiber that some of it will be detected at the far end where it meets a light-sensitive receiver. Since the fiber itself is not electrically conductive, there is no risk of conducting a high-voltage arc back to this receiver. The receiver, meanwhile, serves the purpose of commanding any "upstream" switchgear to trip open in the event of a detected arc fault. The early detection of arc flash by optical means rather than the time-delayed detection of the same fault by overcurrent or current-imbalance detection results in much faster clearing of the faulted switchgear from the power grid, both limiting equipment damage and limiting the potential for injury or death.

Chapter 4

Questions

This learning module, along with all others in the ModEL collection, is designed to be used in an inverted instructional environment where students independently read[1] the tutorials and attempt to answer questions on their own *prior* to the instructor's interaction with them. In place of lecture[2], the instructor engages with students in Socratic-style dialogue, probing and challenging their understanding of the subject matter through inquiry.

Answers are not provided for questions within this chapter, and this is by design. Solved problems may be found in the Tutorial and Derivation chapters, instead. The goal here is *independence*, and this requires students to be challenged in ways where others cannot think for them. Remember that you always have the tools of *experimentation* and *computer simulation* (e.g. SPICE) to explore concepts!

The following lists contain ideas for Socratic-style questions and challenges. Upon inspection, one will notice a strong theme of *metacognition* within these statements: they are designed to foster a regular habit of examining one's own thoughts as a means toward clearer thinking. As such these sample questions are useful both for instructor-led discussions as well as for self-study.

[1] Technical reading is an essential academic skill for any technical practitioner to possess for the simple reason that the most comprehensive, accurate, and useful information to be found for developing technical competence is in textual form. Technical careers in general are characterized by the need for continuous learning to remain current with standards and technology, and therefore any technical practitioner who cannot read well is handicapped in their professional development. An excellent resource for educators on improving students' reading prowess through intentional effort and strategy is the book textitReading For Understanding – How Reading Apprenticeship Improves Disciplinary Learning in Secondary and College Classrooms by Ruth Schoenbach, Cynthia Greenleaf, and Lynn Murphy.

[2] Lecture is popular as a teaching method because it is easy to implement: any reasonably articulate subject matter expert can talk to students, even with little preparation. However, it is also quite problematic. A good lecture always makes complicated concepts seem easier than they are, which is bad for students because it instills a false sense of confidence in their own understanding; reading and re-articulation requires more cognitive effort and serves to verify comprehension. A culture of teaching-by-lecture fosters a debilitating dependence upon direct personal instruction, whereas the challenges of modern life demand independent and critical thought made possible only by gathering information and perspectives from afar. Information presented in a lecture is ephemeral, easily lost to failures of memory and dictation; text is forever, and may be referenced at any time.

General challenges following tutorial reading

- Summarize as much of the text as you can in one paragraph of your own words. A helpful strategy is to explain ideas as you would for an intelligent child: as simple as you can without compromising too much accuracy.
- Simplify a particular section of the text, for example a paragraph or even a single sentence, so as to capture the same fundamental idea in fewer words.
- Where did the text make the most sense to you? What was it about the text's presentation that made it clear?
- Identify where it might be easy for someone to misunderstand the text, and explain why you think it could be confusing.
- Identify any new concept(s) presented in the text, and explain in your own words.
- Identify any familiar concept(s) such as physical laws or principles applied or referenced in the text.
- Devise a proof of concept experiment demonstrating an important principle, physical law, or technical innovation represented in the text.
- Devise an experiment to disprove a plausible misconception.
- Did the text reveal any misconceptions you might have harbored? If so, describe the misconception(s) and the reason(s) why you now know them to be incorrect.
- Describe any useful problem-solving strategies applied in the text.
- Devise a question of your own to challenge a reader's comprehension of the text.

General follow-up challenges for assigned problems

- Identify where any fundamental laws or principles apply to the solution of this problem, especially before applying any mathematical techniques.
- Devise a thought experiment to explore the characteristics of the problem scenario, applying known laws and principles to mentally model its behavior.
- Describe in detail your own strategy for solving this problem. How did you identify and organized the given information? Did you sketch any diagrams to help frame the problem?
- Is there more than one way to solve this problem? Which method seems best to you?
- Show the work you did in solving this problem, even if the solution is incomplete or incorrect.
- What would you say was the most challenging part of this problem, and why was it so?
- Was any important information missing from the problem which you had to research or recall?
- Was there any extraneous information presented within this problem? If so, what was it and why did it not matter?
- Examine someone else's solution to identify where they applied fundamental laws or principles.
- Simplify the problem from its given form and show how to solve this simpler version of it. Examples include eliminating certain variables or conditions, altering values to simpler (usually whole) numbers, applying a limiting case (i.e. altering a variable to some extreme or ultimate value).
- For quantitative problems, identify the real-world meaning of all intermediate calculations: their units of measurement, where they fit into the scenario at hand. Annotate any diagrams or illustrations with these calculated values.
- For quantitative problems, try approaching it qualitatively instead, thinking in terms of "increase" and "decrease" rather than definite values.
- For qualitative problems, try approaching it quantitatively instead, proposing simple numerical values for the variables.
- Were there any assumptions you made while solving this problem? Would your solution change if one of those assumptions were altered?
- Identify where it would be easy for someone to go astray in attempting to solve this problem.
- Formulate your own problem based on what you learned solving this one.

General follow-up challenges for experiments or projects

- In what way(s) was this experiment or project easy to complete?
- Identify some of the challenges you faced in completing this experiment or project.

- Show how thorough documentation assisted in the completion of this experiment or project.
- Which fundamental laws or principles are key to this system's function?
- Identify any way(s) in which one might obtain false or otherwise misleading measurements from test equipment in this system.
- What will happen if (component X) fails (open/shorted/etc.)?
- What would have to occur to make this system unsafe?

4.1 Conceptual reasoning

These questions are designed to stimulate your analytic and synthetic thinking[3]. In a Socratic discussion with your instructor, the goal is for these questions to prompt an extended dialogue where assumptions are revealed, conclusions are tested, and understanding is sharpened. Your instructor may also pose additional questions based on those assigned, in order to further probe and refine your conceptual understanding.

Questions that follow are presented to challenge and probe your understanding of various concepts presented in the tutorial. These questions are intended to serve as a guide for the Socratic dialogue between yourself and the instructor. Your instructor's task is to ensure you have a sound grasp of these concepts, and the questions contained in this document are merely a means to this end. Your instructor may, at his or her discretion, alter or substitute questions for the benefit of tailoring the discussion to each student's needs. The only absolute requirement is that each student is challenged and assessed at a level equal to or greater than that represented by the documented questions.

It is far more important that you convey your *reasoning* than it is to simply convey a correct answer. For this reason, you should refrain from researching other information sources to answer questions. What matters here is that *you* are doing the thinking. If the answer is incorrect, your instructor will work with you to correct it through proper reasoning. A correct answer without an adequate explanation of how you derived that answer is unacceptable, as it does not aid the learning or assessment process.

You will note a conspicuous lack of answers given for these conceptual questions. Unlike standard textbooks where answers to every other question are given somewhere toward the back of the book, here in these learning modules students must rely on other means to check their work. The best way by far is to debate the answers with fellow students and also with the instructor during the Socratic dialogue sessions intended to be used with these learning modules. Reasoning through challenging questions with other people is an excellent tool for developing strong reasoning skills.

Another means of checking your conceptual answers, where applicable, is to use circuit simulation software to explore the effects of changes made to circuits. For example, if one of these conceptual questions challenges you to predict the effects of altering some component parameter in a circuit, you may check the validity of your work by simulating that same parameter change within software and seeing if the results agree.

[3] *Analytical* thinking involves the "disassembly" of an idea into its constituent parts, analogous to dissection. *Synthetic* thinking involves the "assembly" of a new idea comprised of multiple concepts, analogous to construction. Both activities are high-level cognitive skills, extremely important for effective problem-solving, necessitating frequent challenge and regular practice to fully develop.

4.1.1 Reading outline and reflections

"Reading maketh a full man; conference a ready man; and writing an exact man" – Francis Bacon

Francis Bacon's advice is a blueprint for effective education: reading provides the learner with knowledge, writing focuses the learner's thoughts, and critical dialogue equips the learner to confidently communicate and apply their learning. Independent acquisition and application of knowledge is a powerful skill, well worth the effort to cultivate. To this end, students should read these educational resources closely, journal their own reflections on the reading, and discuss in detail their findings with classmates and instructor(s). You should be able to do all of the following after reading any instructional text:

☑ Briefly SUMMARIZE THE TEXT in the form of a journal entry documenting your learning as you progress through the course of study. Share this summary in dialogue with your classmates and instructor. Journaling is an excellent self-test of thorough reading because you cannot clearly express what you have not read or did not comprehend.

☑ Demonstrate ACTIVE READING STRATEGIES, including verbalizing your impressions as you read, simplifying long passages to convey the same ideas using fewer words, annotating text and illustrations with your own interpretations, working through mathematical examples shown in the text, cross-referencing passages with relevant illustrations and/or other passages, identifying problem-solving strategies applied by the author, etc. Technical reading is a special case of problem-solving, and so these strategies work precisely because they help solve any problem: paying attention to your own thoughts (metacognition), eliminating unnecessary complexities, identifying what makes sense, paying close attention to details, drawing connections between separated facts, and noting the successful strategies of others.

☑ Identify IMPORTANT THEMES, especially GENERAL LAWS and PRINCIPLES, expounded in the text and express them in the simplest of terms as though you were teaching an intelligent child. This emphasizes connections between related topics and develops your ability to communicate complex ideas to anyone.

☑ Form YOUR OWN QUESTIONS based on the reading, and then pose them to your instructor and classmates for their consideration. Anticipate both correct and incorrect answers, the incorrect answer(s) assuming one or more plausible misconceptions. This helps you view the subject from different perspectives to grasp it more fully.

☑ Devise EXPERIMENTS to test claims presented in the reading, or to disprove misconceptions. Predict possible outcomes of these experiments, and evaluate their meanings: what result(s) would confirm, and what would constitute disproof? Running mental simulations and evaluating results is essential to scientific and diagnostic reasoning.

☑ Specifically identify any points you found CONFUSING. The reason for doing this is to help diagnose misconceptions and overcome barriers to learning.

4.1.2 Foundational concepts

Correct analysis and diagnosis of electric circuits begins with a proper understanding of some basic concepts. The following is a list of some important concepts referenced in this module's full tutorial. Define each of them in your own words, and be prepared to illustrate each of these concepts with a description of a practical example and/or a live demonstration.

Simplex

Duplex

Bandwidth

Decibels

Wavelength

Crosstalk

Capacitive coupling

Inductive coupling

Time domain

Refraction

Index of refraction

Snell's Law

Total internal reflection

Multi-mode versus single-mode

Modal dispersion

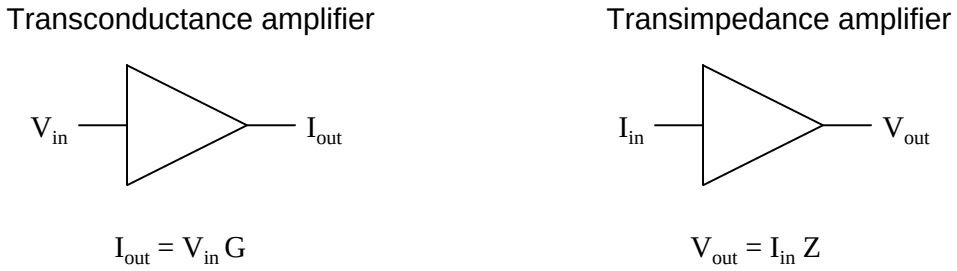
Splicing

Minimum bend radius

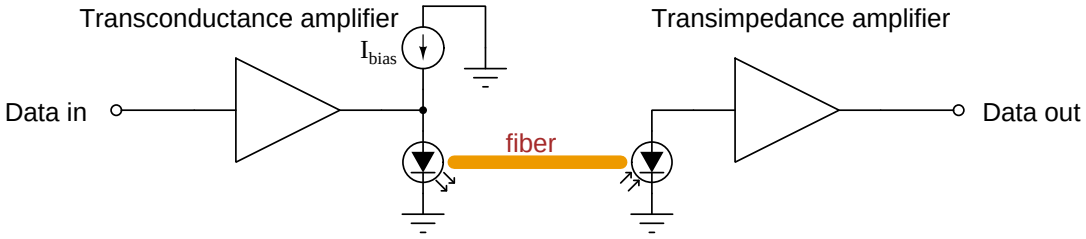
Time-domain reflectometry

4.1.3 Transconductance and transimpedance amplifiers

Devices often used in fiber-optic interface circuits are *transconductance* and *transimpedance* amplifiers:



For example, we would typically see a transconductance amplifier used in the fiber-optic transmitting circuit, and a transimpedance amplifier used in the fiber-optic receiving circuit:



First, explain the names used to describe these special amplifiers – what does *transconductance* and *transimpedance* actually mean?

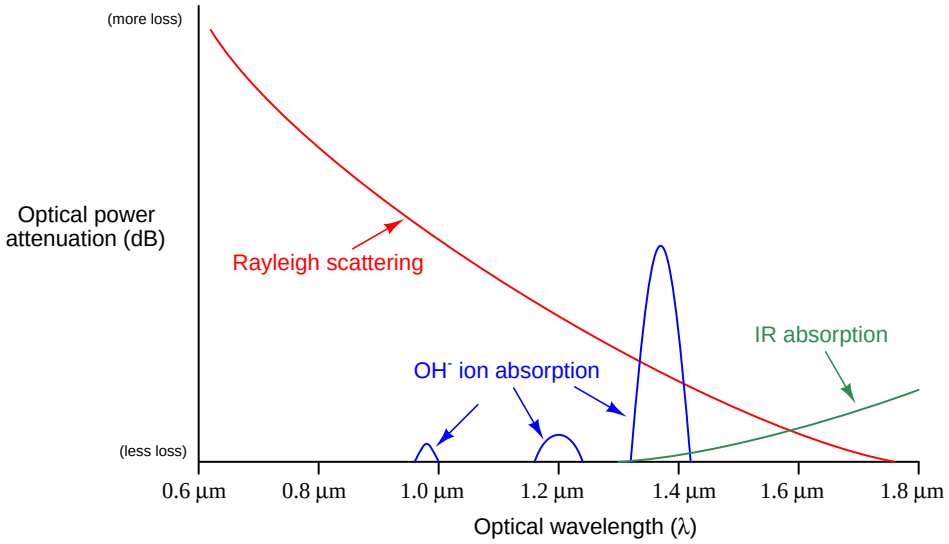
Next, explain how the circuit shown above works to convey digital data through the optical fiber.

Challenges

- Transconductance amplifiers have been described as *ideal transistors*. Explain why.
- The schematic diagram is definitely simplified. If we were drawing it in more detail, what else would be included?

4.1.4 Losses in optical fibers

Most optical fibers are manufactured from ultra-pure glass, but even with the purest of glass compositions there will be some energy lost as photons travel down long lengths of fiber. These energy losses are frequency-specific as well, as shown by the following graphs:



- **Rayleigh scattering** – diffraction and scattering of light due to crystalline imperfections in the glass
- **OH^- ion absorption** – resonance with hydroxyl ions (from aqueous impurities) embedded in the glass
- **IR absorption** – dissipation resulting in direct collisions between photons and glass molecules

Comment on each of these loss mechanisms, and how their relation to wavelength resembles electric circuit phenomenon you are already familiar with.

Also comment on how the laws of thermodynamics relate to optical power losses in glass fibers.

Challenges

- Where does visible light fall along the wavelength scale?

4.2 Quantitative reasoning

These questions are designed to stimulate your computational thinking. In a Socratic discussion with your instructor, the goal is for these questions to reveal your mathematical approach(es) to problem-solving so that good technique and sound reasoning may be reinforced. Your instructor may also pose additional questions based on those assigned, in order to observe your problem-solving firsthand.

Mental arithmetic and estimations are strongly encouraged for all calculations, because without these abilities you will be unable to readily detect errors caused by calculator misuse (e.g. keystroke errors).

You will note a conspicuous lack of answers given for these quantitative questions. Unlike standard textbooks where answers to every other question are given somewhere toward the back of the book, here in these learning modules students must rely on other means to check their work. My advice is to use circuit simulation software such as SPICE to check the correctness of quantitative answers. Refer to those learning modules within this collection focusing on SPICE to see worked examples which you may use directly as practice problems for your own study, and/or as templates you may modify to run your own analyses and generate your own practice problems.

Completely worked example problems found in the Tutorial may also serve as "test cases[4]" for gaining proficiency in the use of circuit simulation software, and then once that proficiency is gained you will never need to rely[5] on an answer key!

[4] In other words, set up the circuit simulation software to analyze the same circuit examples found in the Tutorial. If the simulated results match the answers shown in the Tutorial, it confirms the simulation has properly run. If the simulated results disagree with the Tutorial's answers, something has been set up incorrectly in the simulation software. Using every Tutorial as practice in this way will quickly develop proficiency in the use of circuit simulation software.

[5] This approach is perfectly in keeping with the instructional philosophy of these learning modules: *teaching students to be self-sufficient thinkers*. Answer keys can be useful, but it is even more useful to your long-term success to have a set of tools on hand for checking your own work, because once you have left school and are on your own, there will no longer be "answer keys" available for the problems you will have to solve.

4.2.1 Miscellaneous physical constants

Note: constants shown in **bold** type are *exact*, not approximations. Values inside of parentheses show one standard deviation (σ) of uncertainty in the final digits: for example, the magnetic permeability of free space value given as $1.25663706212(19) \times 10^{-6}$ H/m represents a center value (i.e. the location parameter) of $1.25663706212 \times 10^{-6}$ Henrys per meter with one standard deviation of uncertainty equal to $0.0000000000019 \times 10^{-6}$ Henrys per meter.

Avogadro's number (N_A) = **6.02214076** $\times 10^{23}$ **per mole** (mol^{-1})

Boltzmann's constant (k) = **1.380649** $\times 10^{-23}$ **Joules per Kelvin** (J/K)

Electronic charge (e) = **1.602176634** $\times 10^{-19}$ **Coulomb** (C)

Faraday constant (F) = **96,485.33212...** $\times 10^{4}$ **Coulombs per mole** (C/mol)

Magnetic permeability of free space (μ_0) = $1.25663706212(19) \times 10^{-6}$ Henrys per meter (H/m)

Electric permittivity of free space (ϵ_0) = $8.8541878128(13) \times 10^{-12}$ Farads per meter (F/m)

Characteristic impedance of free space (Z_0) = 376.730313668(57) Ohms (Ω)

Gravitational constant (G) = $6.67430(15) \times 10^{-11}$ cubic meters per kilogram-seconds squared ($m^3/kg\text{-}s^2$)

Molar gas constant (R) = **8.314462618... Joules per mole-Kelvin** (J/mol-K) = 0.08205746(14) liters-atmospheres per mole-Kelvin

Planck constant (h) = **6.62607015** $\times 10^{-34}$ **joule-seconds** (J-s)

Stefan-Boltzmann constant (σ) = **5.670374419...** $\times 10^{-8}$ **Watts per square meter-Kelvin**^{4} ($W/m^2 \cdot K^4$)

Speed of light in a vacuum (c) = **299,792,458 meters per second** (m/s) = 186282.4 miles per second (mi/s)

Note: All constants taken from NIST data "Fundamental Physical Constants – Complete Listing", from `http://physics.nist.gov/constants`, National Institute of Standards and Technology (NIST), 2018 CODATA Adjustment.

4.2.2 Introduction to spreadsheets

A powerful computational tool you are encouraged to use in your work is a *spreadsheet*. Available on most personal computers (e.g. Microsoft Excel), *spreadsheet* software performs numerical calculations based on number values and formulae entered into cells of a grid. This grid is typically arranged as lettered columns and numbered rows, with each cell of the grid identified by its column/row coordinates (e.g. cell `B3`, cell `A8`). Each cell may contain a string of text, a number value, or a mathematical formula. The spreadsheet automatically updates the results of all mathematical formulae whenever the entered number values are changed. This means it is possible to set up a spreadsheet to perform a series of calculations on entered data, and those calculations will be re-done by the computer any time the data points are edited in any way.

For example, the following spreadsheet calculates average speed based on entered values of distance traveled and time elapsed:

	A	B	C	D
1	Distance traveled	46.9	Kilometers	
2	Time elapsed	1.18	Hours	
3	Average speed	= B1 / B2	km/h	
4				
5				

Text labels contained in cells `A1` through `A3` and cells `C1` through `C3` exist solely for readability and are not involved in any calculations. Cell `B1` contains a sample distance value while cell `B2` contains a sample time value. The formula for computing speed is contained in cell `B3`. Note how this formula begins with an "equals" symbol (`=`), references the values for distance and speed by lettered column and numbered row coordinates (`B1` and `B2`), and uses a forward slash symbol for division (`/`). The coordinates `B1` and `B2` function as *variables*[6] would in an algebraic formula.

When this spreadsheet is executed, the numerical value `39.74576` will appear in cell `B3` rather than the formula `= B1 / B2`, because 39.74576 is the computed speed value given 46.9 kilometers traveled over a period of 1.18 hours. If a different numerical value for distance is entered into cell `B1` or a different value for time is entered into cell `B2`, cell `B3`'s value will automatically update. All you need to do is set up the given values and any formulae into the spreadsheet, and the computer will do all the calculations for you.

Cell `B3` may be referenced by other formulae in the spreadsheet if desired, since it is a variable just like the given values contained in `B1` and `B2`. This means it is possible to set up an entire chain of calculations, one dependent on the result of another, in order to arrive at a final value. The arrangement of the given data and formulae need not follow any pattern on the grid, which means you may place them anywhere.

[6] Spreadsheets may also provide means to attach text labels to cells for use as variable names (Microsoft Excel simply calls these labels "names"), but for simple spreadsheets such as those shown here it's usually easier just to use the standard coordinate naming for each cell.

Common[7] arithmetic operations available for your use in a spreadsheet include the following:

- Addition (`+`)
- Subtraction (`-`)
- Multiplication (`*`)
- Division (`/`)
- Powers (`^`)
- Square roots (`sqrt()`)
- Logarithms (`ln()` , `log10()`)

Parentheses may be used to ensure[8] proper order of operations within a complex formula. Consider this example of a spreadsheet implementing the *quadratic formula*, used to solve for roots of a polynomial expression in the form of $ax^2 + bx + c$:

$$x = \frac{-b \pm \sqrt{b^2 - 4ac}}{2a}$$

	A	B
1	x_1	= (-B4 + sqrt((B4^2) - (4*B3*B5))) / (2*B3)
2	x_2	= (-B4 - sqrt((B4^2) - (4*B3*B5))) / (2*B3)
3	a =	9
4	b =	5
5	c =	-2

This example is configured to compute roots[9] of the polynomial $9x^2 + 5x - 2$ because the values of 9, 5, and -2 have been inserted into cells `B3`, `B4`, and `B5`, respectively. Once this spreadsheet has been built, though, it may be used to calculate the roots of *any* second-degree polynomial expression simply by entering the new a, b, and c coefficients into cells `B3` through `B5`. The numerical values appearing in cells `B1` and `B2` will be automatically updated by the computer immediately following any changes made to the coefficients.

[7] Modern spreadsheet software offers a bewildering array of mathematical functions you may use in your computations. I recommend you consult the documentation for your particular spreadsheet for information on operations other than those listed here.

[8] Spreadsheet programs, like text-based programming languages, are designed to follow standard order of operations by default. However, my personal preference is to use parentheses even where strictly unnecessary just to make it clear to any other person viewing the formula what the intended order of operations is.

[9] Reviewing some algebra here, a *root* is a value for x that yields an overall value of zero for the polynomial. For this polynomial ($9x^2 + 5x - 2$) the two roots happen to be $x = 0.269381$ and $x = -0.82494$, with these values displayed in cells `B1` and `B2`, respectively upon execution of the spreadsheet.

Alternatively, one could break up the long quadratic formula into smaller pieces like this:

$$y = \sqrt{b^2 - 4ac} \qquad z = 2a$$

$$x = \frac{-b \pm y}{z}$$

	A	B	C
1	x_1	= (-B4 + C1) / C2	= sqrt((B4^2) - (4*B3*B5))
2	x_2	= (-B4 - C1) / C2	= 2*B3
3	a =	9	
4	b =	5	
5	c =	-2	

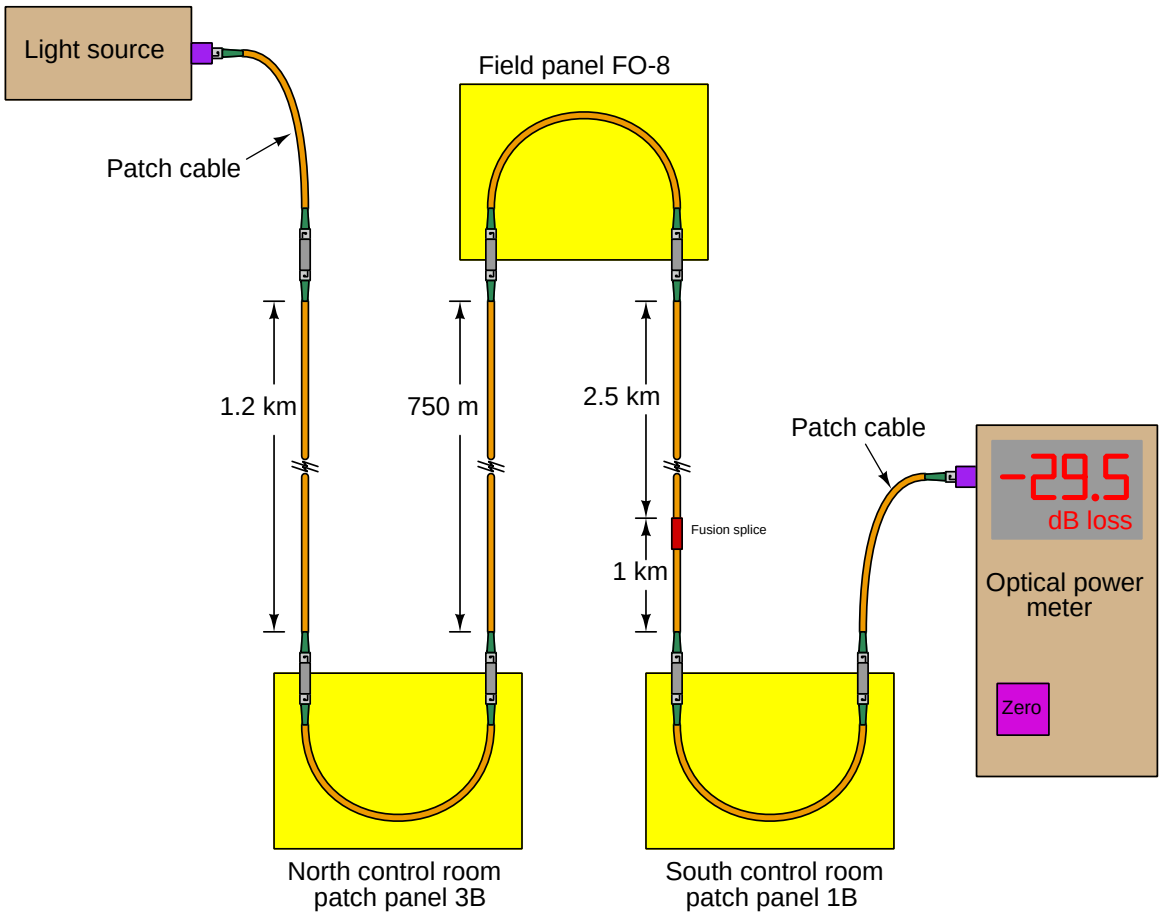
Note how the square-root term (y) is calculated in cell C1, and the denominator term (z) in cell C2. This makes the two final formulae (in cells B1 and B2) simpler to interpret. The positioning of all these cells on the grid is completely arbitrary[10] – all that matters is that they properly reference each other in the formulae.

Spreadsheets are particularly useful for situations where the same set of calculations representing a circuit or other system must be repeated for different initial conditions. The power of a spreadsheet is that it automates what would otherwise be a tedious set of calculations. One specific application of this is to simulate the effects of various components within a circuit failing with abnormal values (e.g. a shorted resistor simulated by making its value nearly zero; an open resistor simulated by making its value extremely large). Another application is analyzing the behavior of a circuit design given new components that are out of specification, and/or aging components experiencing drift over time.

[10] My personal preference is to locate all the "given" data in the upper-left cells of the spreadsheet grid (each data point flanked by a sensible name in the cell to the left and units of measurement in the cell to the right as illustrated in the first distance/time spreadsheet example), sometimes coloring them in order to clearly distinguish which cells contain entered data versus which cells contain computed results from formulae. I like to place all formulae in cells below the given data, and try to arrange them in logical order so that anyone examining my spreadsheet will be able to figure out *how* I constructed a solution. This is a general principle I believe all computer programmers should follow: *document and arrange your code to make it easy for other people to learn from it.*

4.2.3 Optical power test

Suppose a technician performs an optical power test of this optical fiber run and determines there is an excessive end-to-end power loss:



Assuming a typical cable attenuation of -1 dB per kilometer, a typical connector loss of -2 dB per cable-to-cable connection, and a typical fusion splice loss of -0.2 dB per splice, calculate the expected optical power loss for the test configuration shown.

Describe a diagnostic procedure by which you could locate which section(s) of this optical fiber run might account for the excessive power loss.

Identify an error the first technician may have committed that would have given a falsely high power loss measurement (i.e. explain how this fiber optic cable run might actually be within acceptable power loss parameters after all!).

Finally, describe how an OTDR could be used to test this fiber optic run instead of an optical power meter.

Challenges

- What exactly is a "fusion splice" and how does it differ from the "butt connectors" shown elsewhere in this illustration?
- Identify the causes of optical power loss at connectors.
- Identify the causes of optical power loss at fusion splices.
- Identify the causes of optical power loss along the length of an optical fiber.
- Would the result of this test be any different if we swapped locations of the optical source and power meter? Why or why not?
- What would happen to the optical power meter's reading if we were to disconnect one of the junctions in this system?
- What would happen to the optical power meter's reading if we were to sharply bend one of the fibers in this system?

4.2.4 Power concentration program in Python

Calculate the power concentration (i.e. "irradiance") of a 0.4 Watt laser light beam emerging from a 50/125 fiber-optic cable, in units of Watts per square meter.

Now complete this Python program to calculate power concentration in Watts per square meter given a user-input optical power in Watts.

```
from math import *
dia = 50e-6
area = pi * pow(dia/2,2)

print("Enter optical power in Watts: ", end="")
P = float(input())

# (your code here)
```

Challenges

- Explain how your calculated value for power concentration helps explain the danger of unplugging an "energized" fiber.

4.3 Diagnostic reasoning

These questions are designed to stimulate your deductive and inductive thinking, where you must apply general principles to specific scenarios (deductive) and also derive conclusions about the failed circuit from specific details (inductive). In a Socratic discussion with your instructor, the goal is for these questions to reinforce your recall and use of general circuit principles and also challenge your ability to integrate multiple symptoms into a sensible explanation of what's wrong in a circuit. Your instructor may also pose additional questions based on those assigned, in order to further challenge and sharpen your diagnostic abilities.

As always, your goal is to fully *explain* your analysis of each problem. Simply obtaining a correct answer is not good enough – you must also demonstrate sound reasoning in order to successfully complete the assignment. Your instructor's responsibility is to probe and challenge your understanding of the relevant principles and analytical processes in order to ensure you have a strong foundation upon which to build further understanding.

You will note a conspicuous lack of answers given for these diagnostic questions. Unlike standard textbooks where answers to every other question are given somewhere toward the back of the book, here in these learning modules students must rely on other means to check their work. The best way by far is to debate the answers with fellow students and also with the instructor during the Socratic dialogue sessions intended to be used with these learning modules. Reasoning through challenging questions with other people is an excellent tool for developing strong reasoning skills.

Another means of checking your diagnostic answers, where applicable, is to use circuit simulation software to explore the effects of faults placed in circuits. For example, if one of these diagnostic questions requires that you predict the effect of an open or a short in a circuit, you may check the validity of your work by simulating that same fault (substituting a very high resistance in place of that component for an open, and substituting a very low resistance for a short) within software and seeing if the results agree.

4.3.1 Light direction testing

When a piece of energized fiber-optic cable is bent sharper than the critical angle, light will "leak" out of it through the cladding and outer jacket. If the light source is visible-color laser, you will be able to see a faint glow when this bent fiber is held in a dark room.

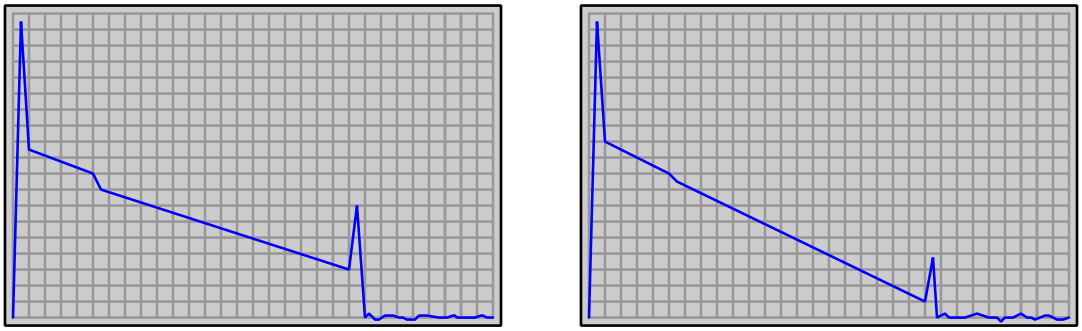
Devise a test using this principle by which you could ascertain the *direction* of light traveling through a laser-energized fiber.

Challenges

- Comment on how this concept applies to digital data security.

4.3.2 Comparing OTDR traces

Compare the following OTDR displays taken on the same fiber-optic cable, but with two different wavelengths of light:



Which of these traces represent the long-wavelength light, and which represent the short-wavelength light?

Identify likely causes for signal loss represented in each of these traces.

Challenges

- How would the OTDR test of this particular fiber look if performed at an optical wavelength matching one of the resonant peaks for OH^- (hydroxyl) ions?

Appendix A

Problem-Solving Strategies

The ability to solve complex problems is arguably one of the most valuable skills one can possess, and this skill is particularly important in any science-based discipline.

- Study principles, not procedures. Don't be satisfied with merely knowing how to compute solutions – learn *why* those solutions work.
- Identify what it is you need to solve, identify all relevant data, identify all units of measurement, identify any general principles or formulae linking the given information to the solution, and then identify any "missing pieces" to a solution. Annotate all diagrams with this data.
- Sketch a diagram to help visualize the problem. When building a real system, always devise a plan for that system and analyze its function *before* constructing it.
- Follow the units of measurement and meaning of every calculation. If you are ever performing mathematical calculations as part of a problem-solving procedure, and you find yourself unable to apply each and every intermediate result to some aspect of the problem, it means you don't understand what you are doing. Properly done, every mathematical result should have practical meaning for the problem, and not just be an abstract number. You should be able to identify the proper units of measurement for each and every calculated result, and show where that result fits into the problem.
- Perform "thought experiments" to explore the effects of different conditions for theoretical problems. When troubleshooting real systems, perform *diagnostic tests* rather than visually inspecting for faults, the best diagnostic test being the one giving you the most information about the nature and/or location of the fault with the fewest steps.
- Simplify the problem until the solution becomes obvious, and then use that obvious case as a model to follow in solving the more complex version of the problem.
- Check for exceptions to see if your solution is incorrect or incomplete. A good solution will work for *all* known conditions and criteria. A good example of this is the process of testing scientific hypotheses: the task of a scientist is not to find support for a new idea, but rather to *challenge* that new idea to see if it holds up under a battery of tests. The philosophical

principle of *reductio ad absurdum* (i.e. disproving a general idea by finding a specific case where it fails) is useful here.

- Work "backward" from a hypothetical solution to a new set of given conditions.
- Add quantities to problems that are qualitative in nature, because sometimes a little math helps illuminate the scenario.
- Sketch graphs illustrating how variables relate to each other. These may be quantitative (i.e. with realistic number values) or qualitative (i.e. simply showing increases and decreases).
- Treat quantitative problems as qualitative in order to discern the relative magnitudes and/or directions of change of the relevant variables. For example, try determining what happens if a certain variable were to increase or decrease before attempting to precisely calculate quantities: how will each of the dependent variables respond, by increasing, decreasing, or remaining the same as before?
- Consider limiting cases. This works especially well for qualitative problems where you need to determine which direction a variable will change. Take the given condition and magnify that condition to an extreme degree as a way of simplifying the direction of the system's response.
- Check your work. This means regularly testing your conclusions to see if they make sense. This does *not* mean repeating the same steps originally used to obtain the conclusion(s), but rather to use some other means to check validity. Simply repeating procedures often leads to *repeating the same errors* if any were made, which is why alternative paths are better.

Appendix B

Instructional philosophy

B.1 First principles of learning

- **Anyone can learn anything** given appropriate time, effort, resources, challenges, encouragement, and expectations. Dedicating time and investing effort are the student's responsibility; providing resources, challenges, and encouragement are the teacher's responsibility; high expectations are a responsibility shared by both student and teacher.

- **Transfer is not automatic.** The human mind has a natural tendency to compartmentalize information, which means the process of taking knowledge learned in one context and applying it to another usually does not come easy and therefore should never be taken for granted.

- **Learning is iterative.** The human mind rarely learns anything perfectly on the first attempt. Anticipate mistakes and plan for multiple tries to achieve full understanding, using the lessons of those mistakes as feedback to guide future attempts.

- **Information is absorbed, but understanding is created.** Facts and procedures may be memorized easily enough by repeated exposure, but the ability to reliably apply principles to novel scenarios only comes through intense personal effort. This effort is fundamentally creative in nature: casting new concepts in one's own words, running mental experiments to perceive patterns and trends, etc. These acts of making knowledge "one's own" need not be perfect in order to be effective, as the value lies in the activity and not necessarily the finished product. Depth of understanding and permanence of memory are both directly related to mental effort during the learning process – i.e. *easy learning is shallow and fleeting.*

- **Education trumps training.** There is no such thing as an entirely isolated subject, as all fields of knowledge are connected. Training is narrowly-focused and task-oriented. Education is broad-based and principle-oriented. When preparing for a life-long technical career, education beats training every time.

- **Character matters.** Poor habits are more destructive than deficits of knowledge or skill. This is especially true in collective endeavors, where a team's ability to function depends on trust between its members. Simply put, no one wants an untrustworthy person on their team. An essential component of education then, is character development.

- **People learn to be responsible by bearing responsibility.** An irresponsible person is someone who has never *had* to be responsible for anything that mattered enough to them. Just as anyone can learn anything, anyone can become responsible if the personal cost of irresponsibility becomes high enough.

- **What gets measured, gets done.** Accurate and relevant assessment of learning is key to ensuring all students learn. Therefore, it is imperative to measure what matters.

- **Failure is nothing to fear.** Every human being fails, and fails in multiple ways at multiple times. Eventual success only happens when we don't stop trying.

B.2 Proven strategies for instructors

- Assume every student is capable of learning anything they desire given the proper conditions. Treat them as capable adults by granting real responsibility and avoiding artificial incentives such as merit or demerit points.
- Create a consistent culture of high expectations across the entire program of study. Demonstrate and encourage patience, persistence, and a healthy sense of self-skepticism. Anticipate and de-stigmatize error. Teach respect for the capabilities of others as well as respect for one's own fallibility.
- Replace lecture with "inverted" instruction, where students first encounter new concepts through reading and then spend class time in Socratic dialogue with the instructor exploring those concepts and solving problems individually. There is a world of difference between observing someone solve a problem versus actually solving a problem yourself, and so the point of this form of instruction is to place students in a position where they *cannot* passively observe.
- Require students to read extensively, write about what they learn, and dialogue with you and their peers to sharpen their understanding. Apply Francis Bacon's advice that "reading maketh a full man; conference a ready man; and writing an exact man". These are complementary activities helping students expand their confidence and abilities.
- Use artificial intelligence (AI) to challenge student understanding rather than merely provide information. Find productive ways for AI to critique students' clarity of thought and of expression, for example by employing AI as a Socratic-style interlocutor or as a reviewer of students' journals. Properly applied, AI has the ability to expand student access to critical review well outside the bounds of their instructor's reach.
- Build frequent and rapid feedback into the learning process so that students know at all times how well they are learning, to identify problems early and fix them before they grow. Model the intellectual habit of self-assessing and self-correcting your own understanding (i.e. a cognitive *feedback loop*), encouraging students to do the same.
- Use "mastery" as the standard for every assessment, which means the exam or experiment or project must be done with 100% competence in order to pass. Provide students with multiple opportunity for re-tries (different versions of the assessment every time).
- Require students to devise their own hypotheses and procedures on all experiments, so that the process is truly a scientific one. Have students assess their proposed experimental procedures for risk and devise mitigations for those risks. Let nothing be pre-designed about students' experiments other than a stated task (i.e. what principle the experiment shall test) at the start and a set of demonstrable knowledge and skill objectives at the end.
- Have students build as much of their lab equipment as possible: building power sources, building test assemblies[1], and building complete working systems (no kits!). In order to provide

[1] In the program I teach, every student builds their own "Development Board" consisting of a metal chassis with DIN rail, terminal blocks, and an AC-DC power supply of their own making which functions as a portable lab environment they can use at school as well as take home.

this same "ground-up" experience for every new student, this means either previous students take their creations with them, or the systems get disassembled in preparation for the new students, or the systems grow and evolve with each new student group.

- Incorporate external accountability for you and for your students, continuously improving the curriculum and your instructional methods based on proven results. Have students regularly network with active professionals through participation in advisory committee meetings, service projects, tours, jobshadows, internships, etc. Practical suggestions include requiring students to design and build projects for external clients (e.g. community groups, businesses, different departments within the institution), and also requiring students attend all technical advisory committee meetings and to dialogue with the industry representatives at those meetings.
- Repeatedly explore difficult-to-learn concepts across multiple courses, so that students have multiple opportunities to build their understanding.
- Relate all new concepts, whenever possible, to previous concepts and to relevant physical laws. Challenge each and every student, every day, to *reason* from concept to concept and to explain the logical connections between. Challenge students to verify their conclusions by multiple approaches (e.g. double-checking their work using different methods). Ask *"Why?"* often.
- Maintain detailed records on each student's performance and share these records privately with them. These records should include academic performance as well as professionally relevant behavioral tendencies.
- Hold mandatory "check-in" meetings between all program faculty and each new student during their first term. Offer these to all other students as an option, except for any students continuing to manifest unprofessional behaviors, poor academic performance, or who have some other need for a face-to-face meeting with faculty.
- Address problems while they are small, before they grow larger. This is equally true for tutoring technical concepts as it is for helping students build professional habits.
- Build rigorous quality control into the curriculum to ensure every student masters every important concept, and that the mastery is retained over time. This includes (1) review questions added to every exam to re-assess knowledge taught in previous terms, (2) cumulative exams at the end of every term to re-assess all important concepts back to the very beginning of the program, and (3) review assessments in practical (hands-on) coursework to ensure critically-important skills were indeed taught and are still retained. What you will find by doing this is that it actually boosts retention of students by ensuring that important knowledge gets taught and is retained over long spans of time. In the absence of such quality control, student learning and retention tends to be spotty and this contributes to drop-out and failure rates later in their education.
- Finally, *never rush learning.* Education is not a race. Give your students ample time to digest complex ideas, as you continually remind yourself of just how long it took you to achieve mastery! Long-term retention and the consistently correct application of concepts are always the result of *focused effort over long periods of time* which means there are no shortcuts to learning.

B.3 Proven strategies for students

The single most important piece of advice I have for any student of any subject is to take responsibility for your own development in all areas of life including mental development. Expecting others in your life to entirely guide your own development is a recipe for disappointment. This is just as true for students enrolled in formal learning institutions as it is for auto-didacts pursuing learning entirely on their own. Learning to think in new ways is key to being able to gainfully use information, to make informed decisions about your life, and to best serve those you care about. With this in mind, I offer the following advice to students:

- **Approach all learning as valuable**. No matter what course you take, no matter who you learn from, no matter the subject, there is something useful in every learning experience. If you don't see the value of every new experience, you are not looking closely enough!
- **Continually challenge yourself**. Let other people take shortcuts and find easy answers to easy problems. The purpose of education is to stretch your mind, in order to shape it into a more powerful tool. This doesn't come by taking the path of least resistance. An excellent analogy for an empowering education is productive physical exercise: becoming stronger, more flexible, and more persistent only comes through intense personal effort.
- **Master the use of language**. This includes reading extensively, writing every day, listening closely, and speaking articulately. To a great extent language channels and empowers thought, so the better you are at wielding language the better you will be at grasping abstract concepts and articulating them not only for your benefit but for others as well.
- **Do not limit yourself to the resources given to you**. Read books that are not on the reading list. Run experiments that aren't assigned to you. Form study groups outside of class. Take an entrepreneurial approach to your own education, as though it were a business you were building for your future benefit.
- **Express and share what you learn**. Take every opportunity to teach what you have learned to others, as this will not only help them but will also strengthen your own understanding[2].
- Realize that **no one can give you understanding**, just as no one can give you physical fitness. These both must be *built*.
- **Above all, recognize that learning is hard work, and that a certain level of frustration is unavoidable**. There are times when you will struggle to grasp some of these concepts, and that struggle is a natural thing. Take heart that it will yield with persistent and varied[3] effort, and never give up! That concepts don't immediately come to you is not a sign of something wrong, but rather of something right: that you have found a worthy challenge!

[2] On a personal note, I was surprised to learn just how much my own understanding of electronics and related subjects was strengthened by becoming a teacher. When you are tasked every day with helping other people grasp complex topics, it catalyzes your own learning by giving you powerful incentives to study, to articulate your thoughts, and to reflect deeply on the process of learning.

[3] As the old saying goes, "Insanity is trying the same thing over and over again, expecting different results." If you find yourself stumped by something in the text, you should attempt a different approach. Alter the thought experiment, change the mathematical parameters, do whatever you can to see the problem in a slightly different light, and then the solution will often present itself more readily.

B.4 Design of these learning modules

"The unexamined circuit is not worth energizing" – Socrates (if he had taught electricity)

These learning modules, although useful for self-study, were designed to be used in a formal learning environment where a subject-matter expert challenges students to digest the content and exercise their critical thinking abilities in the answering of questions and in the construction and testing of working circuits. Every effort has been made to embed the following instructional and assessment philosophies within:

- The first goal of education is to enhance clear and independent thought, in order that every student reach their fullest potential in a highly complex and inter-dependent world. Robust reasoning is *always* more important than particulars of any subject matter, because its application is universal.
- Literacy is fundamental to independent learning and thought because text continues to be the most efficient way to communicate complex ideas over space and time. Those who cannot read with ease are limited in their ability to acquire knowledge and perspective.
- Articulate communication is fundamental to work that is complex and interdisciplinary.
- Faulty assumptions and poor reasoning are best corrected through challenge, not presentation. The rhetorical technique of *reductio ad absurdum* (disproving an assertion by exposing an absurdity) works well to discipline student's minds, not only to correct the problem at hand but also to learn how to detect and correct future errors.
- Important principles should be repeatedly explored and widely applied throughout a course of study, not only to reinforce their importance and help ensure their mastery, but also to showcase the interconnectedness and utility of knowledge.

These learning modules were expressly designed to be used in an "inverted" teaching environment[4] where students first read the introductory and tutorial chapters on their own, then individually attempt to answer the questions and construct working circuits according to the experiment and project guidelines. The instructor never lectures, but instead meets regularly with each individual student to review their progress, answer questions, identify misconceptions, and challenge the student to new depths of understanding through further questioning. Regular meetings between instructor and student should resemble a Socratic[5] dialogue, where questions serve as scalpels to dissect topics and expose assumptions. The student passes each module only after consistently demonstrating their ability to logically analyze and correctly apply all major concepts in each question or project/experiment. The instructor must be vigilant in probing each student's understanding to ensure they are truly *reasoning* and not just *memorizing*. This is why "Challenge" points appear throughout, as prompts for students to think deeper about topics and as starting points for instructor queries. Sometimes these challenge points require additional knowledge that hasn't been covered in the series to answer in full. This is okay, as the major purpose of the Challenges is to stimulate analysis and synthesis on the part of each student.

The instructor must possess enough mastery of the subject matter and awareness of students' reasoning to generate their own follow-up questions to practically any student response. Even completely correct answers given by the student should be challenged by the instructor for the purpose of having students practice articulating their thoughts and defending their reasoning. Conceptual errors committed by the student should be exposed and corrected not by direct instruction, but rather by reducing the errors to an absurdity[6] through well-chosen questions and thought experiments posed by the instructor. Becoming proficient at this style of instruction requires time and dedication, but the positive effects on critical thinking for both student and instructor are spectacular.

An inspection of these learning modules reveals certain unique characteristics. One of these is a bias toward thorough explanations in the tutorial chapters. Without a live instructor to explain concepts and applications to students, the text itself must fulfill this role. This philosophy results in lengthier explanations than what you might typically find in a textbook, each step of the reasoning process fully explained, including footnotes addressing common questions and concerns students raise while learning these concepts. Each tutorial seeks to not only explain each major concept in sufficient detail, but also to explain the logic of each concept and how each may be developed

[4] In a traditional teaching environment, students first encounter new information via *lecture* from an expert, and then independently apply that information via *homework*. In an "inverted" course of study, students first encounter new information via *homework*, and then independently apply that information under the scrutiny of an expert. The expert's role in lecture is to simply *explain*, but the expert's role in an inverted session is to *challenge*, *critique*, and if necessary *explain* where gaps in understanding still exist.

[5] Socrates is a figure in ancient Greek philosophy famous for his unflinching style of questioning. Although he authored no texts, he appears as a character in Plato's many writings. The essence of Socratic philosophy is to leave no question unexamined and no point of view unchallenged. While purists may argue a topic such as electric circuits is too narrow for a true Socratic-style dialogue, I would argue that the essential thought processes involved with scientific reasoning on *any* topic are not far removed from the Socratic ideal, and that students of electricity and electronics would do very well to challenge assumptions, pose thought experiments, identify fallacies, and otherwise employ the arsenal of critical thinking skills modeled by Socrates.

[6] This rhetorical technique is known by the Latin phrase *reductio ad absurdum*. The concept is to expose errors by counter-example, since only one solid counter-example is necessary to disprove a universal claim. As an example of this, consider the common misconception among beginning students of electricity that voltage cannot exist without current. One way to apply *reductio ad absurdum* to this statement is to ask how much current passes through a fully-charged battery connected to nothing (i.e. a clear example of voltage existing without current).

from "first principles". Again, this reflects the goal of developing clear and independent thought in students' minds, by showing how clear and logical thought was used to forge each concept. Students benefit from witnessing a model of clear thinking in action, and these tutorials strive to be just that.

Another feature of these learning modules is that they do not treat topics in isolation. Rather, important concepts are introduced early in the series, and appear repeatedly as stepping-stones toward other concepts in subsequent modules. This helps to avoid the "compartmentalization" of knowledge, demonstrating the inter-connectedness of concepts and simultaneously reinforcing them. Each module is fairly complete in itself, reserving the beginning of its tutorial to a review of foundational concepts.

To high standards of education,

Tony R. Kuphaldt

Appendix C

Tools used

I am indebted to the developers of many open-source software applications in the creation of these learning modules. The following is a list of these applications with some commentary on each.

You will notice a theme common to many of these applications: a bias toward *code*. Although I am by no means an expert programmer in any computer language, I understand and appreciate the flexibility offered by code-based applications where the user (you) enters commands into a plain ASCII text file, which the software then reads and processes to create the final output. Code-based computer applications are by their very nature *extensible*, while WYSIWYG (What You See Is What You Get) applications are generally limited to whatever user interface the developer makes for you.

The `GNU/Linux` computer operating system

> There is so much to be said about Linus Torvalds' `Linux` and Richard Stallman's `GNU` project. First, to credit just these two individuals is to fail to do justice to the *mob* of passionate volunteers who contributed to make this amazing software a reality. I first learned of `Linux` back in 1996, and have been using this operating system on my personal computers almost exclusively since then. It is *free*, it is completely *configurable*, and it permits the continued use of highly efficient `Unix` applications and scripting languages (e.g. shell scripts, Makefiles, `sed`, `awk`) developed over many decades. `Linux` not only provided me with a powerful computing platform, but its open design served to inspire my life's work of creating open-source educational resources.

Bram Moolenaar's `Vim` text editor

> Writing code for any code-based computer application requires a *text editor*, which may be thought of as a word processor strictly limited to outputting plain-ASCII text files. Many good text editors exist, and one's choice of text editor seems to be a deeply personal matter within the programming world. I prefer `Vim` because it operates very similarly to `vi` which is ubiquitous on `Unix`/`Linux` operating systems, and because it may be entirely operated via keyboard (i.e. no mouse required) which makes it fast to use.

Donald Knuth's TEX typesetting system

Developed in the late 1970's and early 1980's by computer scientist extraordinaire Donald Knuth to typeset his multi-volume magnum opus *The Art of Computer Programming*, this software allows the production of formatted text for screen-viewing or paper printing, all by writing plain-text code to describe how the formatted text is supposed to appear. TEX is not just a markup language for documents, but it is also a Turing-complete programming language in and of itself, allowing useful algorithms to be created to control the production of documents. Simply put, TEX *is a programmer's approach to word processing*. Since TEX is controlled by code written in a plain-text file, this means anyone may read that plain-text file to see exactly how the document was created. This openness afforded by the code-based nature of TEX makes it relatively easy to learn how other people have created their own TEX documents. By contrast, examining a beautiful document created in a conventional WYSIWYG word processor such as Microsoft `Word` suggests nothing to the reader about *how* that document was created, or what the user might do to create something similar. As Mr. Knuth himself once quipped, conventional word processing applications should be called WYSIAYG (What You See Is *All* You Get).

Leslie Lamport's LATEX extensions to TEX

Like all true programming languages, TEX is inherently extensible. So, years after the release of TEX to the public, Leslie Lamport decided to create a massive extension allowing easier compilation of book-length documents. The result was LATEX, which is the markup language used to create all ModEL module documents. You could say that TEX is to LATEX as `C` is to `C++`. This means it is permissible to use any and all TEX commands within LATEX source code, and it all still works. Some of the features offered by LATEX that would be challenging to implement in TEX include automatic index and table-of-content creation.

Tim Edwards' `Xcircuit` drafting program

This wonderful program is what I use to create all the schematic diagrams and illustrations (but not photographic images or mathematical plots) throughout the ModEL project. It natively outputs PostScript format which is a true vector graphic format (this is why the images do not pixellate when you zoom in for a closer view), and it is so simple to use that I have never had to read the manual! Object libraries are easy to create for `Xcircuit`, being plain-text files using PostScript programming conventions. Over the years I have collected a large set of object libraries useful for drawing electrical and electronic schematics, pictorial diagrams, and other technical illustrations.

`Gimp` graphic image manipulation program

Essentially an open-source clone of Adobe's `PhotoShop`, I use `Gimp` to resize, crop, and convert file formats for all of the photographic images appearing in the ModEL modules. Although `Gimp` does offer its own scripting language (called `Script-Fu`), I have never had occasion to use it. Thus, my utilization of `Gimp` to merely crop, resize, and convert graphic images is akin to using a sword to slice bread.

`SPICE` circuit simulation program

`SPICE` is to circuit analysis as TEX is to document creation: it is a form of markup language designed to describe a certain object to be processed in plain-ASCII text. When the plain-text "source file" is compiled by the software, it outputs the final result. More modern circuit analysis tools certainly exist, but I prefer `SPICE` for the following reasons: it is *free*, it is *fast*, it is *reliable*, and it is a fantastic tool for *teaching* students of electricity and electronics how to write simple code. I happen to use rather old versions of `SPICE`, version 2g6 being my "go to" application when I only require text-based output. `NGSPICE` (version 26), which is based on Berkeley `SPICE` version 3f5, is used when I require graphical output for such things as time-domain waveforms and Bode plots. In all `SPICE` example netlists I strive to use coding conventions compatible with all `SPICE` versions.

Andrew D. Hwang's `ePiX` mathematical visualization programming library

This amazing project is a `C++` library you may link to any `C/C++` code for the purpose of generating PostScript graphic images of mathematical functions. As a completely free and open-source project, it does all the plotting I would otherwise use a Computer Algebra System (CAS) such as `Mathematica` or `Maple` to do. It should be said that `ePiX` is *not* a Computer Algebra System like `Mathematica` or `Maple`, but merely a mathematical *visualization* tool. In other words, it won't determine integrals for you (you'll have to implement that in your own `C/C++` code!), but it can graph the results, and it does so beautifully. What I really admire about `ePiX` is that it is a `C++` programming library, which means it builds on the existing power and toolset available with that programming language. Mr. Hwang could have probably developed his own stand-alone application for mathematical plotting, but by creating a `C++` library to do the same thing he accomplished something much greater.

`gnuplot` mathematical visualization software

Another open-source tool for mathematical visualization is `gnuplot`. Interestingly, this tool is *not* part of Richard Stallman's GNU project, its name being a coincidence. For this reason the authors prefer "gnu" *not* be capitalized at all to avoid confusion. This is a much "lighter-weight" alternative to a spreadsheet for plotting tabular data, and the fact that it easily outputs directly to an X11 console or a file in a number of different graphical formats (including PostScript) is very helpful. I typically set my `gnuplot` output format to default (X11 on my Linux PC) for quick viewing while I'm developing a visualization, then switch to PostScript file export once the visual is ready to include in the document(s) I'm writing. As with my use of `Gimp` to do rudimentary image editing, my use of `gnuplot` only scratches the surface of its capabilities, but the important points are that it's *free* and that it *works well*.

`Python` programming language

Both Python and C++ find extensive use in these modules as instructional aids and exercises, but I'm listing Python here as a *tool* for myself because I use it almost daily as a *calculator*. If you open a Python interpreter console and type `from math import *` you can type mathematical expressions and have it return results just as you would on a hand calculator. Complex-number (i.e. *phasor*) arithmetic is similarly supported if you include the complex-math library (`from cmath import *`). Examples of this are shown in the Programming References chapter (if included) in each module. Of course, being a fully-featured programming language, Python also supports conditionals, loops, and other structures useful for calculation of quantities. Also, running in a console environment where all entries and returned values show as text in a chronologically-ordered list makes it easy to copy-and-paste those calculations to document exactly how they were performed.

Appendix D

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Appendix E

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Appendix F

Version history

This is a list showing all significant additions, corrections, and other edits made to this learning module. Each entry is referenced by calendar date in reverse chronological order (newest version first), which appears on the front cover of every learning module for easy reference. Any contributors to this open-source document are listed here as well.

21 August 2026 – significant edits to the "Fiber optic connectors and routing" section of the Tutorial, updating it to reflect current state of the art (especially fusion-splicing as a termination technique).

20 February 2025 – minor edits to the Tutorial, including new comments on bandwidth-length ratings for fiber.

25 September 2024 – added comments about advantages of multi-mode optical fiber.

19 September 2024 – divided the Introduction chapter into sections, one with recommendations for students, one with a listing of challenging concepts, and one with recommendations for instructors.

22 February 2024 – minor edits made to image_4310 and image_4311 and image_4318.

1 January 2024 – modified the "Power concentration" Quantitative Reasoning question to be one using Python programming to calculate the same thing.

29 November 2022 – placed questions at the top of the itemized list in the Introduction chapter prompting students to devise experiments related to the tutorial content.

10 May 2021 – commented out or deleted empty chapters.

29 April 2021 – minor edit to image_4310, as well as minor edits to the Tutorial.

10 December 2020 – added "irradiance" to the "Power concentration" question.

7 December 2020 – significantly edited the Introduction chapter to make it more suitable as a pre-study guide and to provide cues useful to instructors leading "inverted" teaching sessions.

14 August 2020 – added content to Tutorial and Question chapters.

12 August 2020 – document first created.

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