Physical Layer Cabling: Fiber-Optic

- Fiber-Optic Basics
- The EM Spectrum: Physics and Math
- Attenuation and Dispersion in Fiber
- Fiber-Optic Hardware
- Networking over Fiber-Optic
- Safety with Fiber

Fiber-Optic Basics

- Fiber-optic cabling is becoming more common for providing high-speed network cabling – displacing copper, in many places
- In particular, it is useful for supporting faster variants of Ethernet, such as 10 Gigabit and higher.
- Requirements are defined in the TIA/EIA 568-B.3 standards.
- A fiber-optic network features four components (*Figure 3.1*):
    1. ***Fibers*** (within cables) that carry data as (modulated) light beams
    2. A light ***source*** that places data/signal onto the beam
    3. A light ***detector*** that converts the (optical) signal back to electrical
    4. Optical ***connectors*** linking the cable to the source and detector

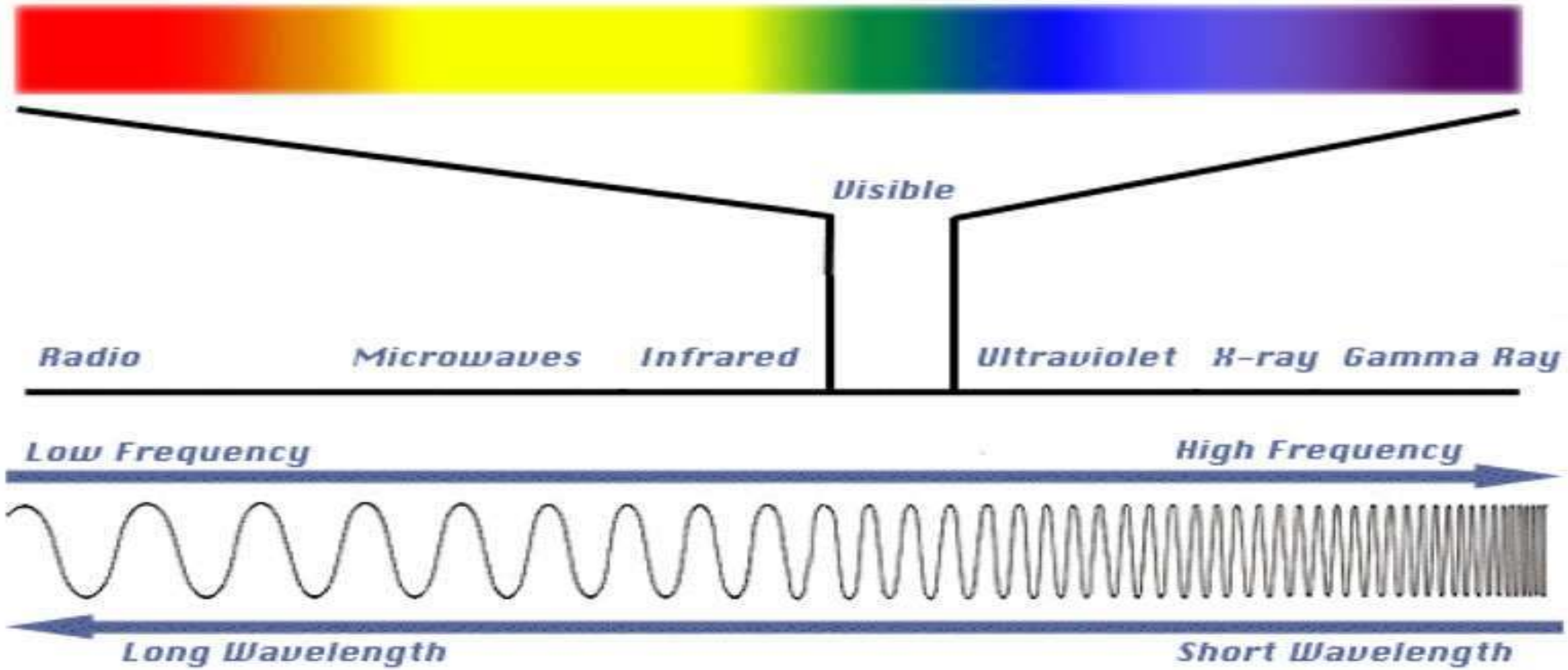
Fiber-Optic Basics

- As compared to copper, fiber-optic cabling features many substantial advantages:
  - Most notably, the bandwidth is much higher – allowing for speeds well over 10 Gbps, when using laser light sources.
  - Also, fiber-optic cabling reduces or eliminates much of the signal issues of copper – electrical noise, crosstalk, and attenuation.
  - In addition, there are several practical advantages outside of speed and signal:
    - Reduced costs of fiber-optic cabling
    - Elimination of electrical hazards
    - No vulnerability to corrosion
    - Very difficult to tap or intercept

The Science Behind It...

- The behavior of fiber optic cabling is based upon the transmission of ***electromagnetic radiation (EMR)***:
  - What is EMR?
  - What are some technologies that make use of it?
    - Radios
    - Microwave Ovens
    - X-Ray machines
- You will hear the term "light" used much more generally to refer to EMR – versus our more common definition of *visible* light.
- These varieties of EMR are all located on the ***electromagnetic spectrum***.

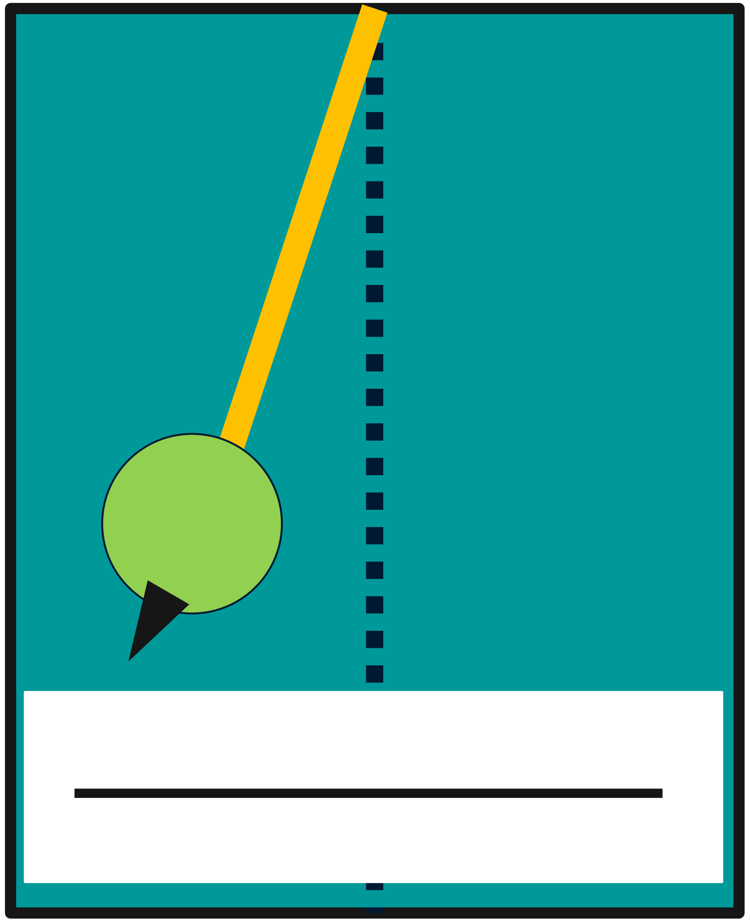
The EM Spectrum



Video: https://www.youtube.com/watch?v=cfXzwh3KadE

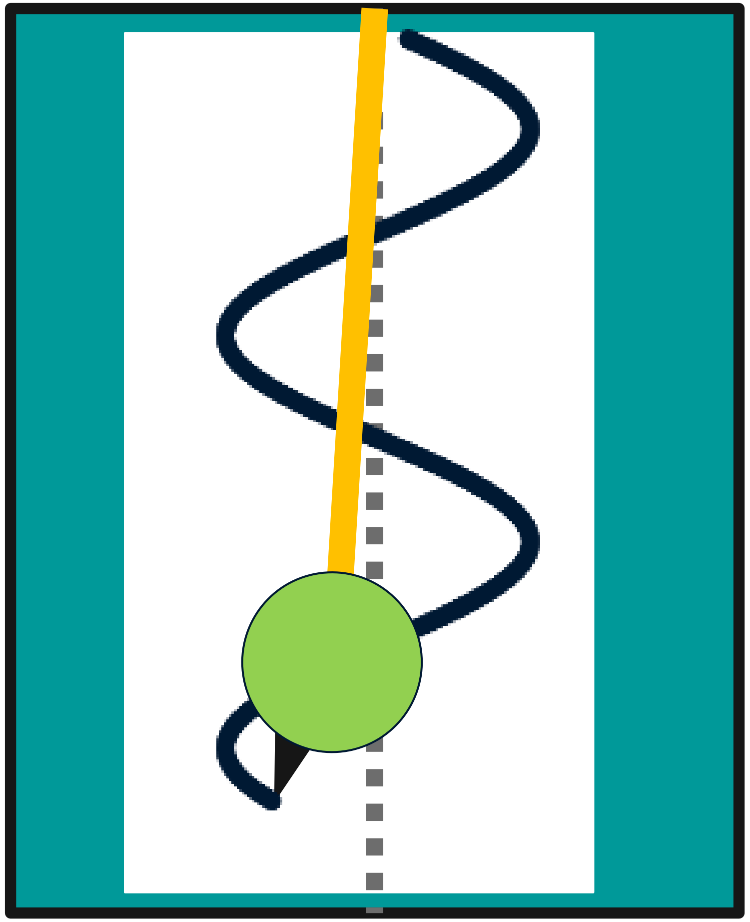
The EM Spectrum

- EMR is generally conceptualized as ***waves*** – cyclic variations about a "center", in which energy is transferred. (In this case, the energy comes from various forms of EM activity.)
- To envision this, imagine a ***pendulum*** swinging to and fro…
  - With a *pencil lead* at the lowest point
  - In constant contact with *paper*
- If the paper is *stationary*, all the marks will remain within a single, one-dimensional space.



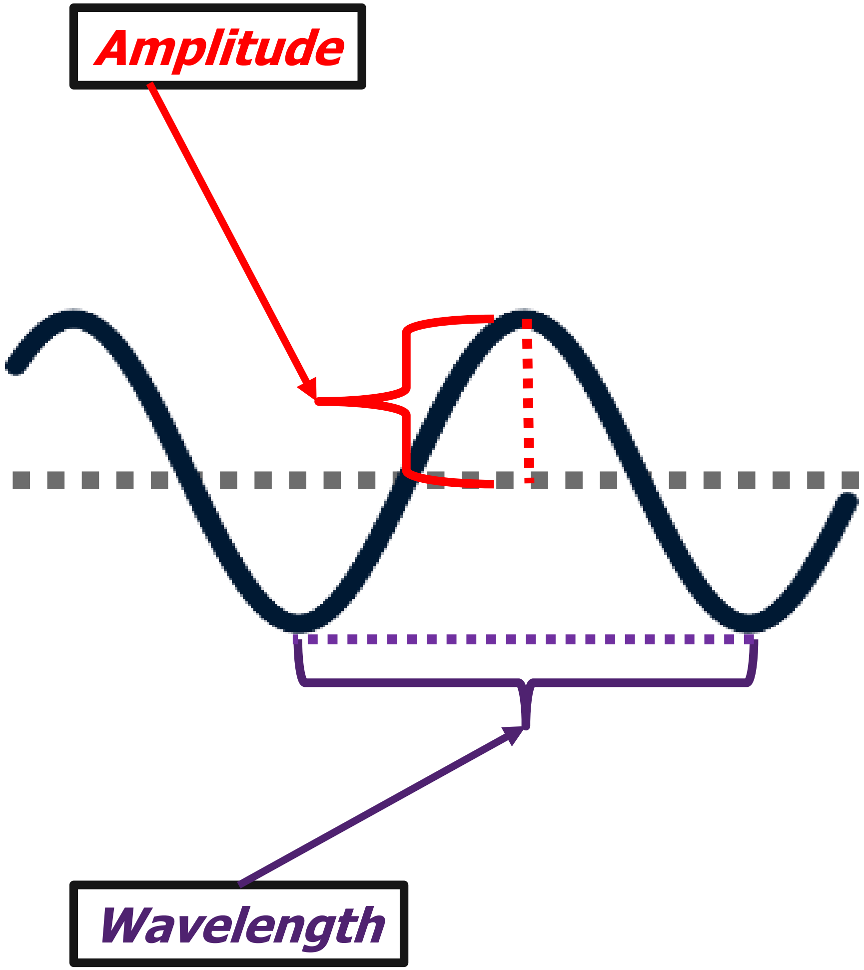
The EM Spectrum

- However, if the paper – here being of indefinite length – is moving...
  - in one direction
  - at a constant speed
  - perpendicular to the pendulum's plane of motion
- ...then you will see a graph of the pendulum's position, relative to the center, *over time*
- In other words, a ***wave***



The EM Spectrum

- A wave – of EM radiation or another type – will feature a number of properties:
  - ***Amplitude* (A):** The height of a wave, from the center. **Unit:** ***meters***.
  - ***Wavelength* (λ):** The distance between two analogous points on the wave graph. **Unit:** ***meters***.
  - ***Frequency* (f):** The number of waves passing a given point during a given time. **Unit:** ***Hertz*** or ***s^{-1}***
  - ***Wave speed* (v):** wavelength multiplied by frequency. **Unit:** ***$m*s^{-1}$*** or ***m/s***



The EM Spectrum

- We will encounter rather large and small numbers, that would normally have a lot of zeros.
- This would quickly become confusing, so we use a method called ***scientific notation*** to simplify this problem.
  - 300000000 = **$3x10^8$**
  - .00000000000000000000000602 = **$6.02*10^{-23}$**
  - In computing context, these may be expressed as **3e8** and **6.02e-23**, respectively
  - We have *prefixes* for the different exponents of 10…

MULTIPLICATION FACTOR	PREFIX	SYMBOL
1 000 000 000 000 000 000 = 10^{18}	exa	E
1 000 000 000 000 000 = 10^{15}	peta	P
1 000 000 000 000 = 10^{12}	tera	T
1 000 000 000 = 10^{9}	giga	G
1 000 000 = 10^{6}	mega	M
1 000 = 10^{3}	kilo	k
100 = 10^{2}	hecto	h
10 = 10^{1}	deka	da
0.1 = 10^{-1}	deci	d
0.01 = 10^{-2}	centi	c
0.001 = 10^{-3}	milli	m
0.000 001 = 10^{-6}	micro	m
0.000 000 001 = 10^{-9}	nano	n
0.000 000 000 001 = 10^{-12}	pico	p
0.000 000 000 000 001 = 10^{-15}	femto	f
0.000 000 000 000 000 001 = 10^{-18}	atto	a

The EM Spectrum

- In a vacuum, light (i.e., electromagnetic radiation) travels at a speed of 3×10^8 m/s (or $\mathbf{m*s^{-1}}$).
- **Recall:** v = f * λ. Therefore, if you know a signal's frequency, then you can calculate its ***wavelength*** by dividing the ***speed of light*** **(c)** by the ***frequency***. **λ = c / f**
- Consider WBZ, a Boston radio station broadcasting at a frequency of 1030 kHz – or 1.03 Mhz:

$$\lambda = \frac{3.00 \times 10^8 \ m*s^{-1}}{1.03 \times 10^6 \ s^{-1}}$$

→

$$\lambda = \frac{3.00 \times 10^{\not 8 \, 2} \ m*\not s^{-1}}{1.03 \times 10^{\not 6} \ \not s^{-1}}$$

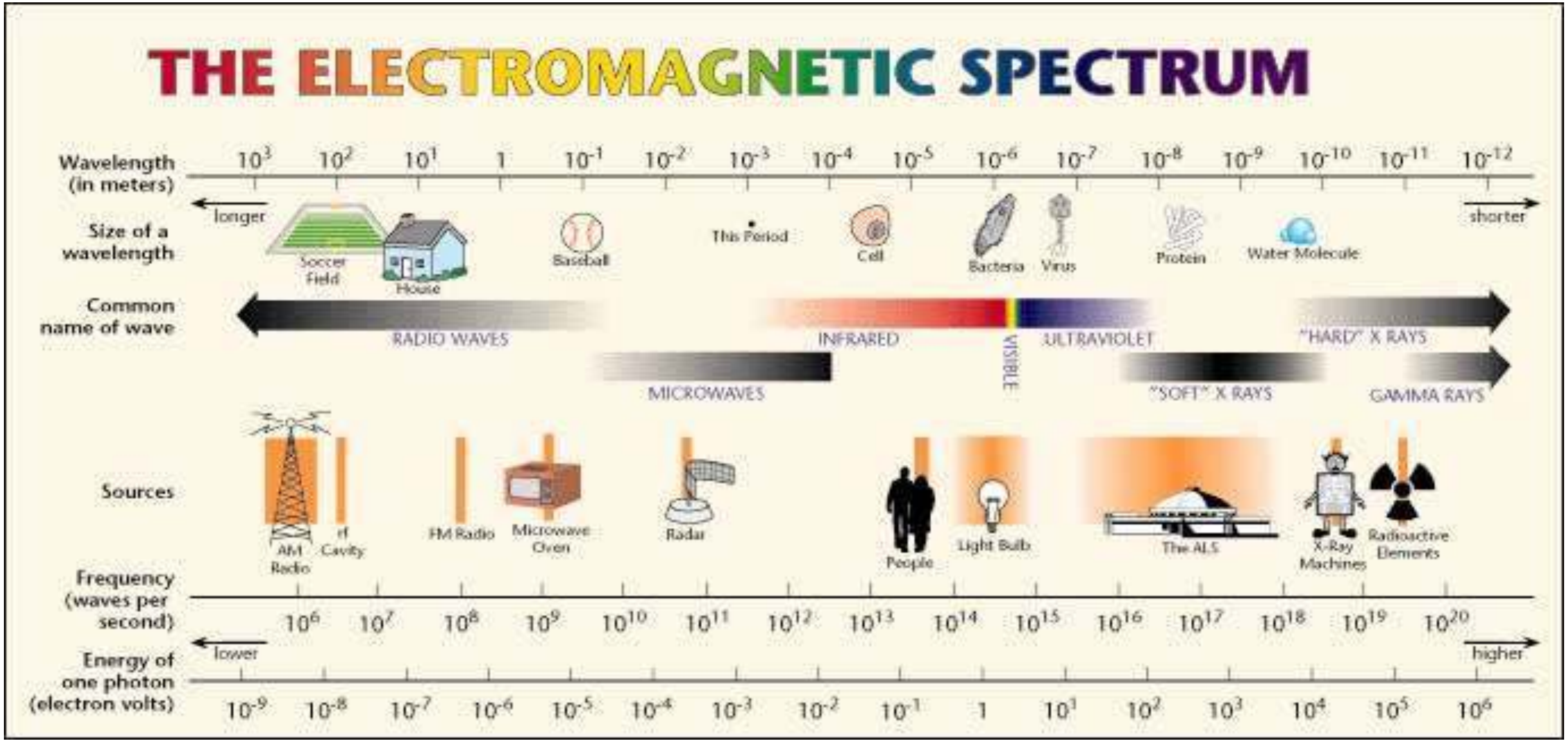
The EM Spectrum

$$\lambda = \frac{3.00 \times 10^{8} \, m \cdot s^{-1}}{1.03 \times 10^{6} \, s^{-1}} \rightarrow \lambda = \frac{3.00 \times 10^{2} \, m}{1.03} \rightarrow \lambda \approx 2.91 \times 10^{2} \, m$$

(In the first fraction, the exponents 8 and 6 are struck through and replaced by 2, and both s^{-1} units are struck through.)

- In doing this, it is important to keep track of your units, including which ones combine or cancel out in the arithmetic.
- Understanding these concepts will be helpful not only for this chapter but also for subsequent chapters, such as wireless networking, which also uses EMR

The EM Spectrum



Nature of Light - *Refraction*

- The aforementioned speed of light **(3×10^8 m/s)** is within a vacuum. However, within a medium, that speed may be reduced.
- When light passes from one physical medium into another – different densities -- its speed can change, causing it to bend. This bending is called **refraction**.
  - You can see this in the textbook in *Figure 3-2*.
  - At the very least, you get an angle off (**part a**). Imagine looking at a pencil in a glass of water, where the pencil will appear "cut".
  - When the light is composed of different frequencies, you may get a *prism* effect (**part b**), as the frequencies experience different levels of change in speed/direction.

Nature of Light - *Refraction*

- Each of the two materials will have a **`refractive index`** **`(n)`** that indicates how much the light bends
  - It is calculated as a ratio of light speed in a vacuum to its speed through the material
  - A higher **n** value indicates that light is slowed down more when passing through the material.
- With *visible light*, in particular, it is often easier to speak of wavelength (in ***nm***) rather than frequency because the numbers for the former are smaller.
- Wavelengths 680nm and above are considered part of the **`optical spectrum`**.

Nature of Light - *Reflection*

- **Reflection** is what happens when light strikes a boundary and bounces back – rather than penetrating or being absorbed.
- First, we should realize that light is always passing through some medium: a vacuum, air, water, glass, etc.
- Each medium has a refractive index.
  - A vacuum, trivially, has an index of 1.000
  - Gases tend to be slightly higher, less than or equal to 1.001
  - Water is at 1.330
  - Solids have even higher refractive indices, such as diamond at 2.419 and the element Germanium (Ge) at over 4.000

Nature of Light - Reflection

- These values, of course, are based upon the media *at particular temperatures*.
  - *Still, the temperature-based variations are rather small, so they would mostly matter in situations where precision is key.*
- But…how does this pertain to *reflection*?
- Reflection is caused by light passing…
  - **from** a medium with a *greater* refractive index …
  - **to** one with a *lower* index.

Nature of Light - *Reflection*

- The reflection can be *partial* – with the rest of the light being refracted or absorbed – or *total*.
  - This is affected by the angle at which the light wave hits the interface between the two media.
  - Within a certain range of angles, the wave will experience ***total internal reflection*** (TIR) – where the wave, as the name implies, will not penetrate the medium at all but, rather, be completely reflected.
  - **Video:** https://www.youtube.com/watch?v=2kBOqfS0nmE
  - This is how light-based signals propagate through a fiber-optic cable – by continuous TIR.

Optical Anatomy

- In some ways, the construction of fiber-optic cables is considerably simpler than that of twisted-pair.
- A basic cable will consist of three layers:
  - **Core:** Carries the light down the cable
  - **Cladding:** Surrounds the core and has a lower refractive index so that the transmitted light will be continuously reflected inside and through the core.
  - **Jacket:** A protective coating of plastic
- Aside from these basics, optic fiber may vary in thickness, material, and modes (of signal propagation).

Optical Anatomy

- One important factor for any kind of fiber is its **numerical aperture**, the ability to accept light and have the signal fully propagate.
  - A cable will have a range of directions – an acceptance cone – from which it can accept light and still experience TIR.
  - The cone will make an angle, and the numerical aperture is calculated based on that cone.
  - Similarly, if you know this value, then you can determine the range of the cone.

Optical Anatomy

- Optical fibers can be differentiated by their *mode* of propagation, which concerns paths light can take through the fiber – i.e., frequency of bounces.
  - **Multi-mode fiber** allows for light to take more than one path through the fiber from start to end.
    - This can lead to **pulse dispersion**, where the signal stretches due to different paths through the cable. This can weaken the signal over longer distances
    - Multi-mode fiber has two varieties:
      - **Step-Index** (Figure 3-6): The modes are discretely separated.
      - **Graded-Index** (Figure 3-7): The variation in refractive index is more gradual, leading to greater preservation of the pulse.

Optical Anatomy

- **Single-mode**: The light follows a single path. Cores are much narrower, as compared to multi-mode.
  - These cables are useful in ***long haul*** applications – transmission of data over extremely long distances.
  - Specifications for single-mode cables will often give the ***mode field diameter***.
- Figure 3-8 shows comparisons in terms of core sizes, light paths, and light pulse preservation.

- Fiber optics systems tend to use light with wavelengths in the range of 850 to 1550 nm, depending on the type of cable.
  - However, longer wavelengths may be explored for single-mode fiber.
  - What type of waves are these?

Distance-Limiting Parameters

- Although fiber-optic cables are capable of providing higher bandwidths over longer distances (as compared to copper twisted-pair), they too have their limitations.
- Signal travels in the form of light pulses, with some distance limits imposed by attenuation and dispersion.
- **Attenuation** is the loss of signal strength as the light propagates over a distance, as a result of four factors:
  1. Most loss is from **scattering** due to slight changes in refractive index – similar to air molecules scattering sunlight, making the sky appear blue.
  2. Signal is also lost to **absorption**, where some of the light interacts with the fiber (at an atomic level) and is converted to heat

Distance-Limiting Parameters

3. **Macrobending** refers to larger-scale (i.e., relative to fiber diameter) bends in the fiber that cause light to penetrate the cladding.
4. **Microbending** loss is from tiny deformations in the fiber caused by physical stress.

- It is typically measured in terms of *decibels per kilometer* (dB/km).
- **Dispersion** – or **pulse broadening** – is when a light pulse widens during transmission, causing possible bit errors (Figure 3-10)
  - Three types of dispersion are distinguished by their causes…
    1. In ***modal dispersion***, a pulse broadens on account of different paths taken by different modes – such that they do not all arrive at the same time.

Distance-Limiting Parameters

3. ***Chromatic dispersion*** occurs because of the velocities of the different frequencies in a light pulse.
4. Finally, light pulses have horizontal and vertical polarizations, where differing velocities for each can lead to ***polarization mode dispersion***.

- A cable with have a **zero-dispersion wavelength** – dependent on refractive index – where there is zero dispersion.
- Shifts in this figure can help to compensate for dispersion, along with technologies such as…
  - **Dispersion compensating fiber**
  - **Fiber Bragg grating**

Optical Hardware

- To recap, the four main piece of fiber optic hardware are: light sources, light detectors, the intermediate components (i.e., fiber), and connections.
- To begin with, the electrical signals must be converted into light pulses by either of two types of ***sources***:
  1. **Diode Laser (DL)**: Can send data more quickly and put more signal power into a thinner fiber, more efficiently than LED. However, it also more expensive than LED and requires more complex circuitry.

Optical Hardware

2. **Light-Emitting Diode (LED):** These are not as fast or powerful as DL, but they are cheaper and easier to maintain. Their wider wavelengths mean that they are more susceptible to problems like dispersion.

- In addition, there are other forms of lasers used:
  - **Distributed feedback (DFB) lasers**, which are used in in **dense wavelength division multiplex (DWDM)** systems
  - **Vertical cavity surface emitting lasers (VCSELs)**
  - **Tunable lasers**, whose emission wavelength can be altered

Optical Hardware

- Light detectors are responsible for converting the received light pulses back into electronic signals – i.e., bits
- Detectors can be characterized by:
    - Responsivity: Current put out for light received
    - Response speed: Potential data output rate of the detector
    - Spectral response: Actual responsivity relative to specified, for a particular wavelength.
- For these two to communicate, we need intermediates to link them…

Optical Hardware

- The primary form of intermediate hardware (i.e., channels of signal transmission) is the fiber-optic strand, often called…
  - **Fiber**
  - **Light pipe**
  - **Glass**
- Beyond this, there are other – more specialized – forms of intermediate hardware:
  - **Isolators**, which keep the optical power flowing in a single direction
  - **Attenuators**, which reduce signal into a receiver
  - Other devices for splitting or altering signal

Optical Hardware

- For effective signal transmission, fibers must be properly aligned with sources and detectors.
- Various alignment problems (Figure 3-13) may result in signal loss. Much of this can be achieved through effective joining:
  - Splicing is joining two fibers together, by one of two methods:
    1. **Fusion splicing**: A more permanent physical fusing/welding of the two. Video: https://youtu.be/DIiBVuuRUtM?t=175
    2. **Mechanical splicing**: Here, the splices leaves an air gap between the two fiber ends, which is filled with an **index-matching gel**

Optical Hardware

- Just as copper twisted-pair cables have (typically) RJ-45 ***connectors***, there are also several for fiber-optic cables.
- Some of the more common ones are SC, ST, FC, LC, and MT-RJ – which you can see in Figure 3-14
- Several concerns factor into connector choice
  - Ease of installation
  - Insertion loss and return loss
  - Repeatability
  - Cost
- Fiber-optic cable termination:
  https://www.youtube.com/watch?v=rKWLCVgkNtM

Optical Networking

- As networking needs increase – so do demands for transmission bandwidth, creating scenarios that fiber-optic networking is well positioned to address:
  - Fiber expense (relative to copper) is diminishing
  - Fiber offers higher bandwidth and security – and over longer distances than copper
- Fiber-optic network types
  - **SONET/SDH**
  - **Optical Ethernet**

Optical Networking

- For many years, the SONET (**s**ynchronous **o**ptical **net**work) and SDH (**s**ynchronous **d**igital **h**ierarchy) were key in long-haul optical networking, offering…
  - Increase in network reliability
  - Network management
  - Defining methods for synchronous multiplexing of digital signals
  - Defining a set of generic operating/equipment standards
  - Flexible architecture

<u>Optical Networking</u>

- SONET/SDH defines a <u>*hierarchy*</u> of data rates:

Signal	Bit Rate	Capacity
OC-1 (STS-1)	51.840Mbps	28DS-Is or 1 DS-3
OC-3 (STS-3)	155.52Mbps	84DS-Is or 3 DS-3s
OC-12 (STS-12)	622.080Mbps	336 DS-1s or 12 DS-3s
OC-48 (STS-48)	2.48832Gbps	1344 DS-1s or 48 DS-3s
OC-192 (STS-192)	9.95328Gbps	5376 DS-Is or 192 DS-3s

- Acronyms:
  - **OC – optical carrier**
  - **STS – synchronous transport signals**
  - **DS – digital signal (**1 → 1.544 Mbps**,** 3 → 44.736 Mbps**)**

Optical Networking

- Optical Ethernet has several numerics, similar to those given for twisted pair
  - In the case of fiber-optic, we assume distances of up to **2 km** (for multimode fiber) or **10 km** (for single mode)
  - Examples include:
    - ***10BASE-F*** : 10 Mbps over fiber (generic specification)
    - ***100BASE-FX*** : 100 Mbps over two strands of fiber
    - ***1000BASE-LX/SX*** : Gigabit with long-/short-wavelength transmitters
    - ***10GBASE-R/W*** : 10 Gigabit for LANs and WANs
- Converters will be required.

Optical Networking

- Distribution in a fiber network will involve a number of considerations:
  - ***Lines:*** At least two fibers, Tx and Rx, for full-duplex operation
  - ***Cross-connects:***
    - Joining fibers, often through mechanical splicing
    - Converters, for moving between optic and electrical signals
  - ***Fiber Maps:***
    - ***Logical:*** A model of the network's structure, with links and levels
    - ***Physical:*** Fiber routes, within the concrete environmental context

Safety

- Working with fiber optic cables may entail some hazards beyond those of twisted-pair, so be careful…
  - One primary danger is getting light in your eyes
    - Even more so because fiber is transmitting wavelengths the eye cannot see
    - Never look into a cable's end!
  - Also be wary of mechanical hazards, such as brittle ends of fiber.
- Safety glasses are a must!