Radio Physics

Training materials for wireless trainers

The Abdus Salam
International Centre
for Theoretical Physics

United Nations
Educational, Scientific and
Cultural Organization

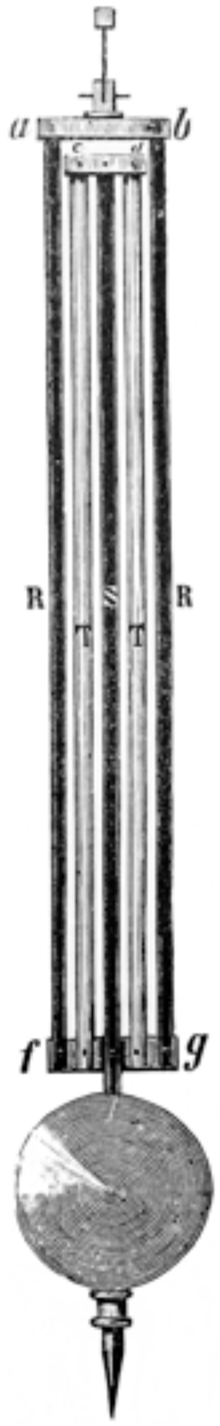
This talk covers the essential properties of electromagnetic waves and basics of radio propagation.
It is intended to be the first lecture and it has a duration of 60 minutes approx.

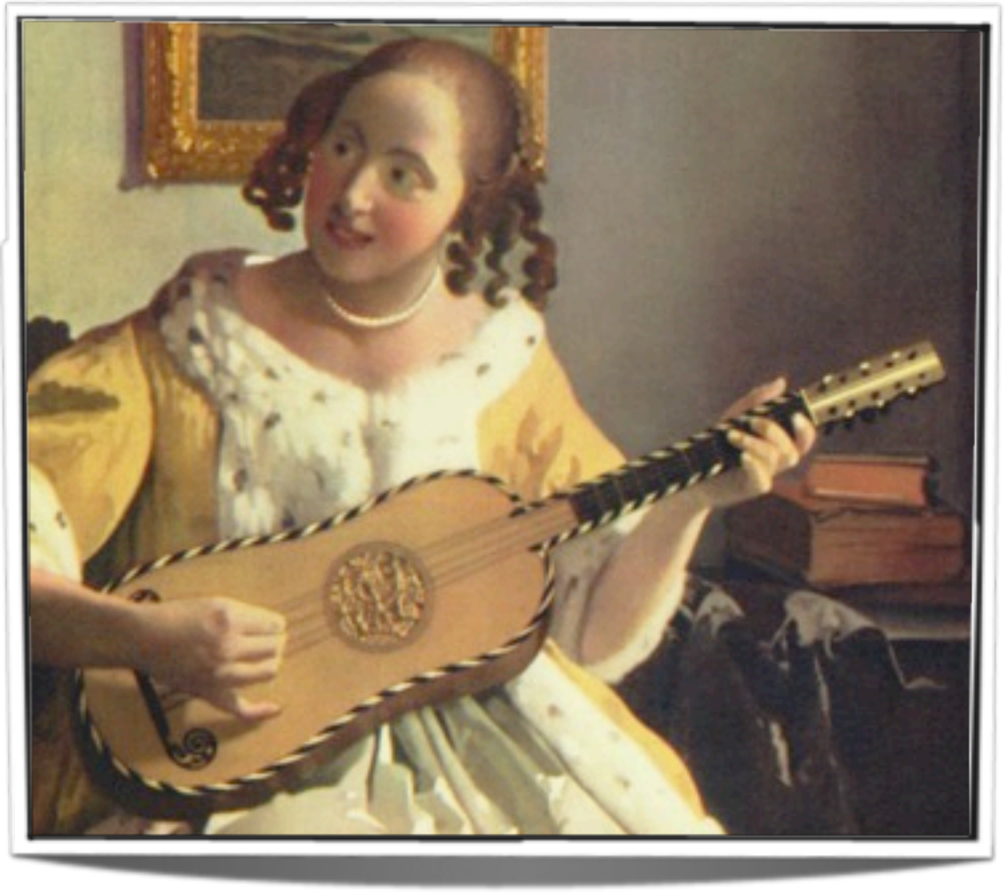
Version 4.5 by Rob, @2009-11-17
Version 4.6 by Rob, @2010-02-24
Version 4.7 by Rob, @2010-03-12

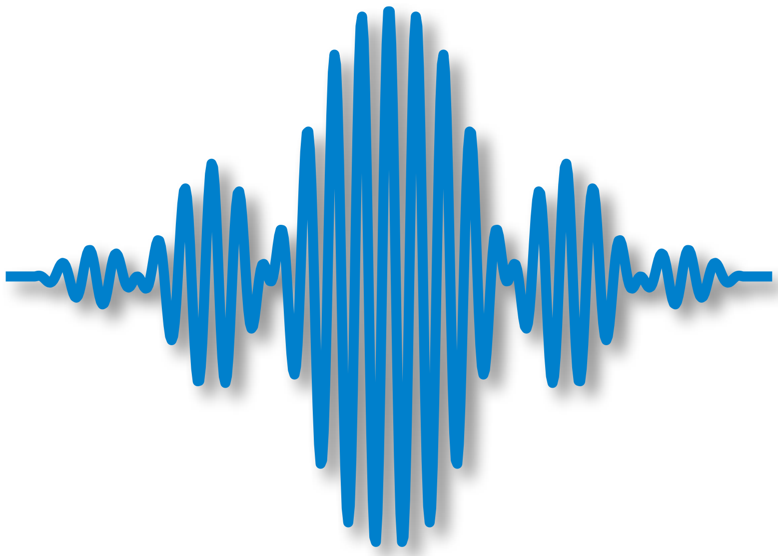
Goals

- to introduce the fundamental concepts related to electromagnetic waves (frequency, amplitude, speed, wavelength, polarization, phase)
- to show where WiFi is placed, within the broader range of frequencies used in telecommunications
- to give an understanding of behavior of radio waves as they move through space (absorption, reflection, diffraction, refraction, interference)
- to introduce the concept of the Fresnel zone

What is a Wave?







We are all familiar with vibrations or oscillations in various forms: a pendulum, a tree swaying in the wind, the string of a guitar - these are all examples of oscillations.

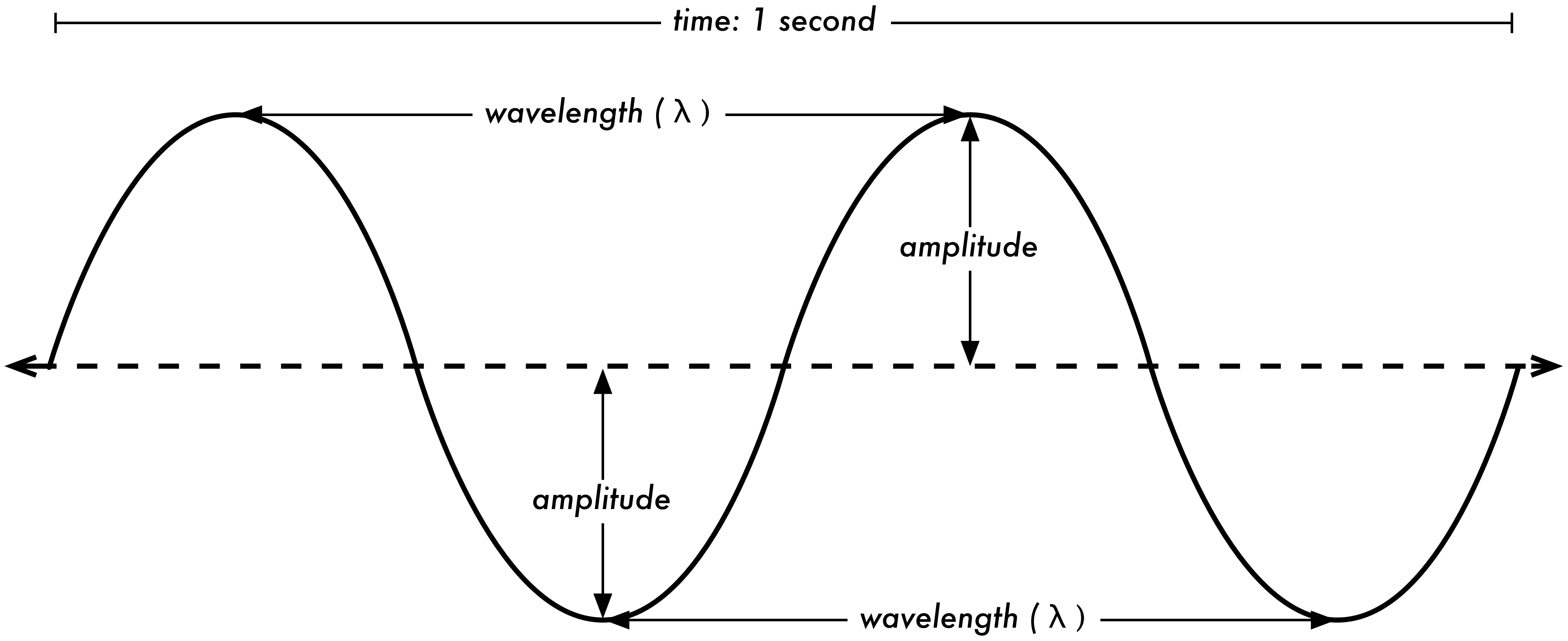
What they have in common is that something, some medium or object, is swinging in a periodic manner, with a certain number of cycles per unit of time. This kind of wave is sometimes called a ***mechanical wave***, since it is defined by the motion of an object or its propagating medium.

When such oscillations travel (that is, when the swinging does not stay bound to one place) then we speak of waves propagating in space. For example, a singer singing creates periodic oscillations in his or her vocal cords. These oscillations periodically compress and decompress the air, and this periodic change of air pressure then leaves the singers mouth and travels, at the speed of sound. A stone plunging into a lake causes a disturbance, which then travels across the lake as a ***wave***.

Waves in water are easy to visualize. Simply drop a stone into the lake and you can see the waves as they move across the water over time. In the case of electromagnetic waves, the part that might be hardest to understand is: "What is it that is oscillating?"

Electromagnetic Waves

- Characteristic wavelength, frequency, and amplitude
- No need for a carrier medium
- Examples: light, X-rays and radio waves



The wavelength (sometimes referred to as ***lambda***, **λ**) is the distance measured from a point on one wave to the equivalent part of the next, for example from the top of one peak to the next. The frequency is the number of whole waves that pass a fixed point in a period of time.

Waves also have a property called ***amplitude***. This is the distance from the center of the wave to the extreme of one of its peaks, and can be thought of as the "height" of a water wave.

Unlike waves in water, electromagnetic waves require no medium to carry them through space. It may be said that the media that oscillates is the electromagnetic field.

Quick review of unit prefixes

Powers of ten			
Nano-	10^{-9}	1/1000000000	n
Micro-	10^{-6}	1/1000000	µ
Milli-	10^{-3}	1/1000	m
Centi-	10^{-2}	1/100	c
Kilo-	10^{3}	1 000	k
Mega-	10^{6}	1 000 000	M
Giga-	10^{9}	1 000 000 000	G

In physics, math, and engineering, we often express numbers by powers of ten. We will meet these terms again, e.g. in Giga-Hertz (GHz), Centi-meters (cm), Micro-seconds (µs), and so on.

Wavelength and Frequency

$$c = f * \lambda$$

c = speed (meters / second)

f = frequency (cycles per second, or Hz)

λ = wavelength (meters)

If a wave on water travels at one meter per second, and it oscillates five times per second, then each wave will be twenty centimeters long:

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1 meter/second = 5 cycles/second * λ
λ = 1 / 5 meters
λ = 0.2 meters = 20 cm
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A wave has a certain ***speed***, ***frequency***, and ***wavelength***. These are connected by a simple relation:

Speed = Frequency * Wavelength

The wavelength (sometimes referred to as ***lambda***, **λ**) is the distance measured from a point on one wave to the equivalent part of the next, for example from the top of one peak to the next. The frequency is the number of whole waves that pass a fixed point in a period of time. Speed is measured in meters/second, frequency is measured in cycles per second (or Hertz, abbreviated ***Hz***), and wavelength is measured in meters.

Wavelength and Frequency

Since the speed of light is approximately 3×10^8 m/s, we can calculate the wavelength for a given frequency.

Let us take the example of the frequency of 802.11b/g wireless networking, which is:

$$
\begin{aligned}
f &= 2.4 \text{ GHz} \\
  &= 2{,}400{,}000{,}000 \text{ cycles / second}
\end{aligned}
$$

$$
\begin{aligned}
\text{wavelength } (\lambda) &= c / f \\
&= 3 * 10^{8} \text{ m/s} / 2.4 * 10^{9} \text{ s}^{-1} \\
&= 1.25 * 10^{-1} \text{ m} \\
&= 12.5 \text{ cm}
\end{aligned}
$$

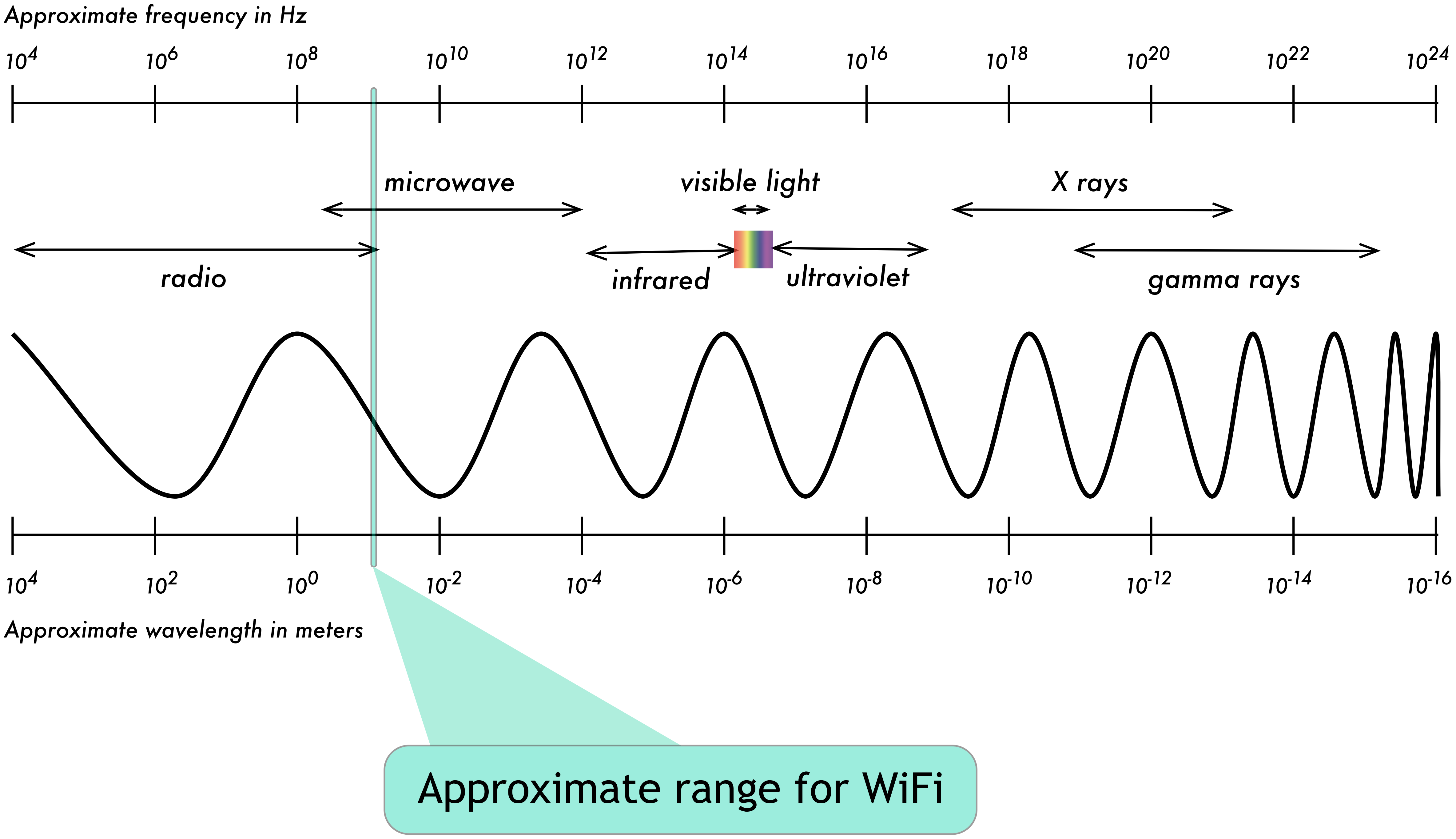
Therefore, the wavelength of 802.11b/g WiFi is about ***12.5 cm***.

There are many more frequencies used in WiFi networking: one possible range spans over 85 MHz, starting at 2400 MHz and ending at 2485 MHz (but note that the ending value may be different in different countries).

What is the wavelength of 5.3GHz 802.11a?

$\lambda = 3 * 10^{8} / 5.3 * 10^{9} = 5.66$ cm

Electromagnetic Spectrum

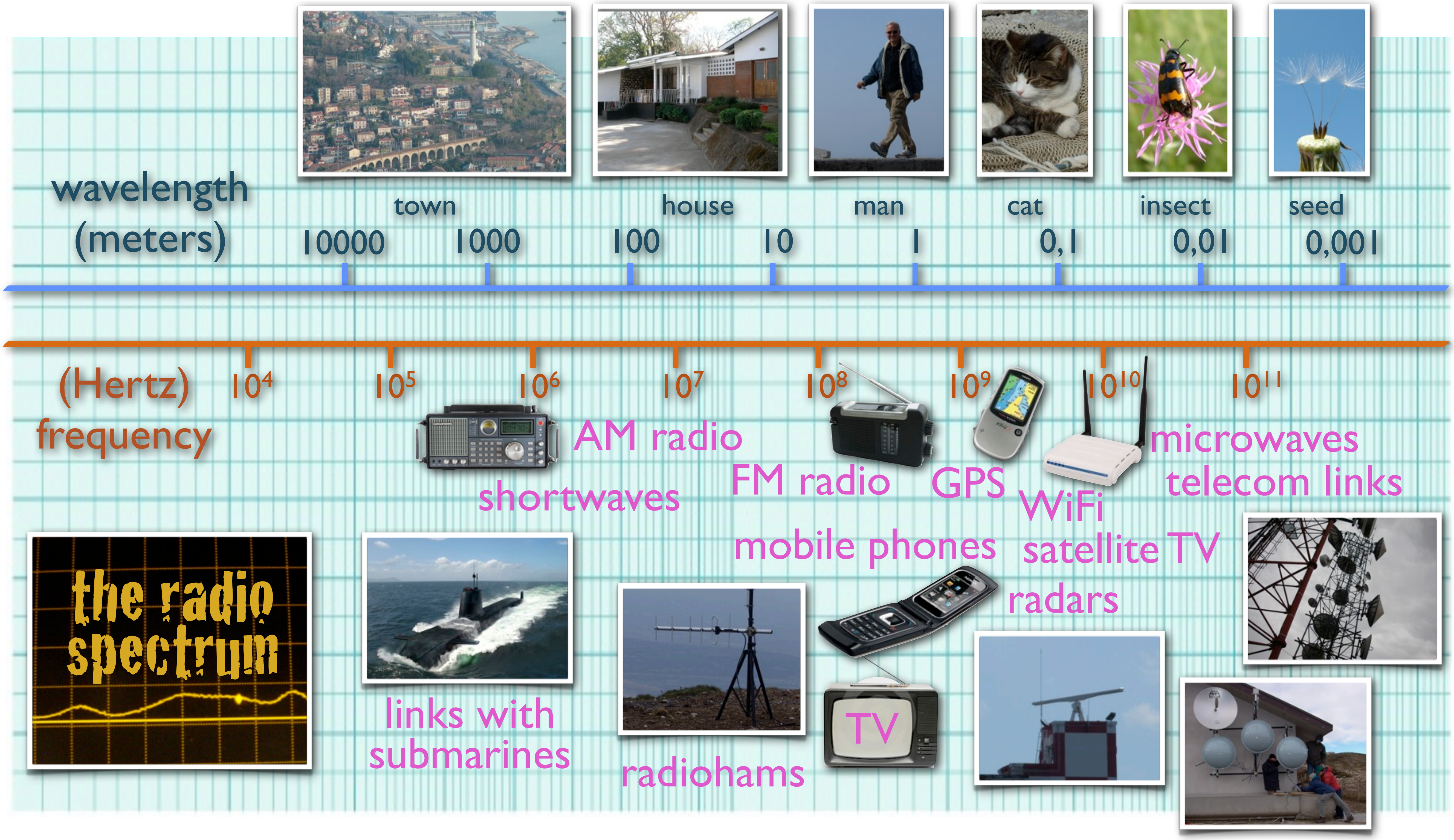


This picture represents the entire electromagnetic spectrum. It goes all the way from very low frequency radio waves on the left, to very high frequency X-rays and gamma rays on the right.

In the middle, there's a very small region that represents visible light. In the scope of the entire electromagnetic spectrum, the range of frequencies that we can actually perceive with our eyes is very small. You can see on either side of visible light is infrared and ultraviolet.

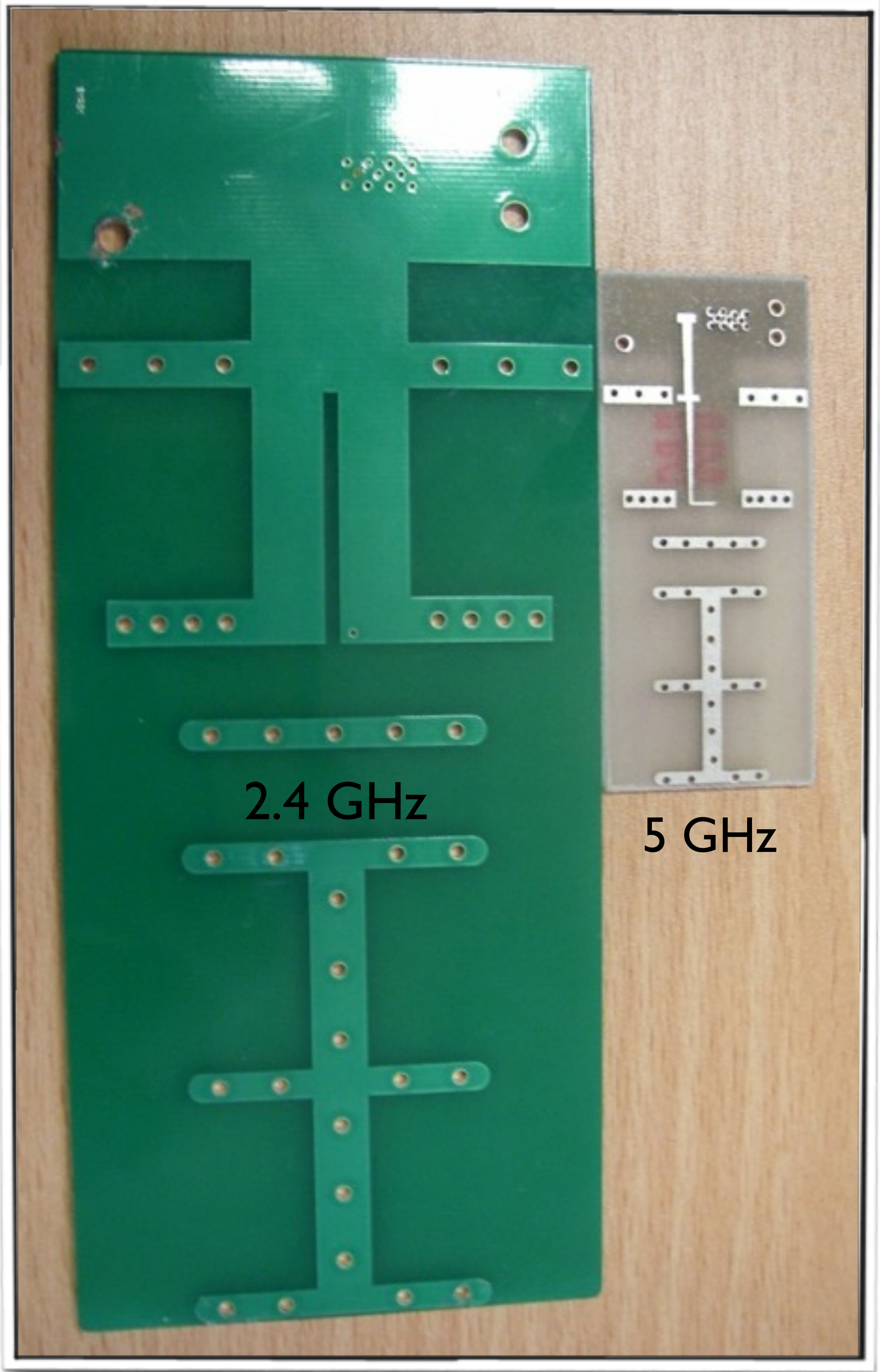
But the area that we are interested in is the very narrow range of frequencies used by WiFi equipment. That is the very thin sliver at the low end of the microwave range.

Perspective



This picture represents some of the many different usages of the e.m. spectrum, from low frequency radio up to microwaves.

E.m. communications with **submarines** are forced to use very low e.m. frequencies, because of the difficulties of propagation of higher frequency RF signals under water. Most of the other usages are concentrated on higher frequencies, because of the wider capacity available there (more channels and more data per channel). Examples are:
shortwaves (international AM broadcast, maritime communications, radio amateurs HF bands, etc.): from 1 to 30 MHz
FM radio: from 88 to 108 MHz
TV broadcast: VHF channels in many bands from 40 to 250 MHz; UHF channels in many bands from 470 to 885 MHz (depending from the country)
VHF and UHF **radio ham** bands: around 140-150 and 440-450 MHz, together with many other users (services, security, police, etc...)
mobile phones: 850, 900, 1800, 1900 and 2100 MHz for GSM and CDMA cellular networks;
GPS: 1227 and 1575 MHz
WiFi: 2400-2485 MHz and 4915-5825 MHz (depending from the country). See *http://en.wikipedia.org/wiki/List_of_WLAN_channels* for details.
radars: common bands for radars are: L band (1–2 GHz), S band (2–4 GHz), C band (4–8 GHz), X band (8–12 GHz) but others are also used.
satellite TV: C-band (4–8 GHz) and Ku-band (12–18 GHz)
microwave telecom links: for example in the United States, the band 38.6 - 40.0 GHz is used for licensed high-speed microwave data links, and the 60 GHz band can be used for unlicensed short range data links with data throughputs up to 2.5 Gbit/s. The 71-76, 81-86 and 92–95 GHz bands are also used for point-to-point high-bandwidth communication links.



WiFi frequencies and wavelengths

Standard	Frequency	Wavelength
802.11 b/g/n	2.4 GHz	12.5 cm
802.11 a/n	5.x GHz	5 to 6 cm

This photo shows two Yagi antennas made from PC-board materials. The Yagi (sometimes referred also as Yagi-Uda, from the names of the two inventors) is one of the many designs for antennas.

The antenna on the left is designed to work at 2.4 GHz, while the antenna on the right works for 5 GHz. The two antennas have similar characteristics and gain at their respective frequencies.

You may notice that the ratio of the typical dimensions of the two antennas is the inverse ratio of the two frequencies:

5000:2400 = 12,5 : 6 = circa 2

It's almost always true that antennas of comparable characteristics at 2.4 and 5 GHz have this same dimensional ratio of 2, i.e. a 5GHz antenna is half the size of a 2.4GHz antenna (with approx. the same gain).

Behavior of radio waves

There are a few simple rules of thumb that can prove extremely useful when making first plans for a wireless network:

- The ***longer*** the wavelength, the further it goes
- The ***longer*** the wavelength, the better it travels through and around things
- The ***shorter*** the wavelength, the more data it can transport

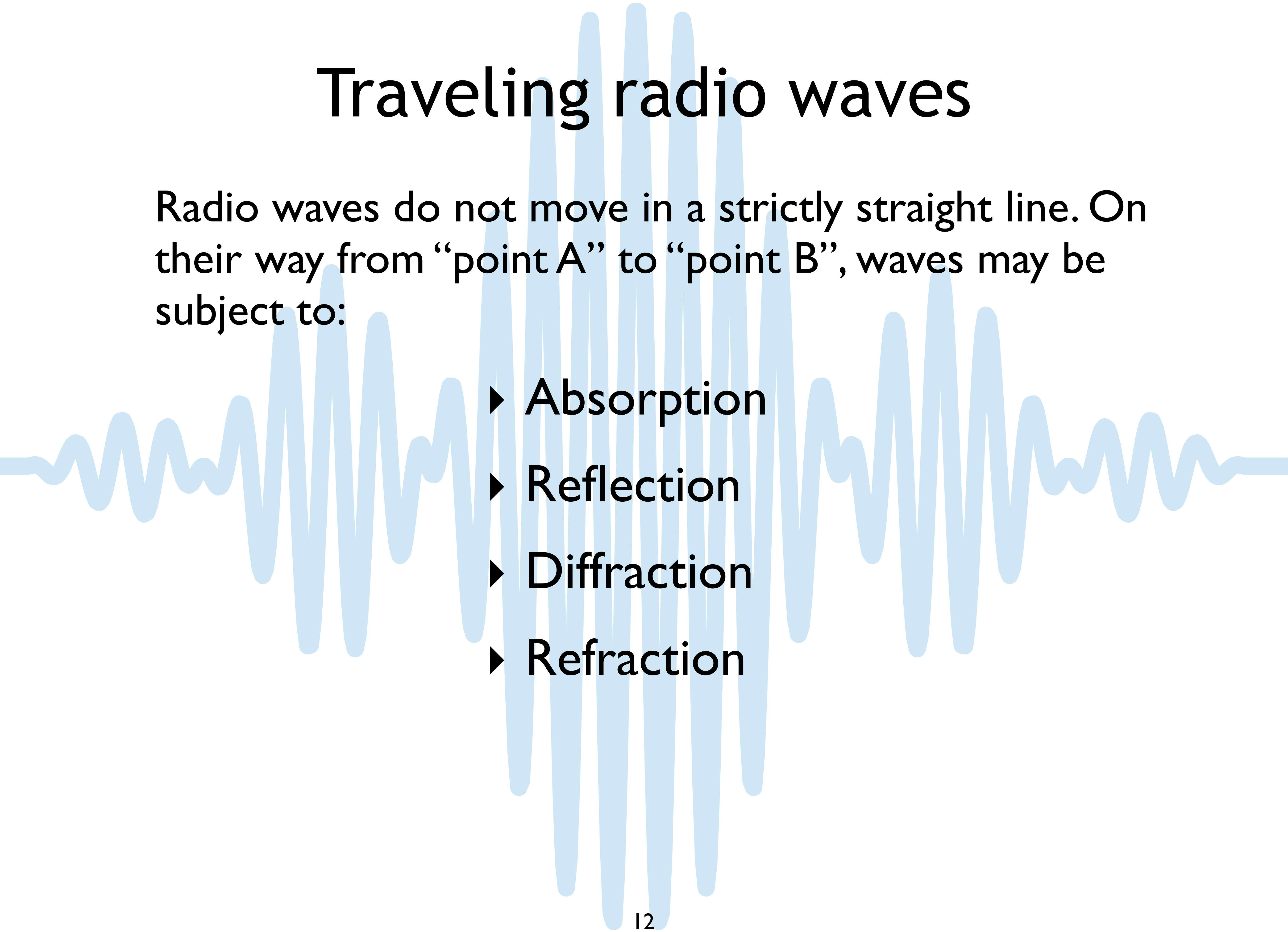
All of these rules, simplified as they may be, are rather easy to understand by example.

Assuming equal power levels, waves with longer wavelengths tend to travel further than waves with shorter wavelengths. Lower frequency transmitters can reach greater distances than high frequency transmitters at the same power.

A wave on water which is 5 meters long will not be stopped by a 5 mm piece of wood sticking out of the water. If instead the piece of wood were 50 meters big (e.g. a ship), it would easily stop the wave. The distance a wave can travel depends on the relationship between the wavelength of the wave and the size of obstacles in its path of propagation.

It is harder to visualize waves moving "through" solid objects, but this is the case with electromagnetic waves. Longer wavelength (and therefore lower frequency) waves tend to penetrate objects better than shorter wavelength (and therefore higher frequency) waves. For example, FM radio (88-108MHz) can travel through buildings and other obstacles easily, while shorter waves (such as GSM phones operating at 900MHz or 1800MHz) have a harder time penetrating buildings. This effect is partly due to the difference in power levels used for FM radio and GSM, but is also partly due to the shorter wavelength of GSM signals.

The faster the wave swings or beats, the more information it can carry - every beat or cycle could for example be used to transport a digital bit, a '0' or a '1', a 'yes' or a 'no'.



Traveling radio waves

Radio waves do not move in a strictly straight line. On their way from “point A” to “point B”, waves may be subject to:

- Absorption
- Reflection
- Diffraction
- Refraction

We are going to examine all of these effects in detail in the next slides.

Absorption

When electromagnetic waves go through some material, they generally get weakened or dampened.

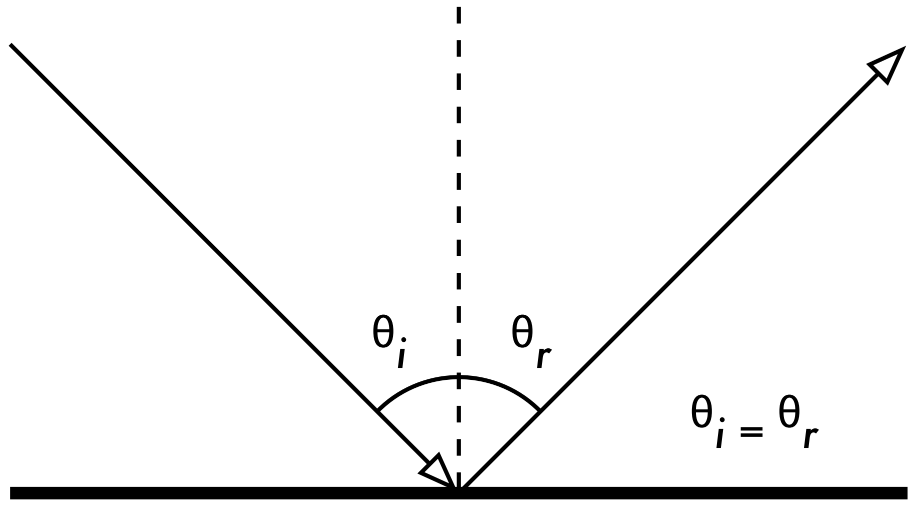
Materials that absorb energy include:

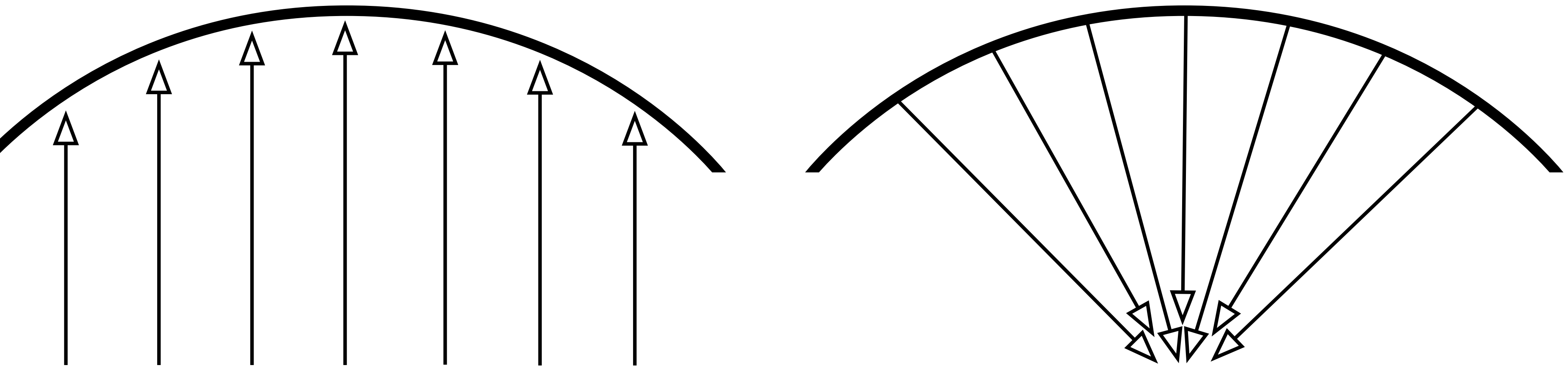
- ***Metal***. Electrons can move freely in metals, and are readily able to swing and thus absorb the energy of a passing wave.
- ***Water*** molecules jostle around in the presence of radio waves, thus absorbing some energy.
- ***Trees*** and ***wood*** absorb radio energy proportionally to the amount of water contained in them.
- ***Humans*** are mostly water: we absorb radio energy quite well!

Plastics and similar materials generally do not absorb a lot of radio energy- but this varies depending on the frequency and type of material. Before you build a component from plastic (e.g. weather protection for a radio device and its antennas), it is a good idea to verify that the material does not absorb radio energy around 2.4 GHz. One simple method of measuring the absorption of plastic at 2.4 GHz is to put a sample in a microwave oven for a couple of minutes. If the plastic heats up, then it absorbs radio energy and should not be used for weatherproofing.

Reflection

The rules for reflection are quite simple: the angle at which a wave hits a surface is the same angle at which it gets deflected. **Metal** and **water** are excellent reflectors of radio waves.





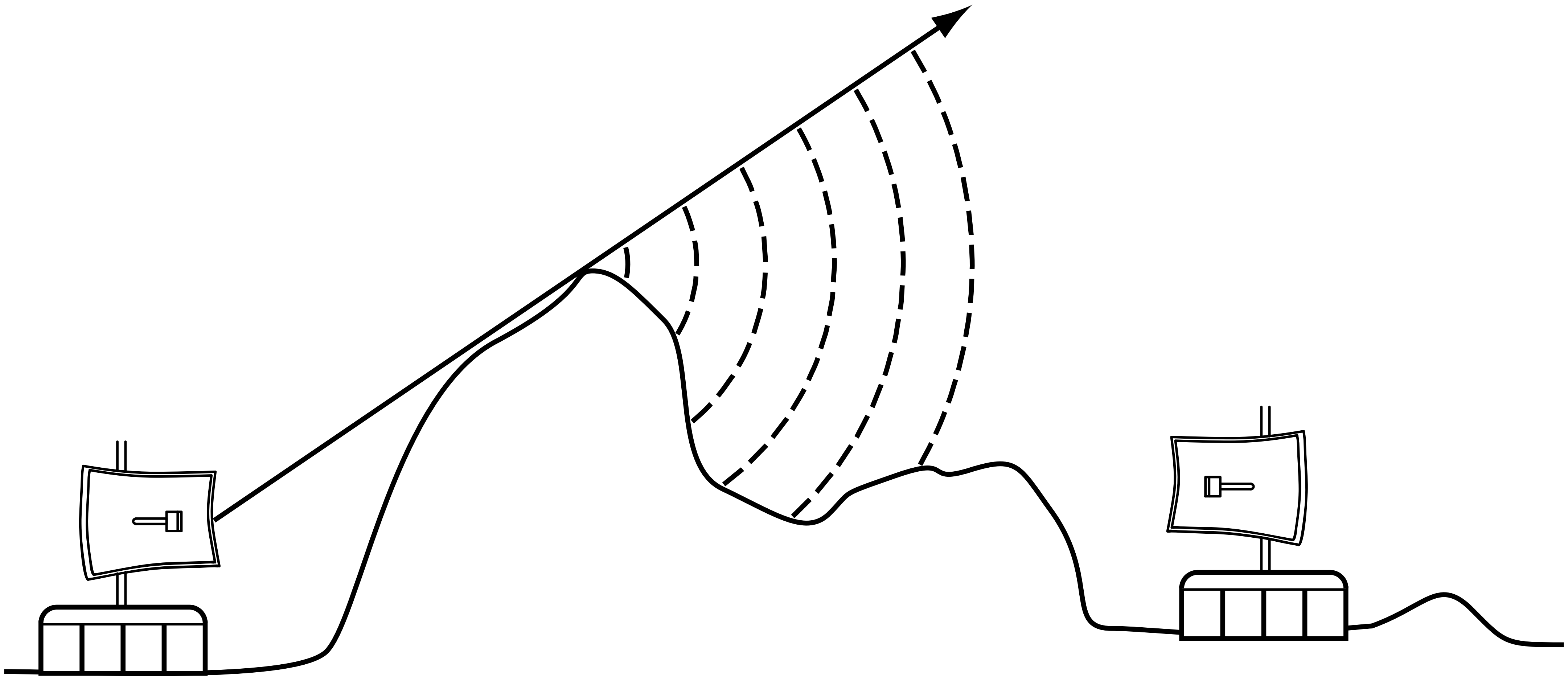
Although the rules of reflection are quite simple, things can become very complicated when you imagine an office interior with many many small metal objects of various complicated shapes. The same goes for urban situations: look around you in city environment and try to spot all of the metal objects. This explains why **multipath** effects (i.e. signal reaching their target along different paths, and therefore at different times) play such an important role in wireless networking. Water surfaces, with waves and ripples changing all the time, effectively make for a very complicated reflection object which is more or less impossible to calculate and predict precisely.

We use reflection to our advantage in antenna building: e.g. we put huge parabolas behind our radio transmitter/receiver to collect and bundle the radio signal into a fine point.

Big metallic panels can be used as *passive radio reflectors* to cover areas that cannot be normally reached using a straight path, this is sometimes done to increase the TV coverage in mountain and valley areas.

Diffraction

Because of the effect of diffraction, waves will “bend” around corners or through an opening in a barrier.



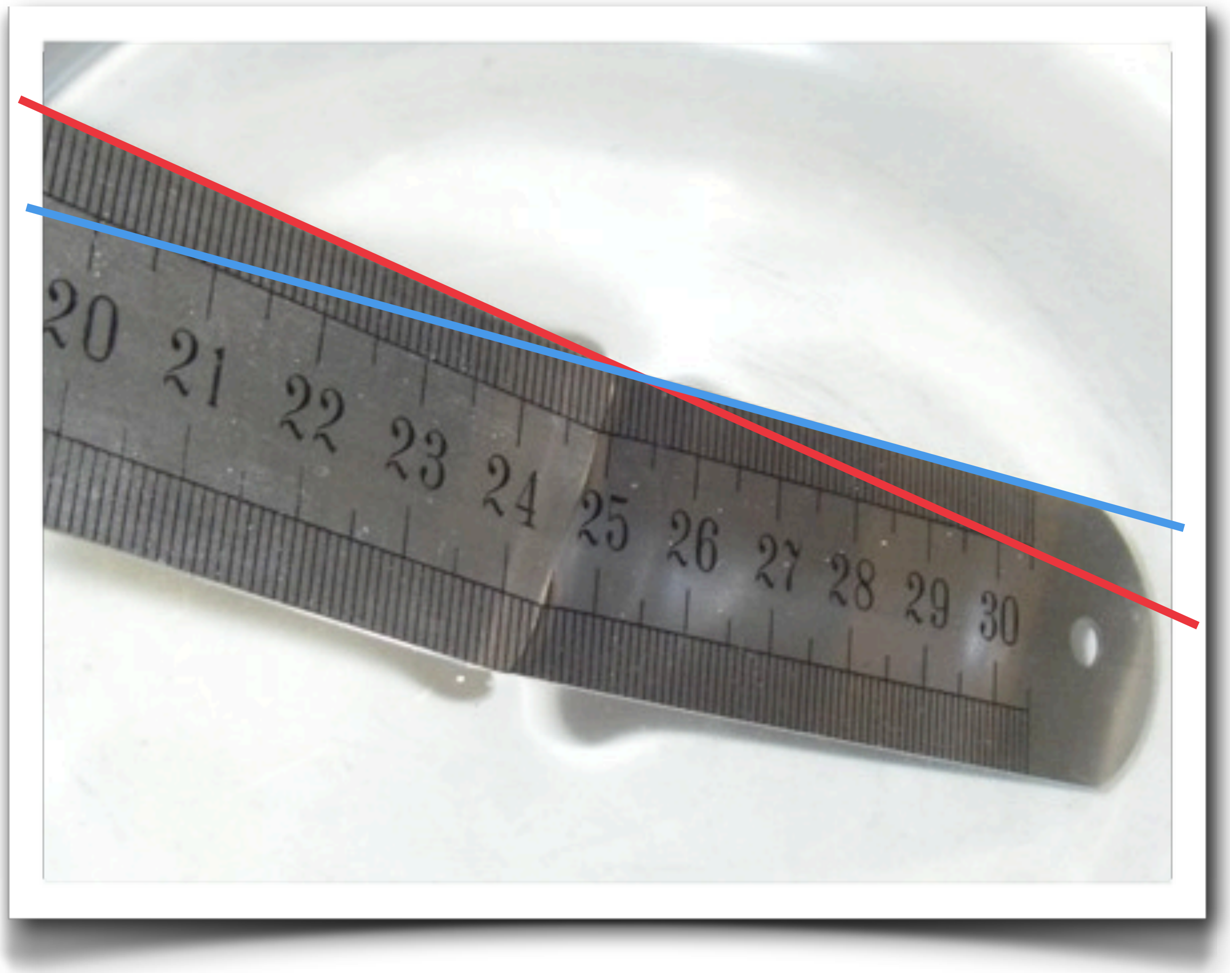
The wavelengths of visible light are far too small for humans to observe this effect directly. Microwaves, with a wavelength of several centimeters, will show the effects of diffraction when waves hit walls, mountain peaks, and other obstacles. It seems as if the obstruction causes the wave to change its direction and go around corners.

Note that diffraction comes at the cost of power: the energy of the diffracted wave is significantly less than that of the wavefront that caused it. But in some very specific applications, you can take advantage of the diffraction effect to circumvent obstacles.

Refraction

Refraction is the apparent “bending” of waves when they meet a material with different characteristics.

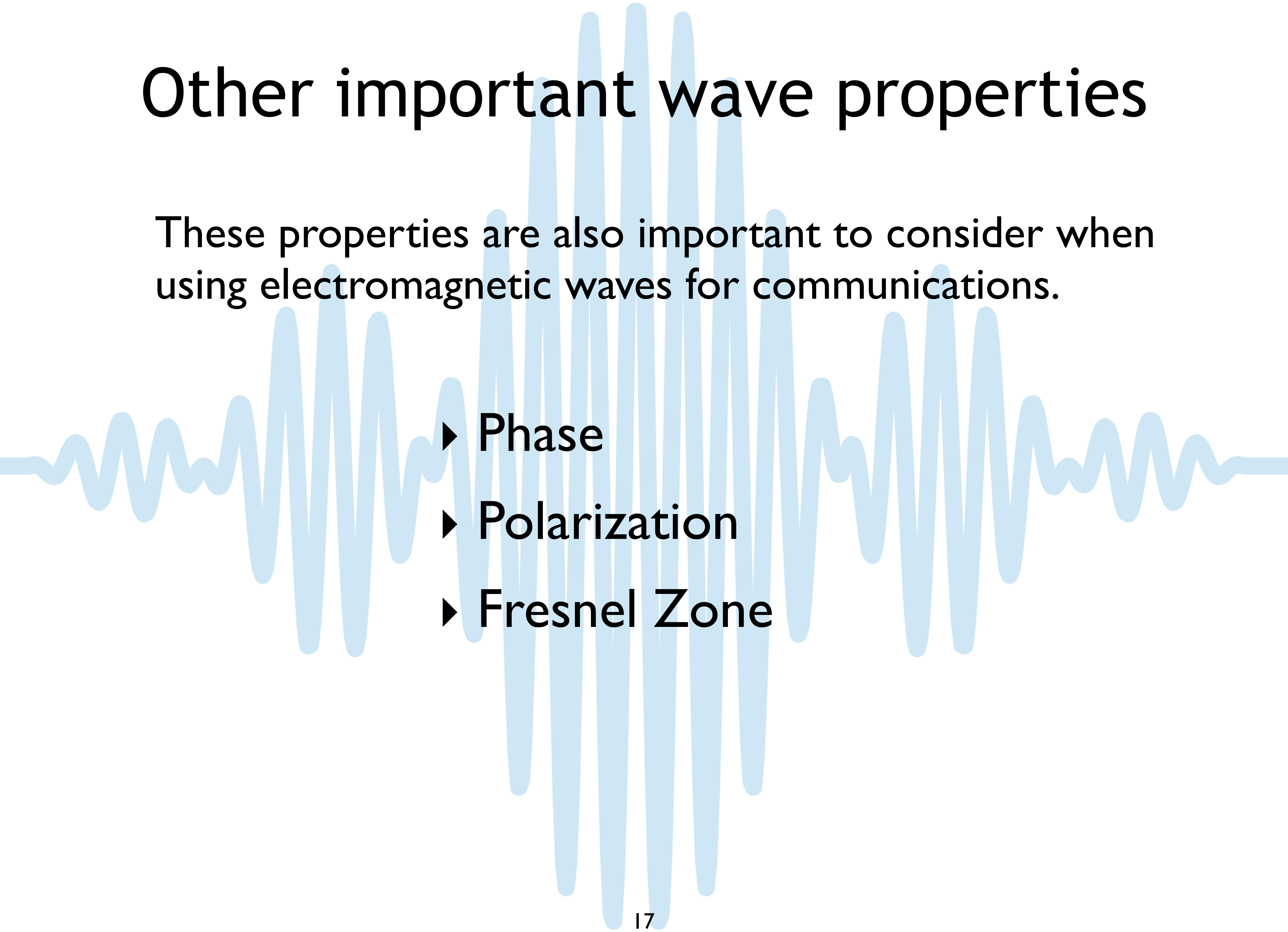
When a wave moves from one medium to another, it changes speed and direction upon entering the new medium.



This is a common effect when a ray of light is passing trough materials with different refractive indexes (like air and water).

Refraction is described mathematically by Snell's law (http://en.wikipedia.org/wiki/Snell's_law), which states how the angle of incidence is related to the angle of refraction and take into consideration the refractive indexes of the two media. Basically the ratio of the sin functions of the two angles is equal to the ratio of the two indexes.

Other important wave properties



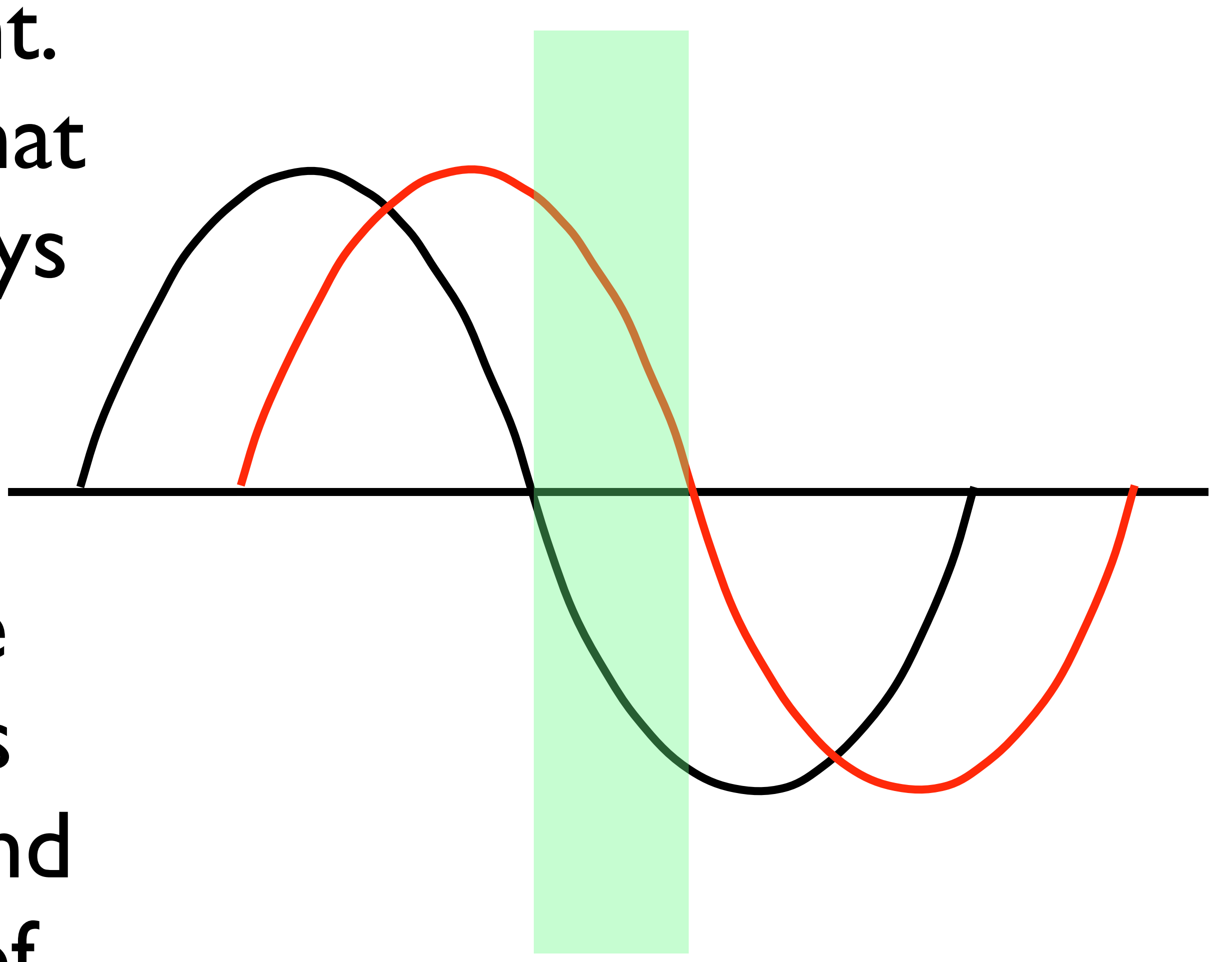
These properties are also important to consider when using electromagnetic waves for communications.

- Phase
- Polarization
- Fresnel Zone

Phase

The **phase** of a wave is the fraction of a cycle that the wave is offset from a reference point. It is a relative measurement that can be express in different ways (radians, cycles, degrees, percentage).

Two waves that have the same frequency and different phases have a **phase difference**, and the waves are said to be out of phase with each other.



from Wikipedia http://en.wikipedia.org/wiki/Phase_(waves)

A phase difference is analogous to two athletes running around a race track at the same speed and direction but starting at different positions on the track. They pass a point at different instants in time. But the time difference (phase difference) between them is a constant - same for every pass since they are at the same speed and in the same direction. If they were at different speeds (different frequencies), the phase difference is undefined and would only reflect different starting positions.

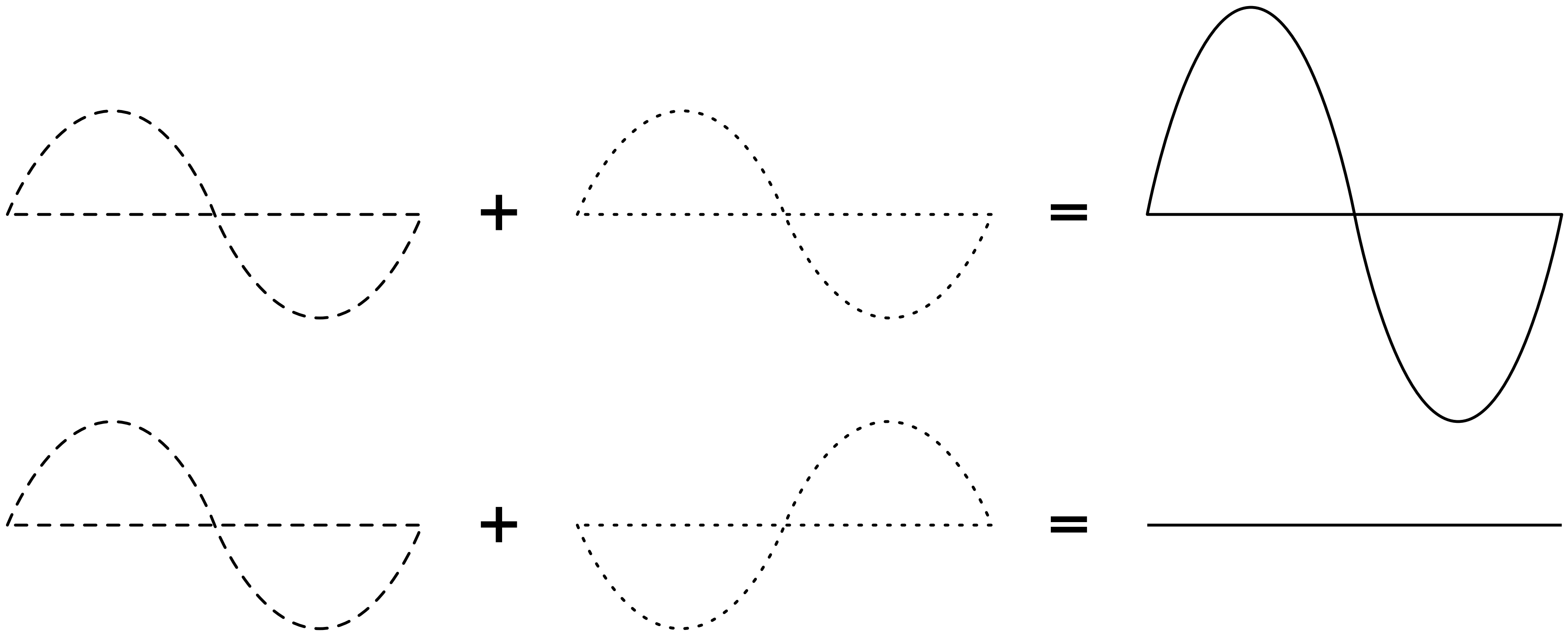
Java applet for a demo: http://phy.hk/wiki/englishhtm/phase.htm

Interference (constructive and destructive) will be explained in the next slide using the concept of phase difference between the interfering waves.

Interference

When two waves of the same frequency, amplitude and **phase** meet, the result is ***constructive interference***: the amplitude doubles.

When two waves of the same frequency and amplitude and **opposite phase** meet, the result is ***destructive interference***: the wave is annihilated.



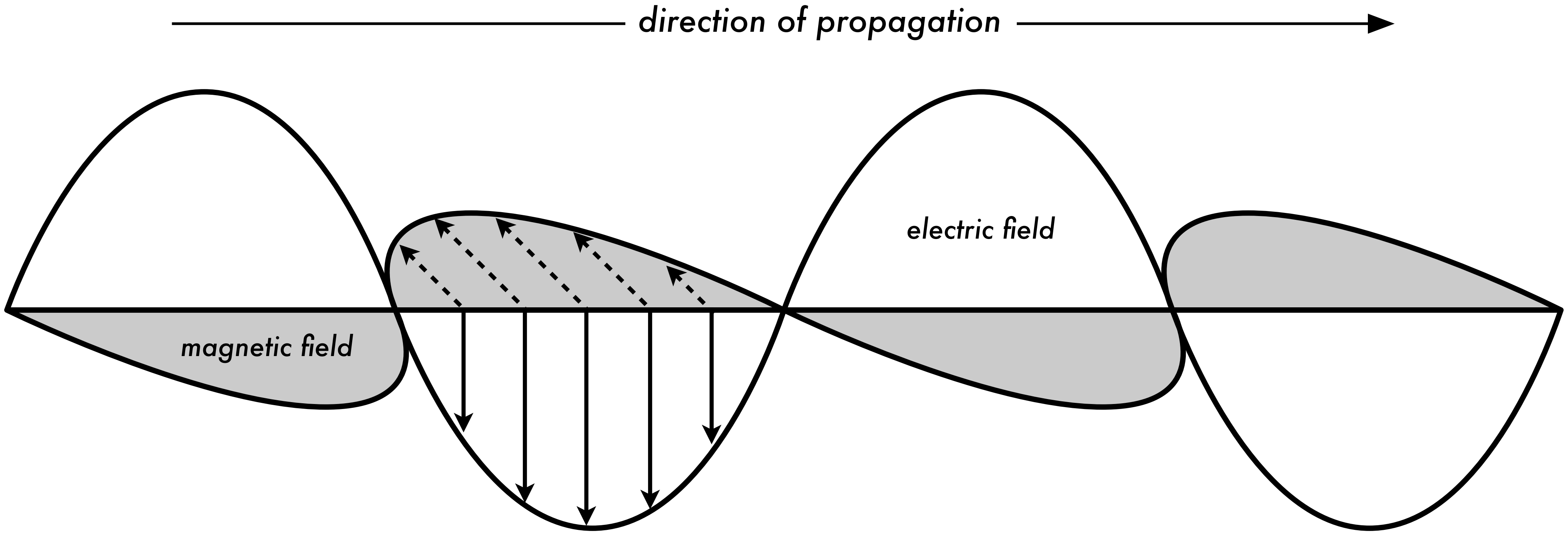
When working with waves, one plus one does not necessarily equal two. It can also result in zero.

This is easy to understand when you draw two sine waves and add up the amplitudes. When peak hits peak, you will have maximum results (1 + 1 = 2). This is called constructive interference. When peak hits valley, you will have complete annihilation ((1 + (-)1 = 0) - destructive interference.

Interference also happens when two or more waves of different frequencies meet together: the results are simply more complex and difficult to visualize.

Polarization

- Electromagnetic waves have electrical and magnetic components.
- The electrical and magnetic components oscillate perpendicular to each other and to the direction of the propagation.



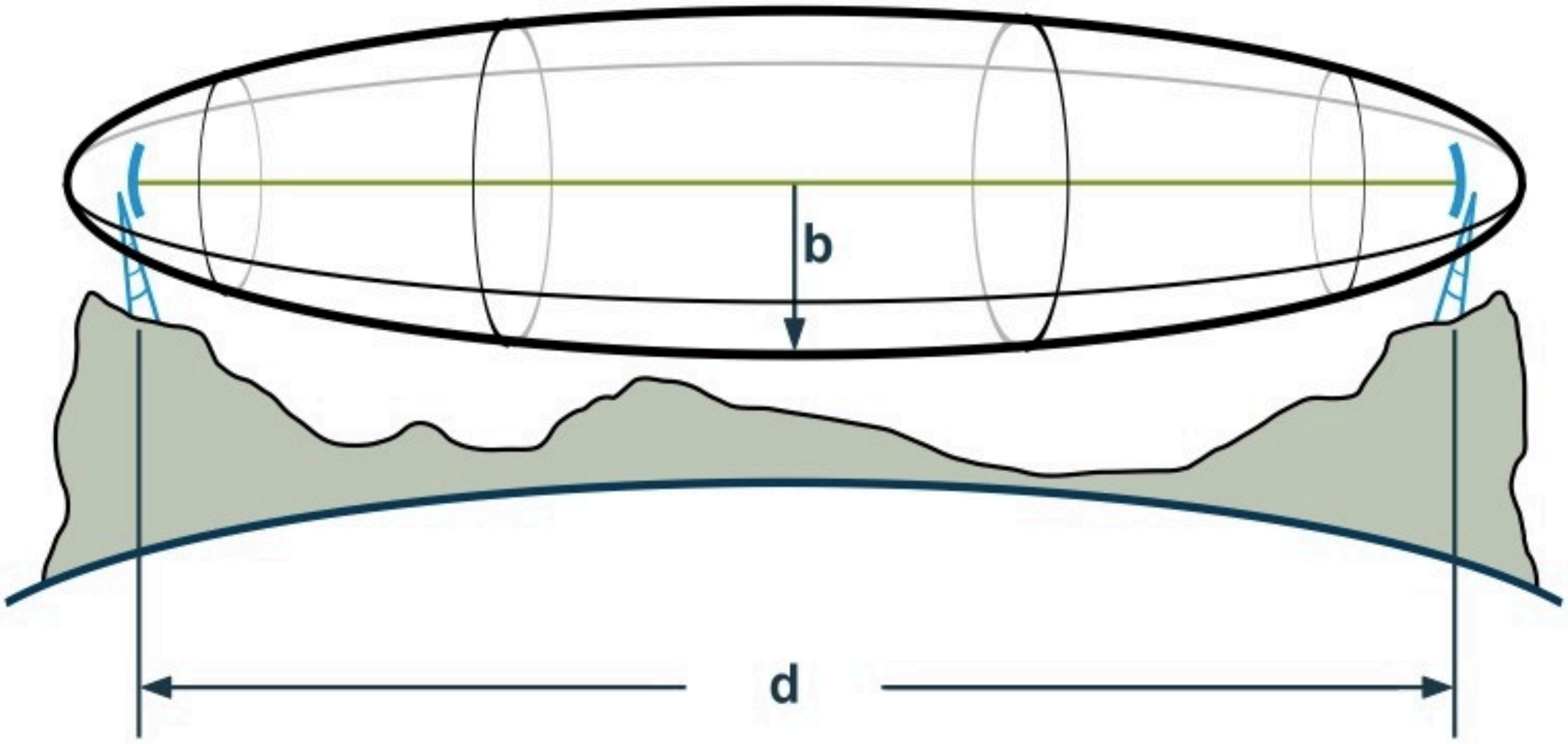
Another important quality of electromagnetic waves is ***polarization***. Polarization describes the direction of the electrical field vector.

If you imagine a vertically aligned dipole antenna (a straight piece of wire), electrons only move up and down, not sideways (because there is no room to move) and thus electrical fields only ever point up or down, vertically. The energy leaving the wire and traveling as a wave has a strict linear (and in this case, vertical) polarization. If we put the antenna flat on the ground, we would find horizontal linear polarization.

Most WiFi antennas we work with are linearly polarized, but circularly polarized antennas are also sometimes used (for special purposes).

The polarization of a transmitting and receiving antenna **MUST MATCH** for optimum communications.

Line of Sight and Fresnel Zones



a free line-of-sight **IS NOT EQUAL TO** a free Fresnel Zone

Simply draw a line between two points, and if nothing is in the way, we have optical **line of sight**.

But radio waves are not confined to a perfectly straight line, they occupy a volume in space. **Fresnel zone** theory describes how a propagating wave can cause interference with itself.

The strongest signals are on the direct line between transmitter and receiver and always lie in the (first) Fresnel Zone. If this zone is partially blocked by an obstruction, the signal arriving at the far end would be diminished.

See wikipedia for more details: *http://en.wikipedia.org/wiki/Fresnel_zone*

Conclusions

- Radio waves have a characteristic wavelength, frequency and amplitude, which affect the way they travel through space.
- WiFi uses a tiny part of the electromagnetic spectrum
- Lower frequencies travel further, but at the expense of throughput.
- Radio waves occupy a volume in space, the Fresnel zone, which should be unobstructed for optimum reception.

Thank you for your attention

For more details about the topics presented in this lecture, please see the book ***Wireless Networking in the Developing World***, available as free download in many languages at:

http://wndw.net