RF Fundamentals Seminar
Part 1: Introduction to RF

ROHDE&SCHWARZ

Make ideas real

Introduction to RF – Agenda

- The Electromagnetic Spectrum
- A Short Discussion of Units
- Voltage, Current, Resistance, Impedance
- Power
- Fourier Representation
- Maxwell's Equations
- Electromagnetic Waves & Propagation

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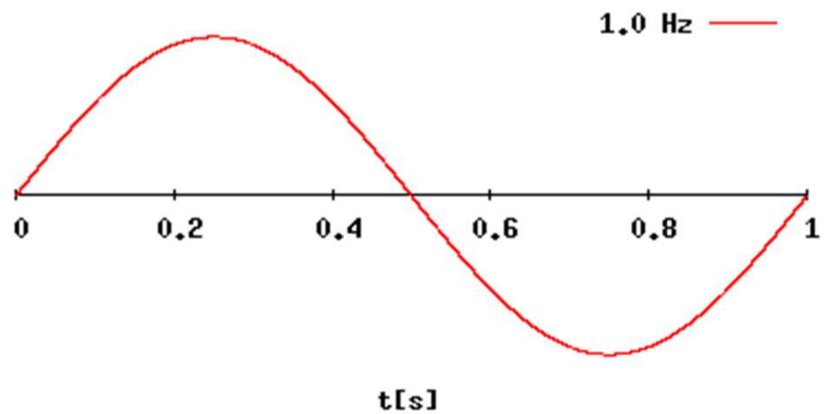
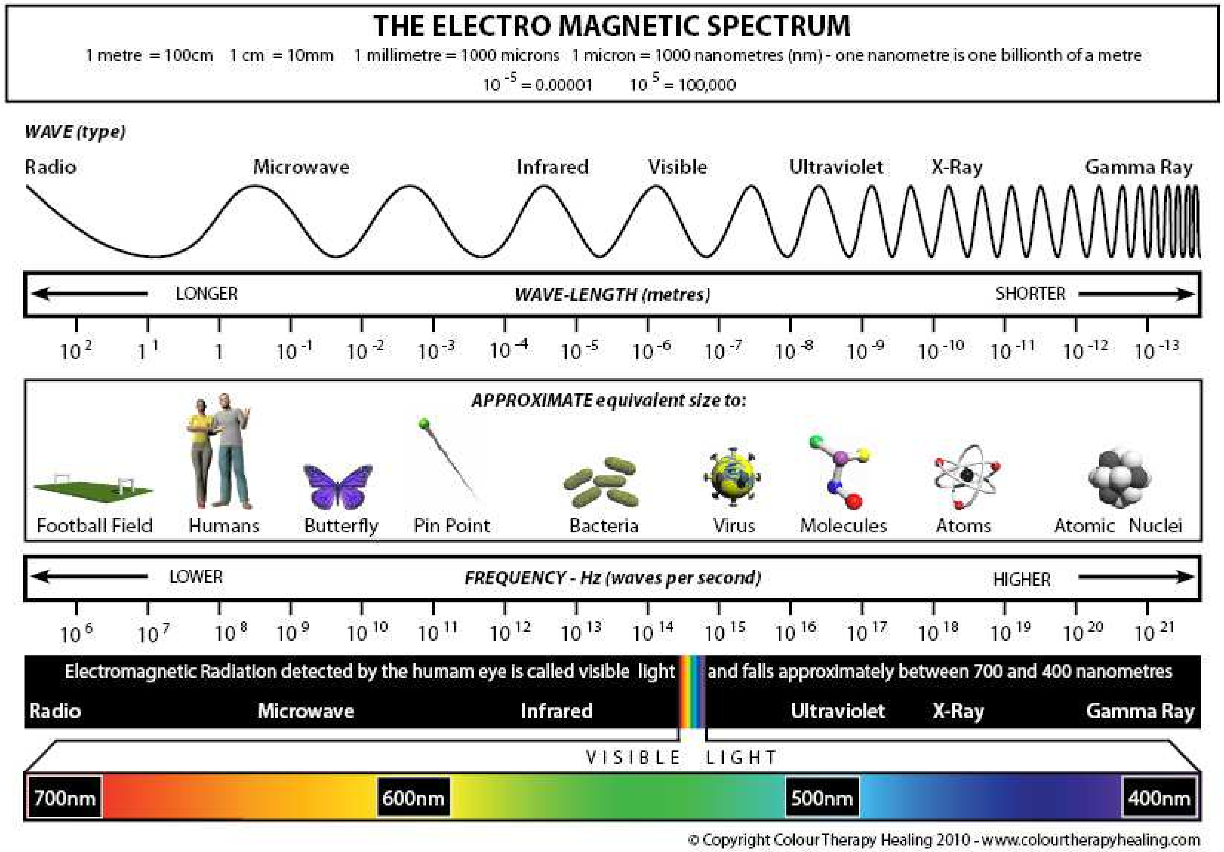
What is Frequency?

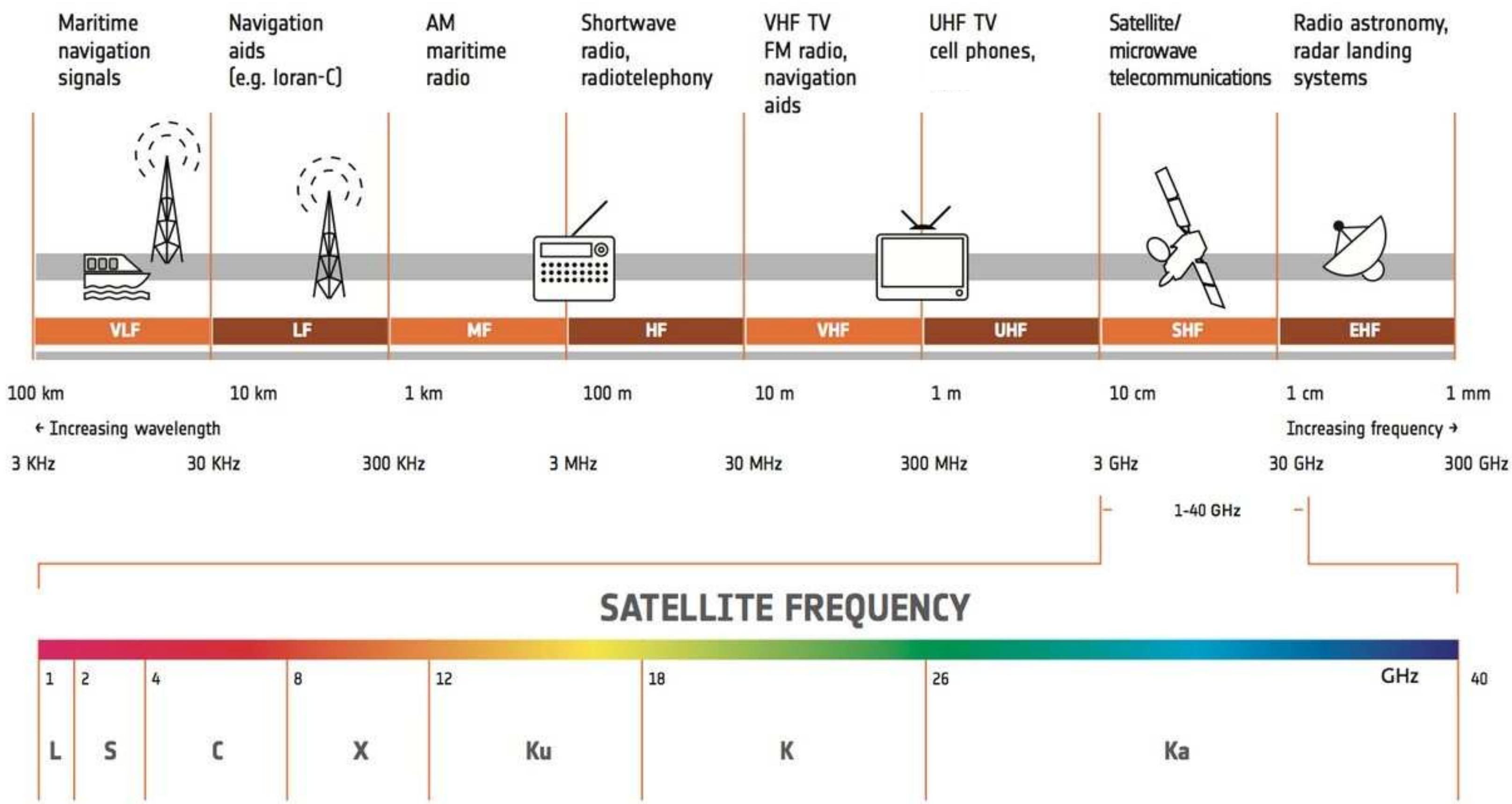
- Frequency is the number of occurrences in a given amount of time.
  - $Frequency = \frac{1}{Time}$
  - Hertz (Hz) – The units of Frequency, Cycles per second (1/seconds)
    - Named in Honor of Heinrich Hertz



Spectrum As Seen By Physicists



Spectrum As Seen By Engineers



Spectrum As Seen By Politicians

FCC rakes in $45 billion from wireless spectrum auction

The record-breaking auction highlights the demand for high-speed wireless service and signals strong promise for the upcoming auction of TV broadcast spectrum.

c|net

by **Marguerite Reardon**
January 29, 2015 1:07 PM PST
@maggie_reardon

Wireless Spectrum Auction Raises $19 Billion

By Stephen Labaton

The New York Times

March 19, 2008

REUTERS

TECHNOLOGY NEWS | Fri Feb 10, 2017 | 7:44pm EST

FCC spectrum auction bidding ends at $19.6 billion

FierceWireless

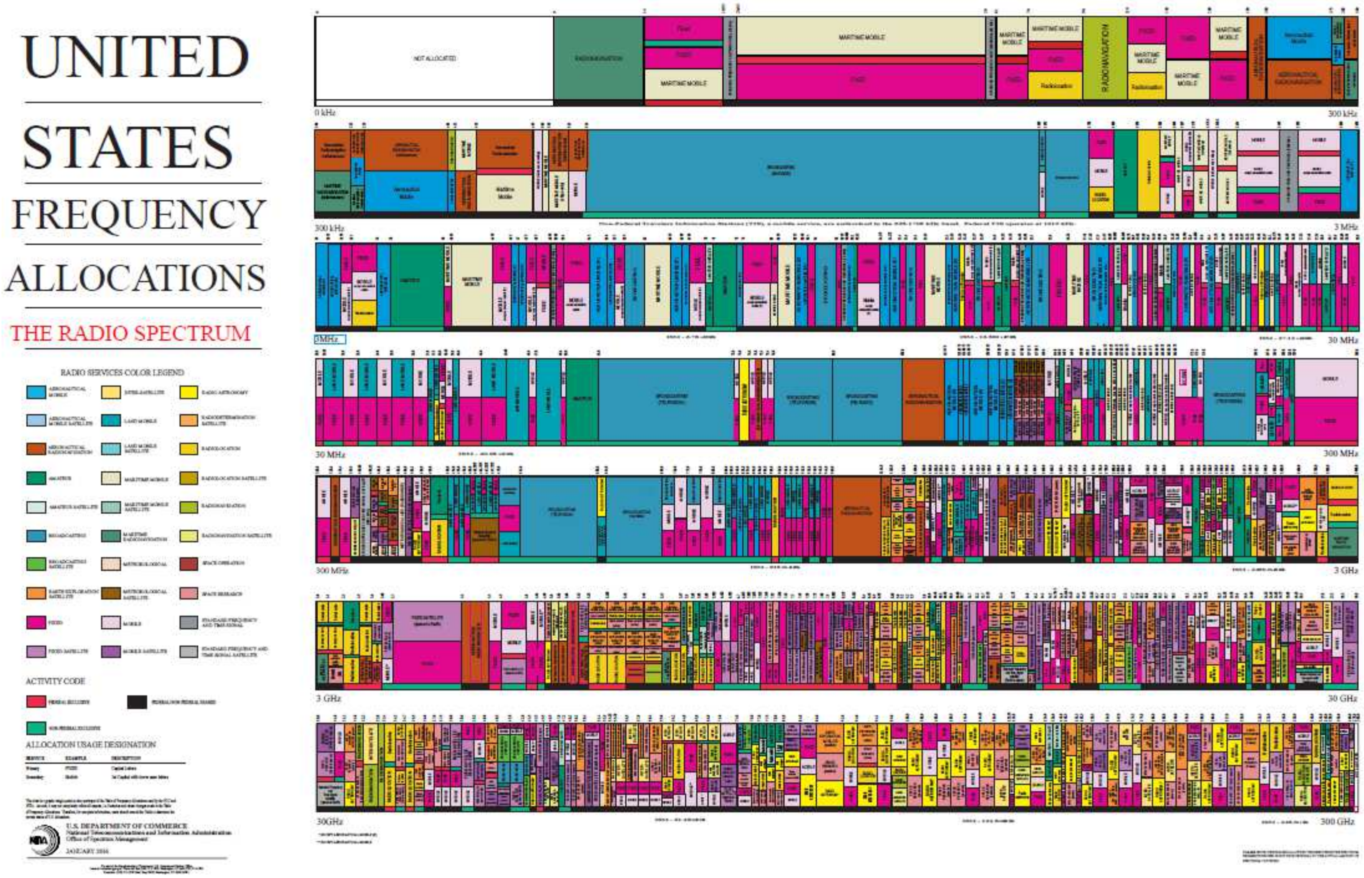
Verizon to acquire Straight Path for $3.1B, ending bidding war with AT&T

by *Colin Gibbs* | May 11, 2017 10:32am

BUSINESS

FCC to hold huge 5G spectrum auction, spend $20B for rural internet

Spectrum As Seen By Regulators



Certain blocks of the EM spectrum are designated for exclusive use by a licensee or for a specific purpose

Cellular falls in the region of 300 MHz – 3 GHz

Federal Communications Commission

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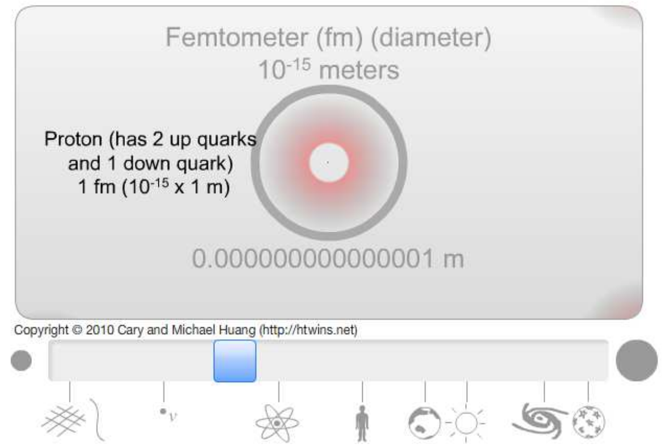
Metric Prefixes and Scientific Notation

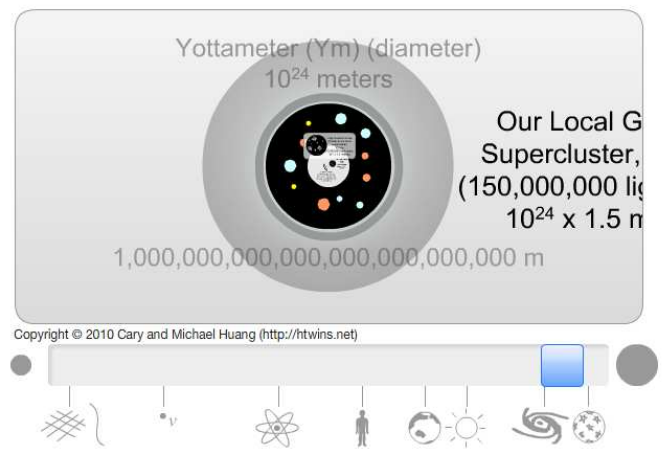
Prefix	Scale	Decimal	Slang
peta	10^{15}	1,000,000,000,000,000	"quadrillion"
tera	10^{12}	1,000,000,000,000	"trillion"
giga	10^{9}	1,000,000,000	"billion"
mega	10^{6}	1,000,000	"million"
kilo	10^{3}	1,000	"thousand"
-	$10^{0}=1$	1	""
milli	10^{-3}	0.001	"thousandth"
micro	10^{-6}	0.000001	"millionth"
nano	10^{-9}	0.000000001	"billionth"
pico	10^{-12}	0.000000000001	"trillionth"
femto	10^{-15}	0.000000000000001	"quadrillionth"

We experience millimeters to kilometers every day

Difference in scale between a single proton and our local galactic supercluster

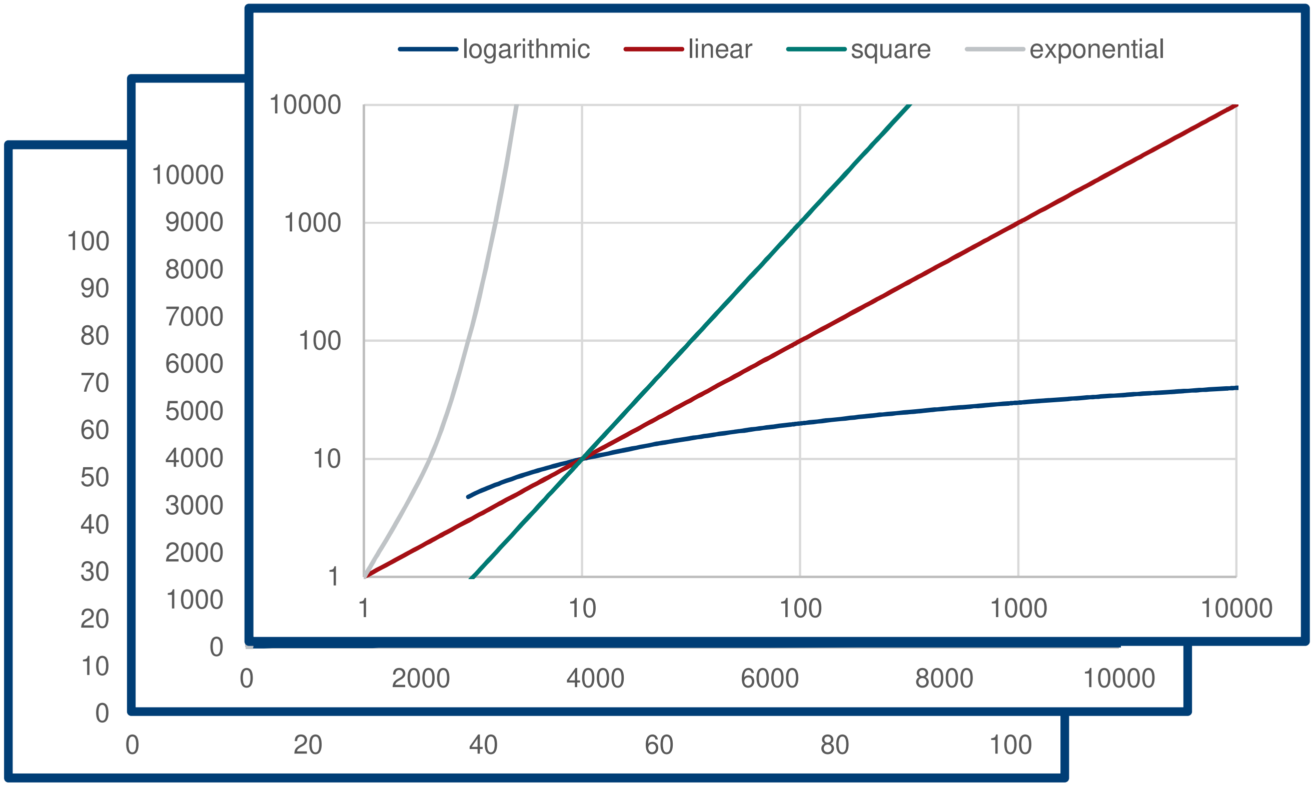
- about 1 femtometer vs. 1 Yottameter
- which is 10^{-15} meters vs. 10^{24} meters
- this ratio is 1 followed by (15 + 24 =) 39 zeros!





http://htwins.net/scale/

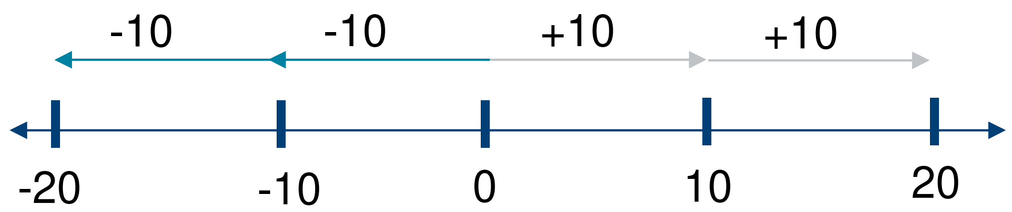
Logarithmic Scales



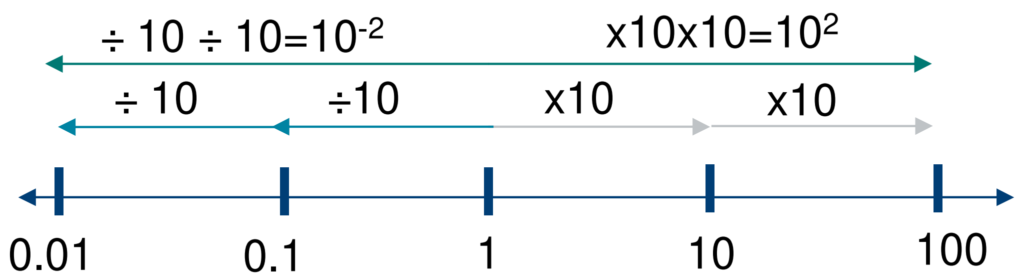
Logarithmic Scaling is useful for comparisons over a very large range

Logarithmic Scales

Linear



Log



Bel = $\log_{10}$ (ratio)

dB = 10 x $\log_{10}$ (ratio)

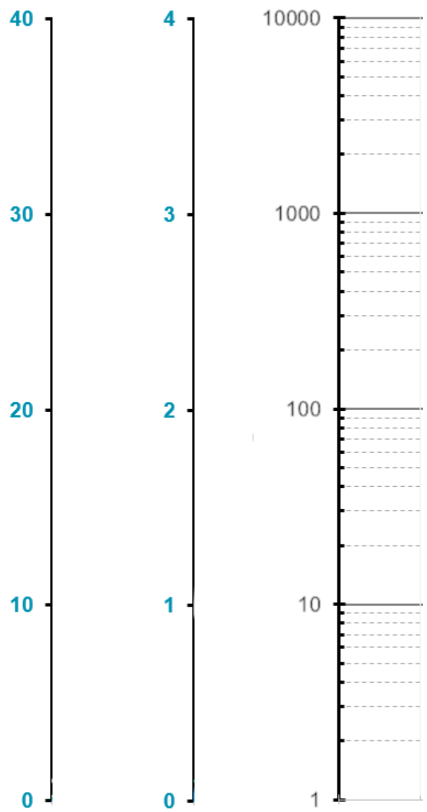
eg. 100x = 2 Bel = 20 dB

Bell Telephone Laboratories was trying to quantify the signal loss in telegraph and telephone circuits

They defined one “Bel” as a ratio of 10x

1 Bel = 10 deciBels [dB]

Logarithmic Scales, the Bel, and the deciBel



9.1

1.0

VIBRATION
(Richter Scale)

140 dB_{SPL}

0 dB_{SPL}

SOUND
(dB SPL)

Some Common Log (dB) Values to Remember

$$10 \cdot \log\left(\frac{1/4}{1}\right) = -6.02 \approx -6\ dB$$

$$10 \cdot \log\left(\frac{1/2}{1}\right) = -3.01 \approx -3\ dB$$

$$10 \cdot \log\left(\frac{1}{1}\right) = 0\ dB$$

$$10 \cdot \log\left(\frac{2}{1}\right) = 3.01 \approx 3\ dB$$

$$10 \cdot \log\left(\frac{4}{1}\right) = 6.02 \approx 6\ dB$$

$$10 \cdot \log\left(\frac{10}{1}\right) = 10\ dB$$

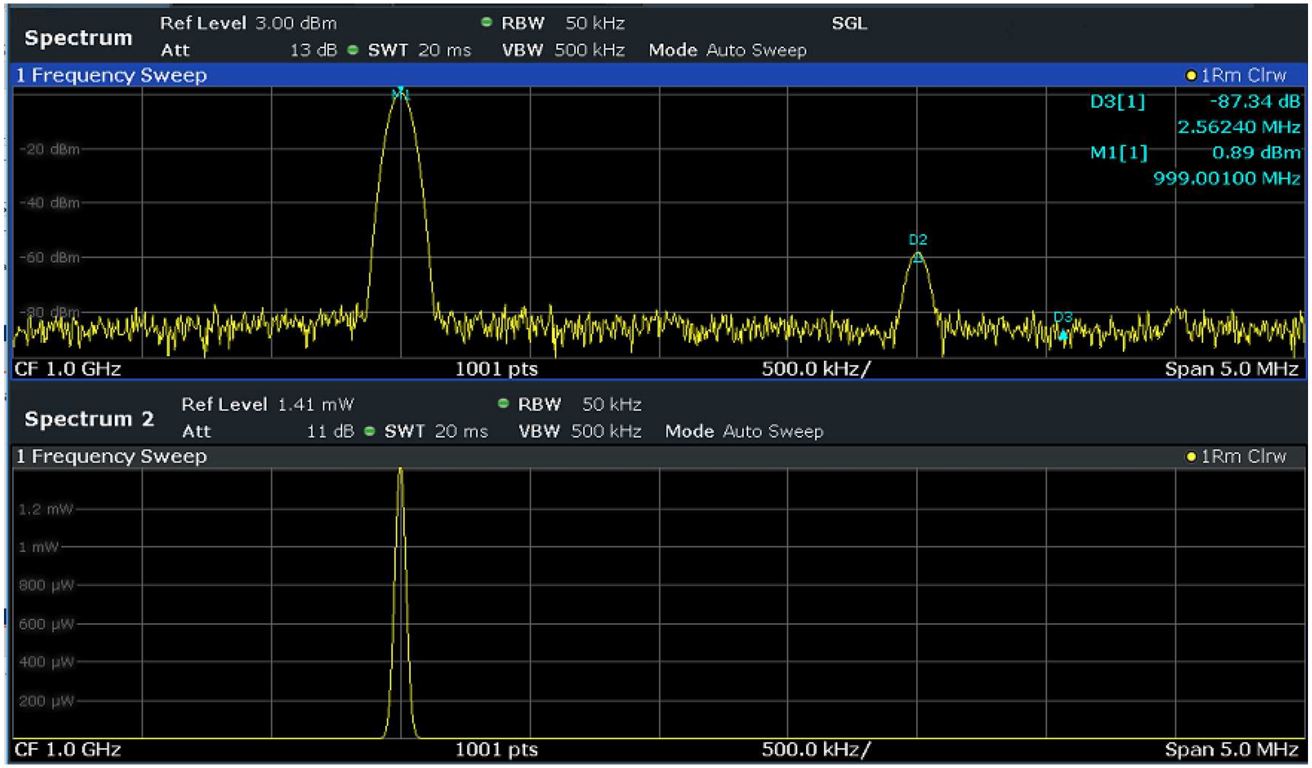
$$10 \cdot \log\left(\frac{100}{1}\right) = 20\ dB$$

What is a factor of 250x?

Hint: It's ¼ of 1000x…

30 dB – 6 dB = 24 dB

Logarithmic vs Linear Scales



Y-axis logarithmic
- shows full range of signal, including the noise floor.
100 dB of range (10 Billion)

Y-axis linear
- shows small fraction of signal, cannot see difference between Lower level signal and noise floor

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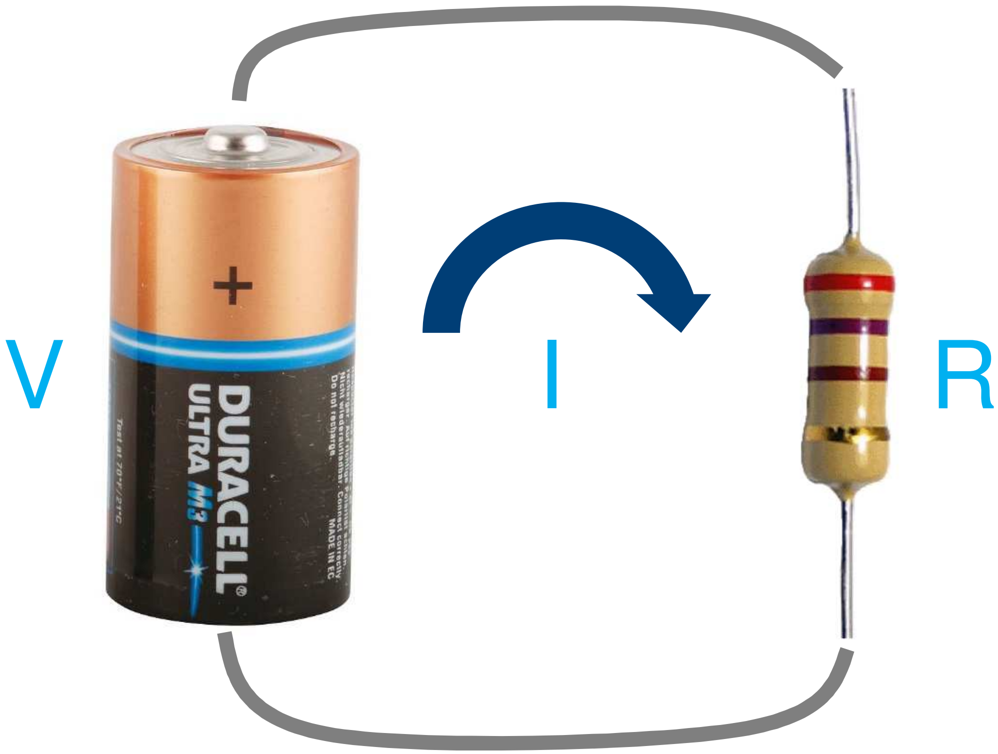
Voltage, Current, and Resistance – Ohm's Law



$$V = IR$$

$$= 5.6\ \text{mA} \cdot 270\ \Omega$$

$$= 1.5\ \text{V}$$

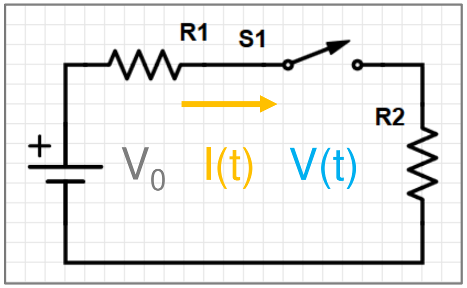
$$I = \frac{V}{R}$$

$$= \frac{1.5\ \text{V}}{270\ \Omega}$$

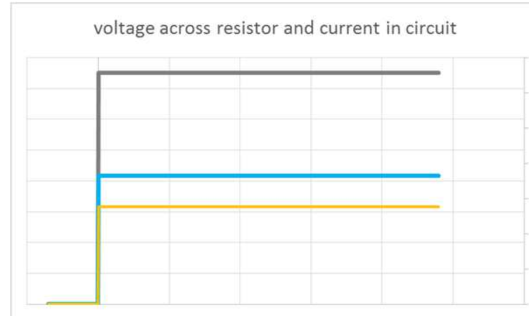
$$= 0.0056\ \text{A}$$

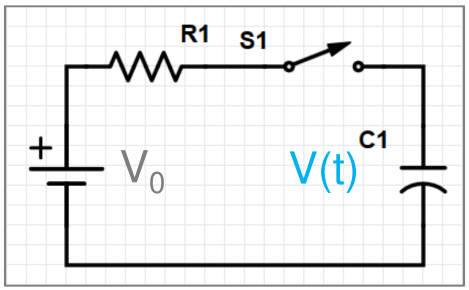
$$= 5.6\ \text{mA}$$

Resistance vs Reactance

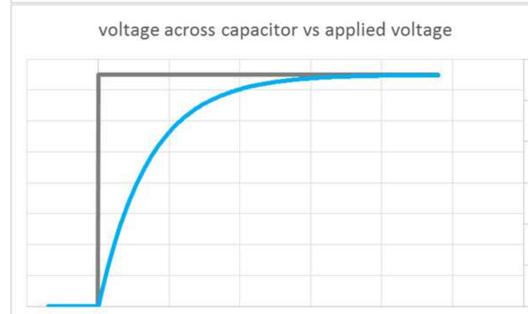


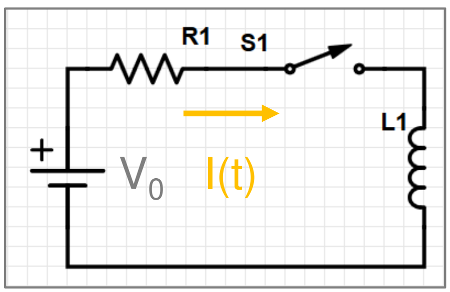
The current through a resistor is proportional to the voltage across it, and the voltage across it is proportional to the current through it



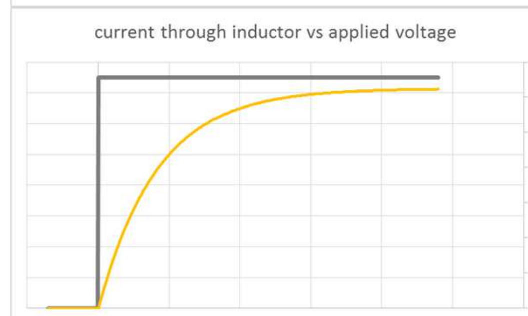


Capacitors resist any instantaneous changes in voltage.

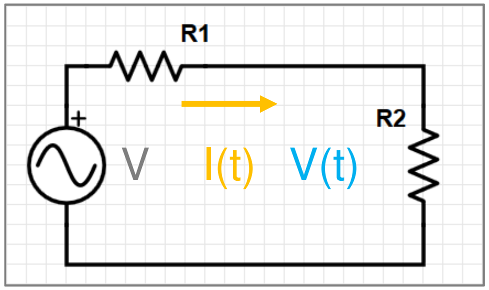


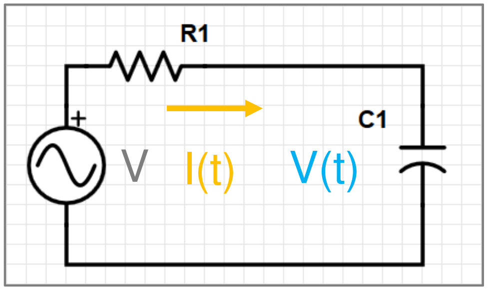


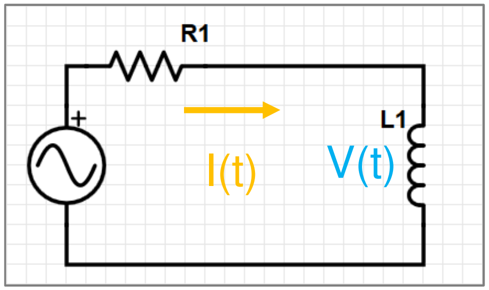
Inductors resist any instantaneous changes in current.

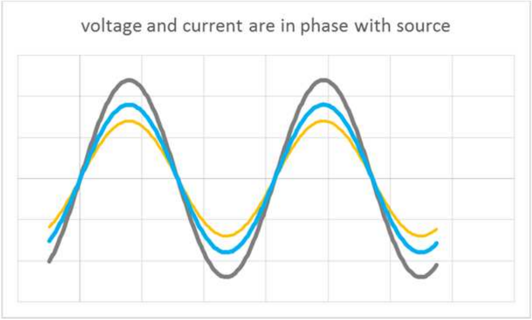


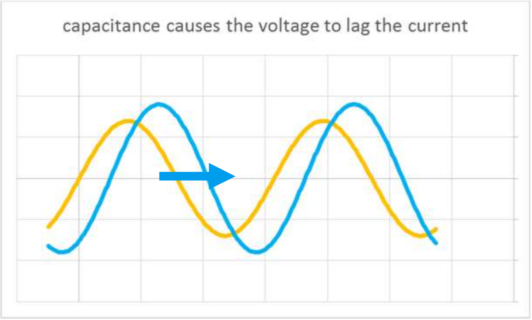
Sinusoidal Signals and Reactance

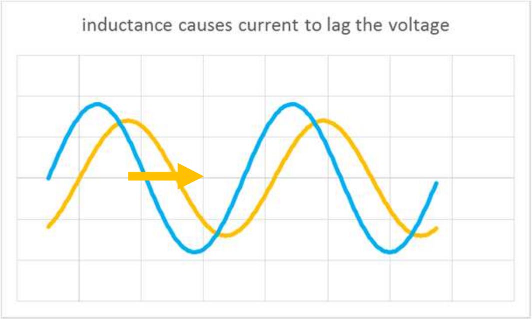




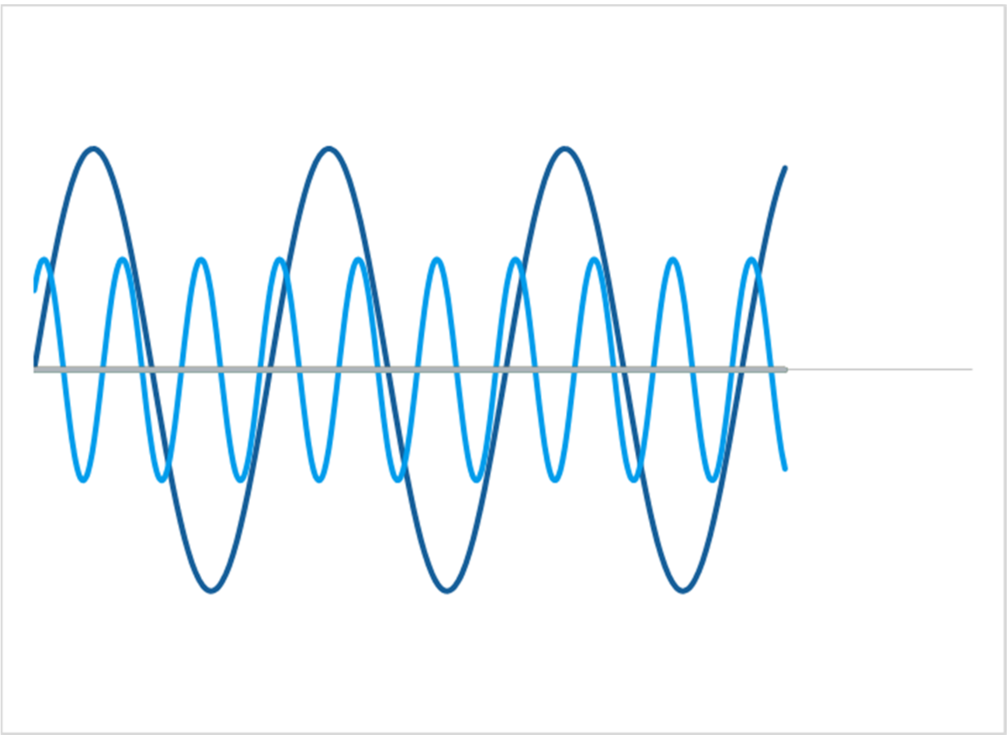








Describing Sinusoidal Signals



Frequency

Amplitude

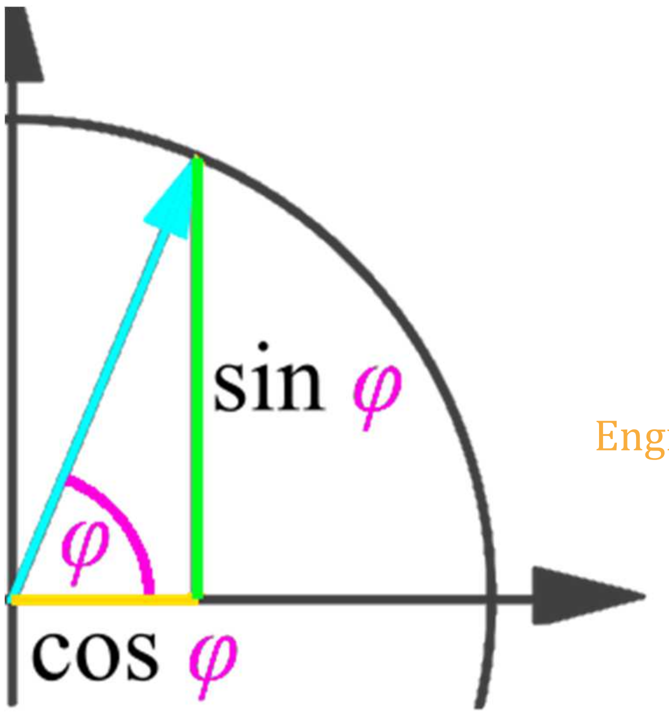
Phase

$$f(t) = c\cos(2\pi f t + \delta)$$

Harmonic Addition Theorem

$$f(t) = a\cos(2\pi f t) + b\sin(2\pi f t)$$

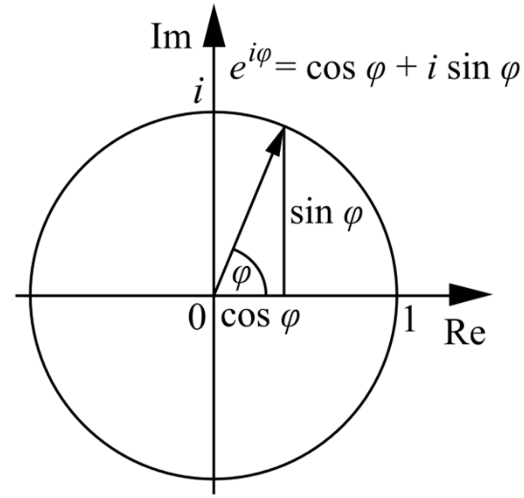
Phase Angle and the Complex Plane



Euler's Formula

$$e^{ix} = \cos x + i \sin x$$

$$e^{j\varphi} = \cos\varphi + j\sin\varphi$$

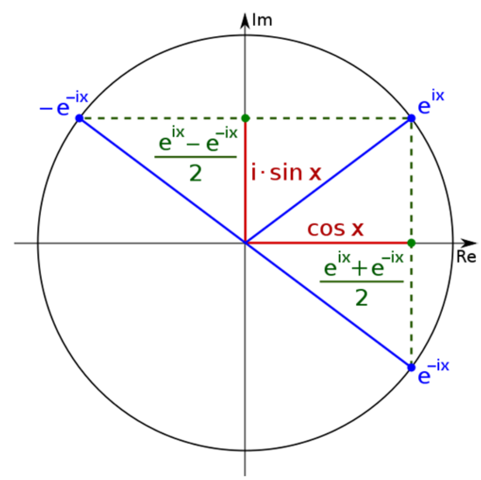


Mathemeticians use i for $\sqrt{-1}$

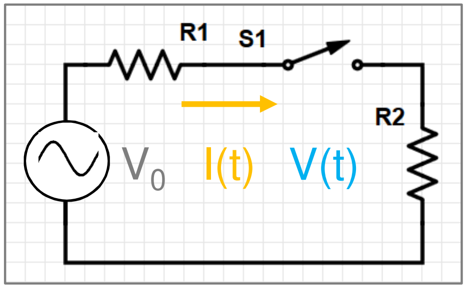
Engineers use j because i is for current!

$$\cos x = \mathrm{Re}\left(e^{ix}\right) = \frac{1}{2}\left(e^{ix} + e^{-ix}\right)$$

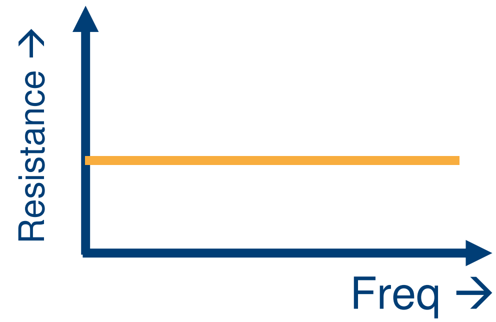
$$\sin x = \mathrm{Im}\left(e^{ix}\right) = \frac{1}{2i}\left(e^{ix} - e^{-ix}\right)$$

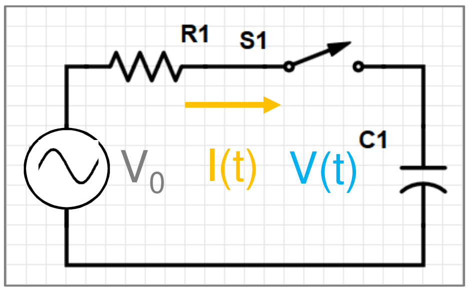


Resistance and Reactance vs Frequency

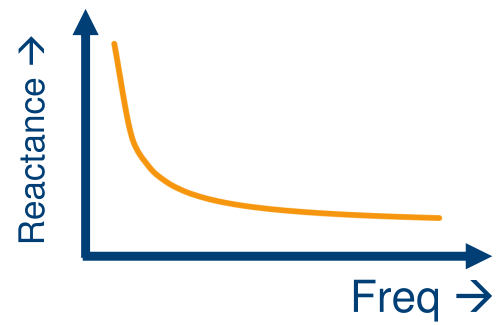


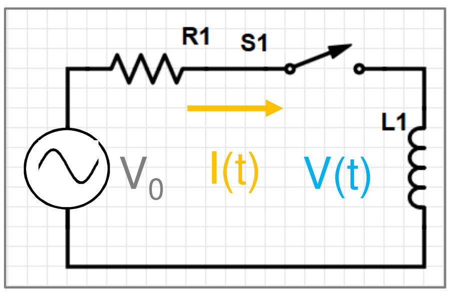
The voltage/current ratio is independent of frequency





The higher the frequency, the lower the voltage, thus higher current. In general this means lower *impedance.*





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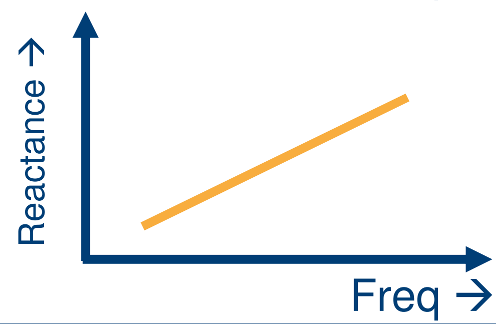


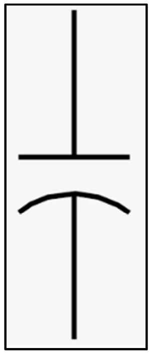
Impedance

$$Z = R + jX$$

Z = Impedance (ratio of Voltage/Current)

R = Resistance

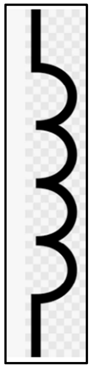
X = Reactance



Capacitor

$$Z = X_c = 1/j\omega C = -j/\omega C$$

Reminder $\omega = 2\,\pi\,f$



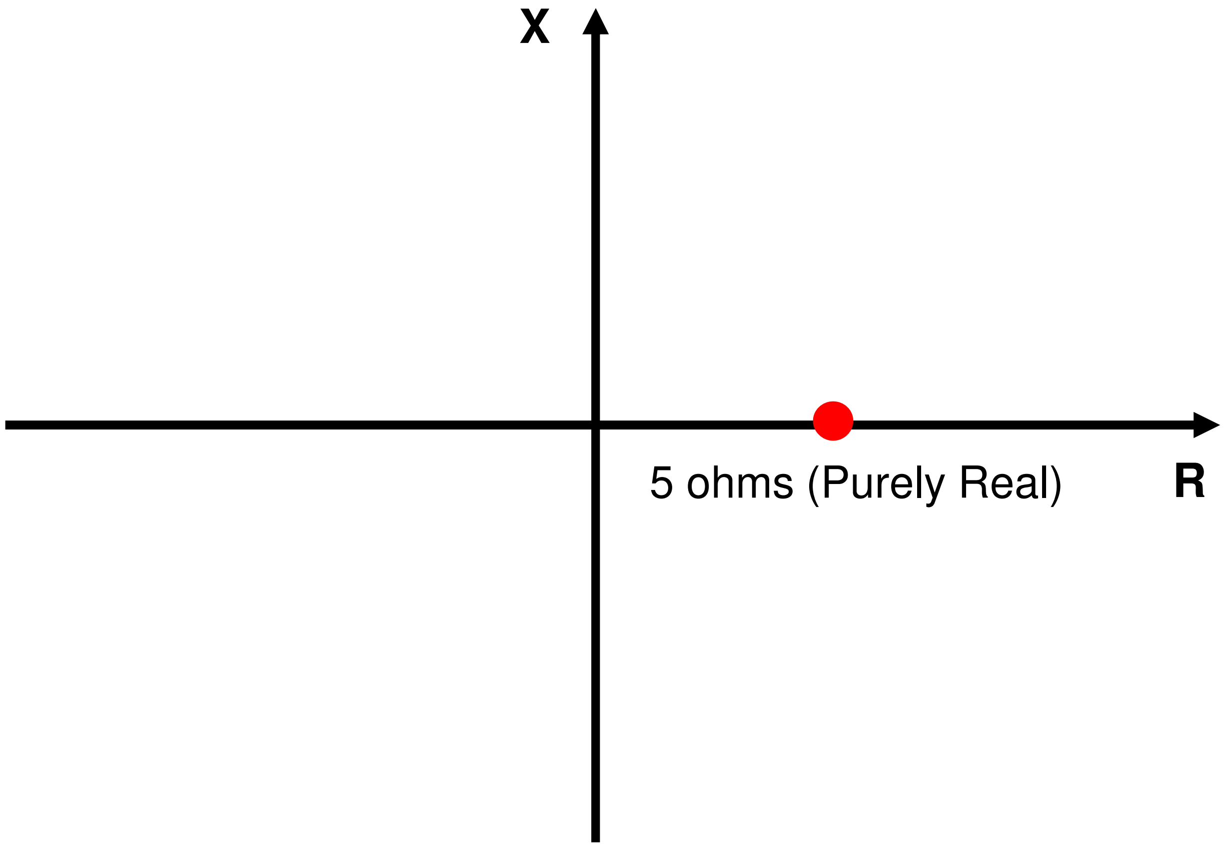
Inductor

$$Z = X_L = j\omega L$$

Mathemeticians use i for $\sqrt{-1}$

Engineers use j because i is for current!

Impedance is a Complex Quantity



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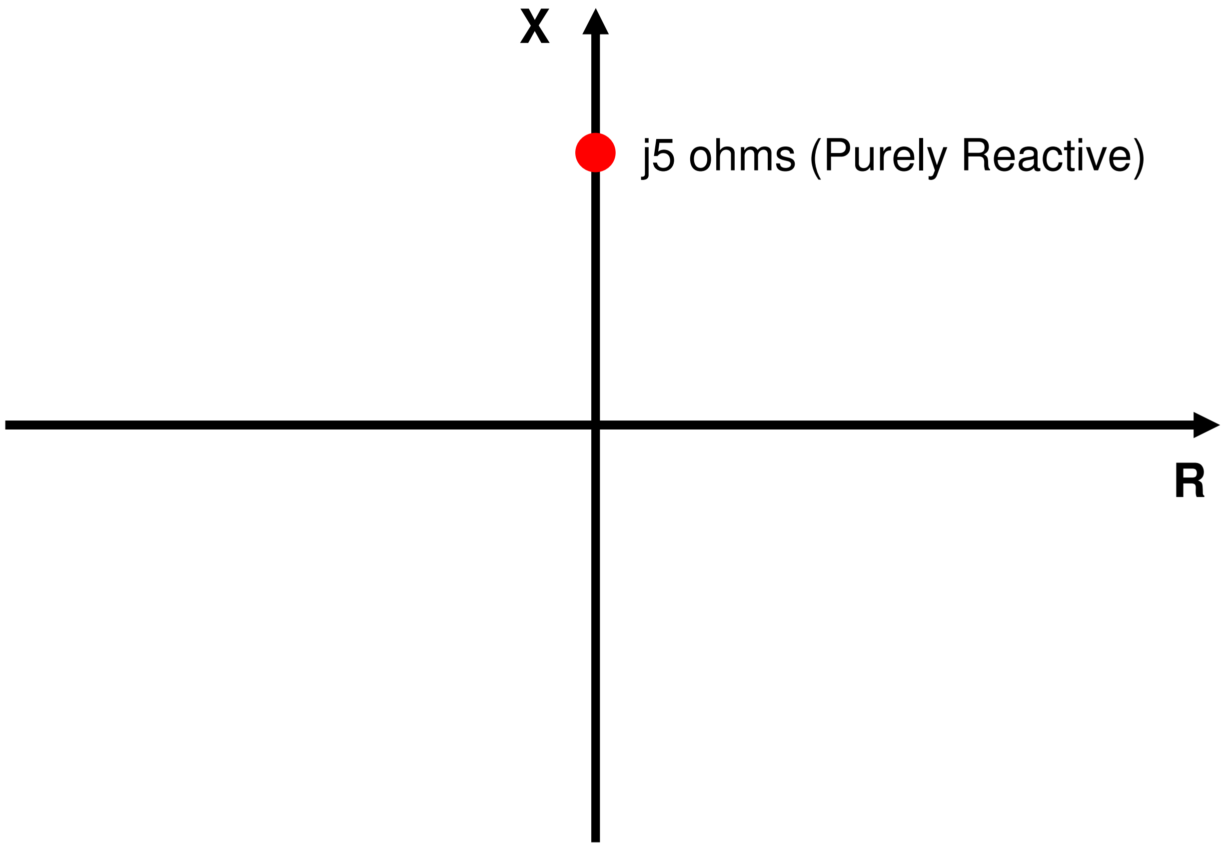

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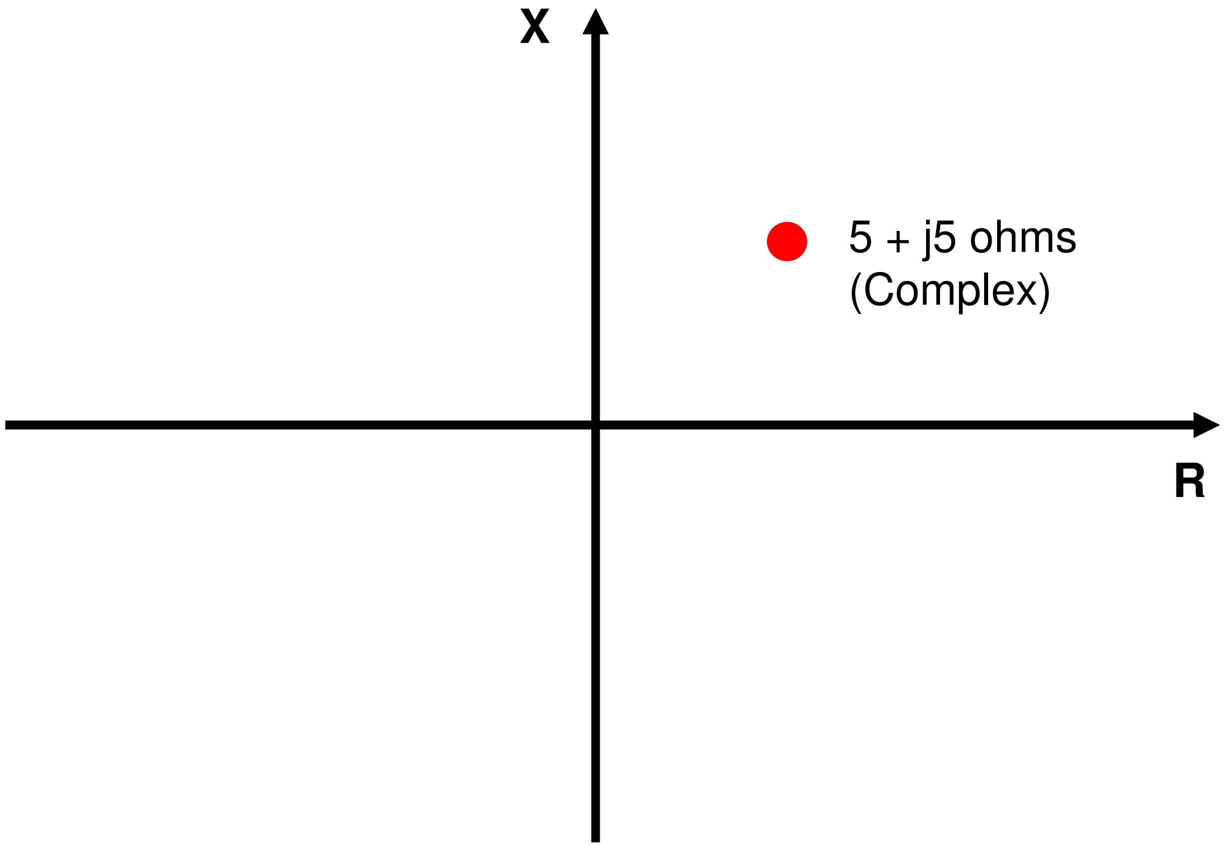

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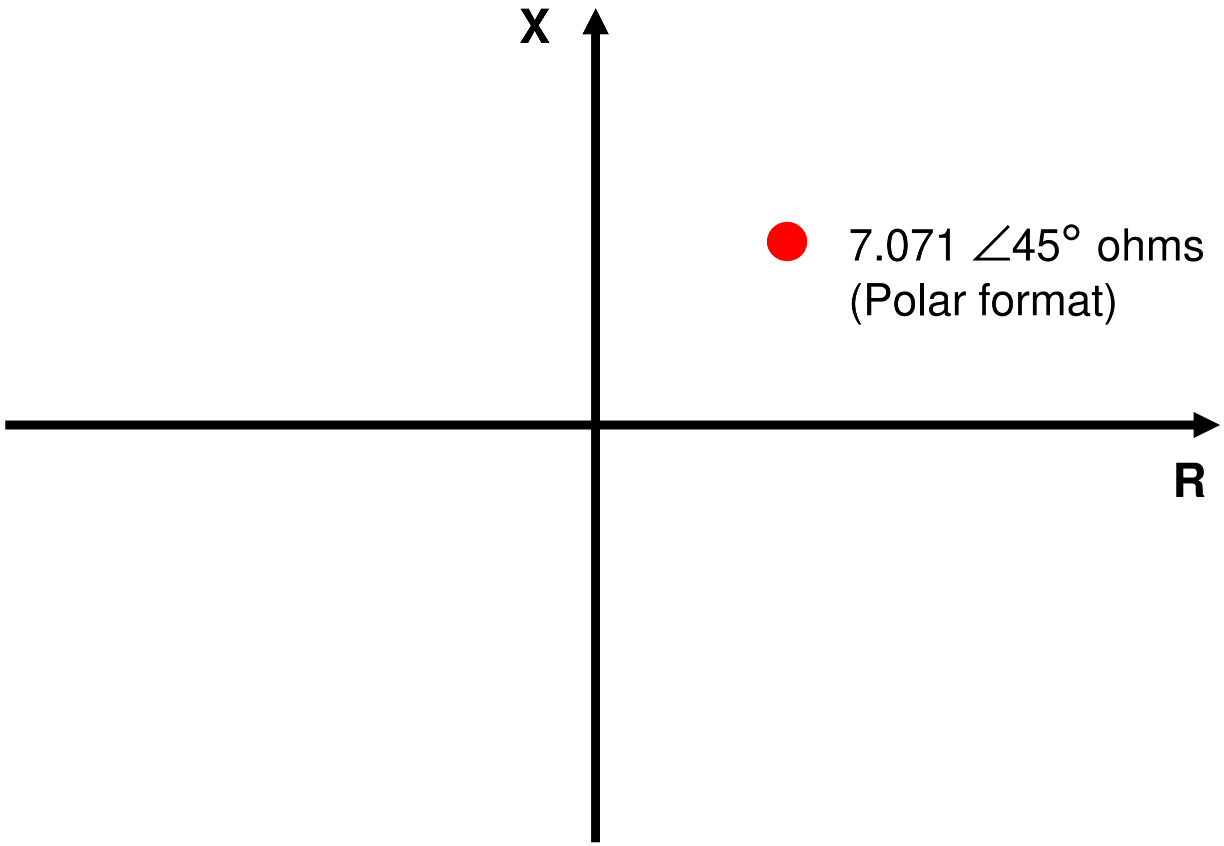
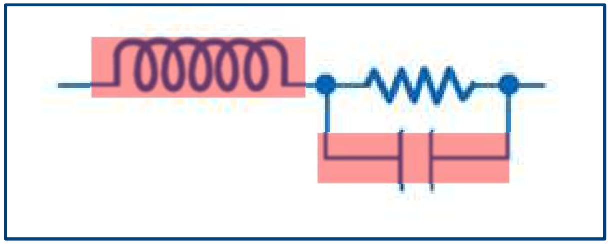
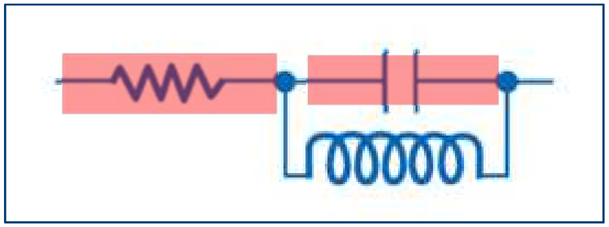


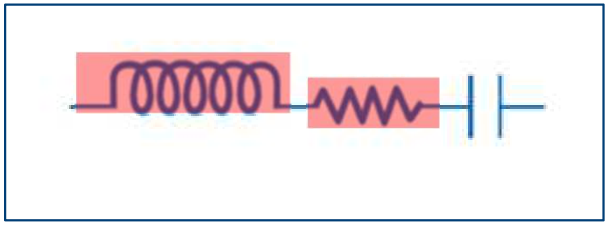
High Frequency Model of Components
Parasitics



Resistor: includes capacitance of the structure and lead inductance



Inductor: includes capacitance of the coil and resistance of the wire



Capacitor: includes the lead inductance and series resistance

* High Frequency *Parasitics*

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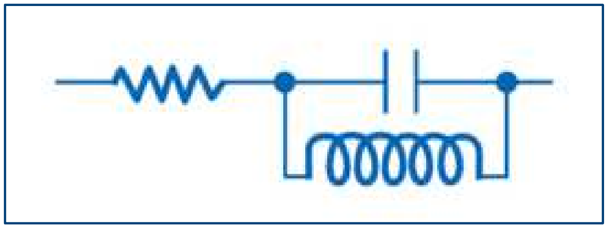
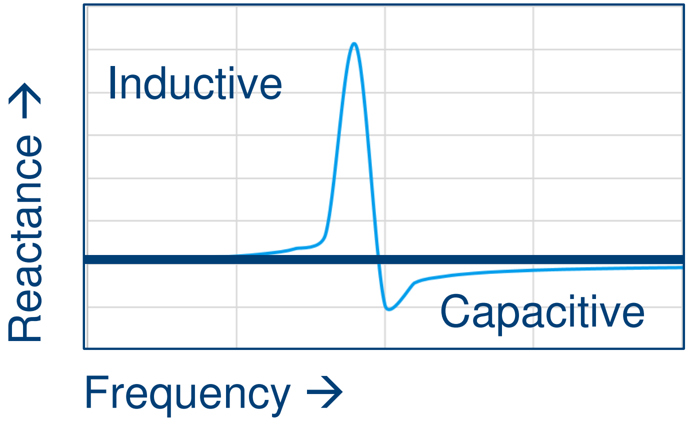
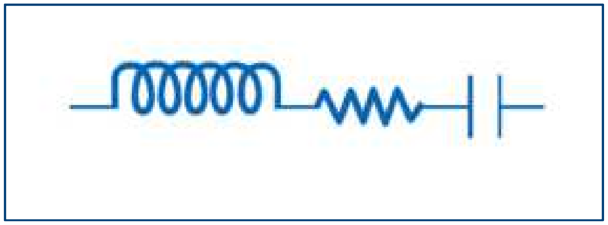
High Frequency Model of Components
Parasitics

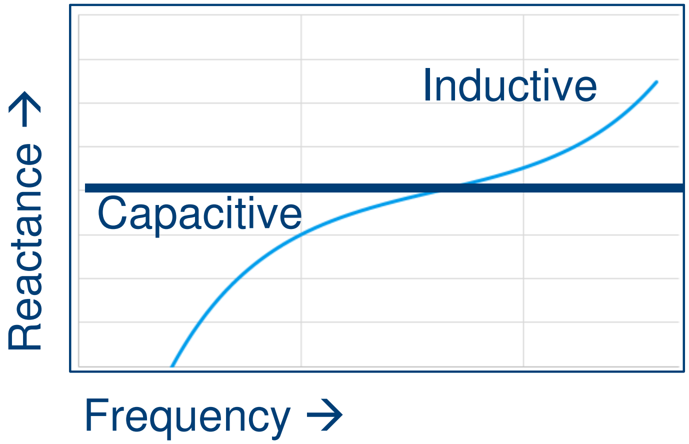


INDUCTOR





CAPACITOR



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- **Power**
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Power Requires both Current and Voltage

High Voltage
(no current)

High Current
(no voltage)

Plenty of Both!

Calculating Power and Its Units

$$P = V \cdot I$$

$$volts\ [V] \cdot amps\ [A] = watts\ [W] = (1\ Joule\,/\,s)$$

Remember?

$V = IR$ and

$I = \dfrac{V}{R}$ so

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

Linear $ratio = \dfrac{P_1}{P_0}$ (eg. “triple”, “half”, 10x, etc.)

Log scale $ratio = 10 \log\left(\dfrac{P_1}{P_0}\right)$ dB

Saying something is “3 dB” is like saying it’s “twice” or “200%”.

“Twice of what?”

dB or Not dB?

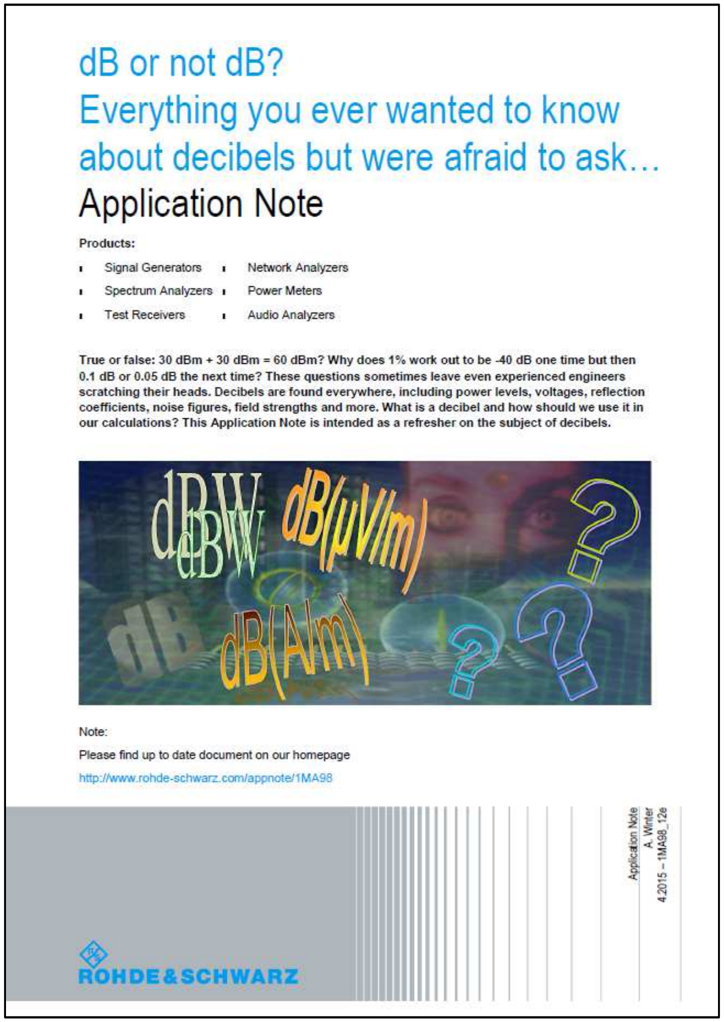
Since “dB”s measure a relative difference, how can we talk about actual, absolute power levels?

Easy!
We simply define a reference power (by custom) and use it for P_0

Let’s use P_0 = 1 milliwatt [mW]

$$P\ [dBm] = 10\log\left(\frac{P\ [mW]}{P_0}\right) = 10\log\left(\frac{P\ [mW]}{1\ mW}\right)$$

R&S Application Note 1MA98


dB or not dB?
Everything you ever wanted to know about decibels but were afraid to ask…
Application Note

Products:

- Signal Generators
- Spectrum Analyzers
- Test Receivers
- Network Analyzers
- Power Meters
- Audio Analyzers

True or false: 30 dBm + 30 dBm = 60 dBm? Why does 1% work out to be -40 dB one time but then 0.1 dB or 0.05 dB the next time? These questions sometimes leave even experienced engineers scratching their heads. Decibels are found everywhere, including power levels, voltages, reflection coefficients, noise figures, field strengths and more. What is a decibel and how should we use it in our calculations? This Application Note is intended as a refresher on the subject of decibels.

Note:
Please find up to date document on our homepage
http://www.rohde-schwarz.com/appnote/1MA98

Application Note
A. Winter
4.2015 – 1MA98_12e

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Some dBm Math…

$$1\ mW = 10 \cdot \log\left(\frac{1\ mW}{1\ mW}\right) = 0\ dBm$$

$$10\ mW = 10 \cdot \log\left(\frac{10\ mW}{1\ mW}\right) = 10\ dBm$$

$$1\ W = 10 \cdot \log\left(\frac{1000\ mW}{1\ mW}\right) = 30\ dBm$$

$$2\ W = 10 \cdot \log\left(\frac{2000\ mW}{1\ mW}\right) = 33\ dBm$$

$$\begin{aligned} 11\ mW &= 10\ mW + 1\ mW \\ &= 10 \cdot \log\left(\frac{11\ mW}{1\ mW}\right) \\ &= 10.4\ dBm \end{aligned}$$

$$\begin{aligned} 110\ mW &= 100\ mW + 10\ mW \\ &= 10 \cdot \log\left(\frac{110\ mW}{1\ mW}\right) \\ &= 20.4\ dBm \end{aligned}$$

Common (Typical) Power Levels

80 dBm	100 kW	Typical transmission power of FM radio station with 50-kilometre (31 mi) range
62 dBm	1.588 kW	1500 W is the maximal legal power output of a U.S. ham radio station
60 dBm	1 kW	Typical combined radiated RF power of microwave oven elements
55 dBm	~300 W	Typical single-channel RF output power of a Ku-band geostationary satellite
50 dBm	100 W	Typical maximal output RF power from a ham radio HF transceiver
37 dBm	5 W	Typical maximal output RF power from a handheld ham radio VHF/UHF transceiver
36 dBm	4 W	Typical maximal output power for a citizens band radio station (27 MHz) in many countries
33 dBm	2 W	Maximal output from a GSM850/900 mobile phone
24 dBm	251 mW	Maximal output from a UMTS/3G mobile phone (Power class 3 mobiles)
15 dBm	32 mW	Typical wireless LAN transmission power in laptops
4 dBm	2.5 mW	Bluetooth Class 2 radio, 10 m range
–10 dBm	100 µW	Maximal received signal power of wireless network (802.11 variants)
–100 dBm	0.1 pW	Minimal received signal power of wireless network (802.11 variants)
–127.5 dBm	0.178 fW	Typical received signal power from a GPS satellite
–174 dBm	0.004 aW	Thermal noise floor for 1 Hz bandwidth at room temperature (20 °C)

What to do with Volts and dB?

- **When using dB, ALWAYS think POWER, even if you're talking about Voltage!!!**
  - **Example: A 1 Volt signal is passed through a 10 dB Attenuator**
    - What is the resulting voltage on the output, assuming a 50 ohm system?

$10\text{ dB} = 10\text{ LOG (Pin / Pout)}$

$10\text{ dB} = 10\text{ LOG }[(\text{Vin}^2/50) / (\text{Vout}^2/50)]$

$10\text{ dB} = 10\text{ LOG }[(\text{Vin / Vout})^2]$

$\boxed{10\text{ dB} = 20\text{ LOG }[1\text{V / Vout}]}$

$10\text{^}(10/20) = 1\text{ V / Vout}$

$\text{Vout} = 1\text{ V} / 10\text{ ^ }(0.5) = 0.316\text{ Volts}$

Example: Convert dBm to dBuV

- Reminder, ALWAYS think POWER!
  - Example: Convert a 0 dBm signal to dBuV for a 50 ohm System

Power Ratio $= 10\ LOG\ [\ (1\ mW) / (\ V^2/R)]$

Power Ratio $= 10\ LOG\ \{\ (1\ mW) / [(1uV)^2/50]\ \}$

Power Ratio $= 10\ LOG\ \{\ (1\ mW) / (2E\text{-}14\ W)\ \}$

Power Ratio $= 107$ dBuV

To convert dBm into dBuV, add 107 dB

What are some other dB terms you will see?

- dBc
  - The ratio of a signal to a carrier (c).
  - Used for harmonic test, Spurious test ….
  - $P\ [dBc] = 10 \log \left(\frac{\text{Signal}\ [mW]}{\text{Carrier0}\ [\text{mW}]} \right)$ =Signal [dBm] – Carrier0 [dBm]

- dBm/Hz
  - The power is ratio vs a 1 Hz BW.
  - Used for power measurements of Noise like signals.

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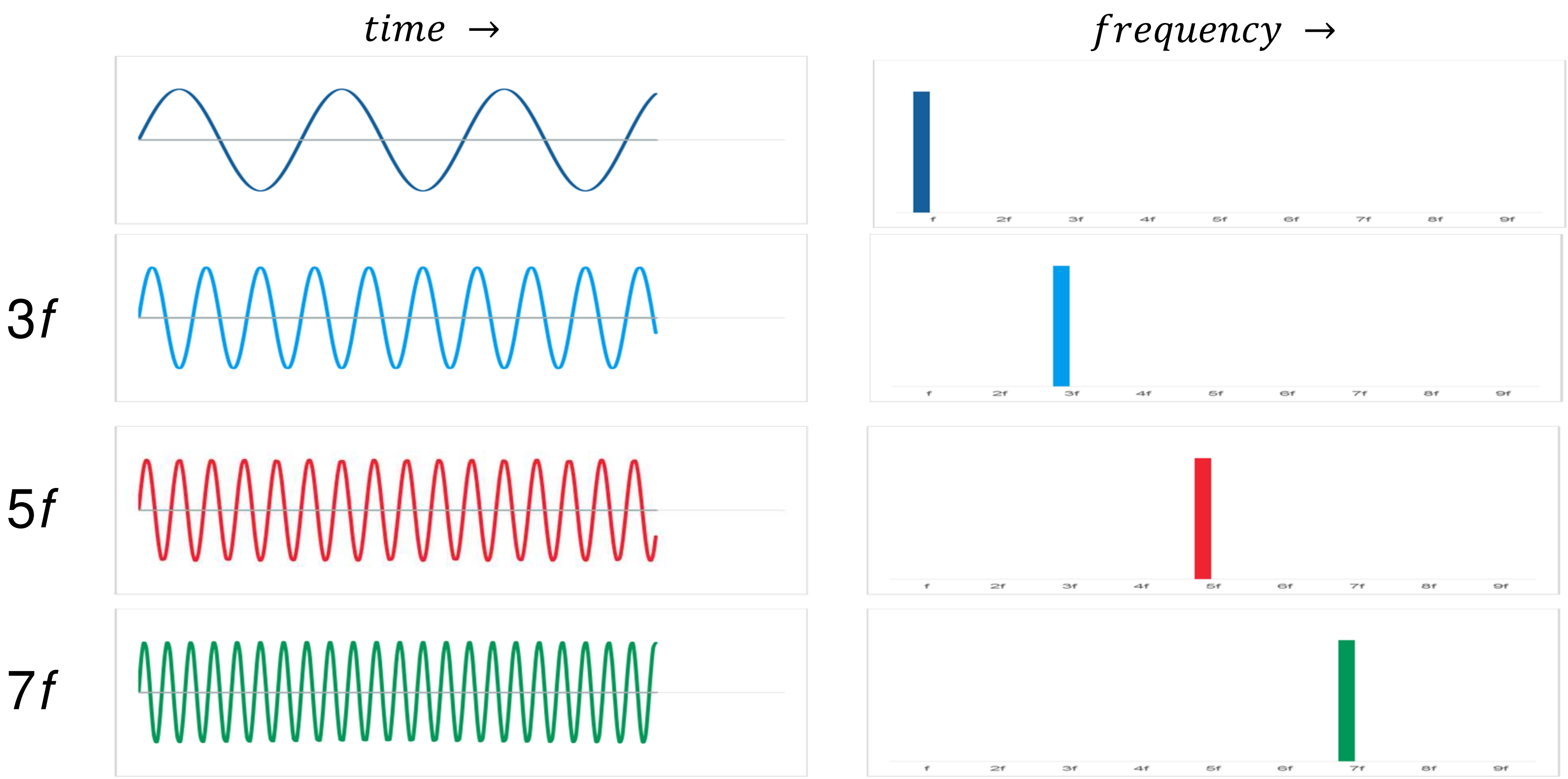
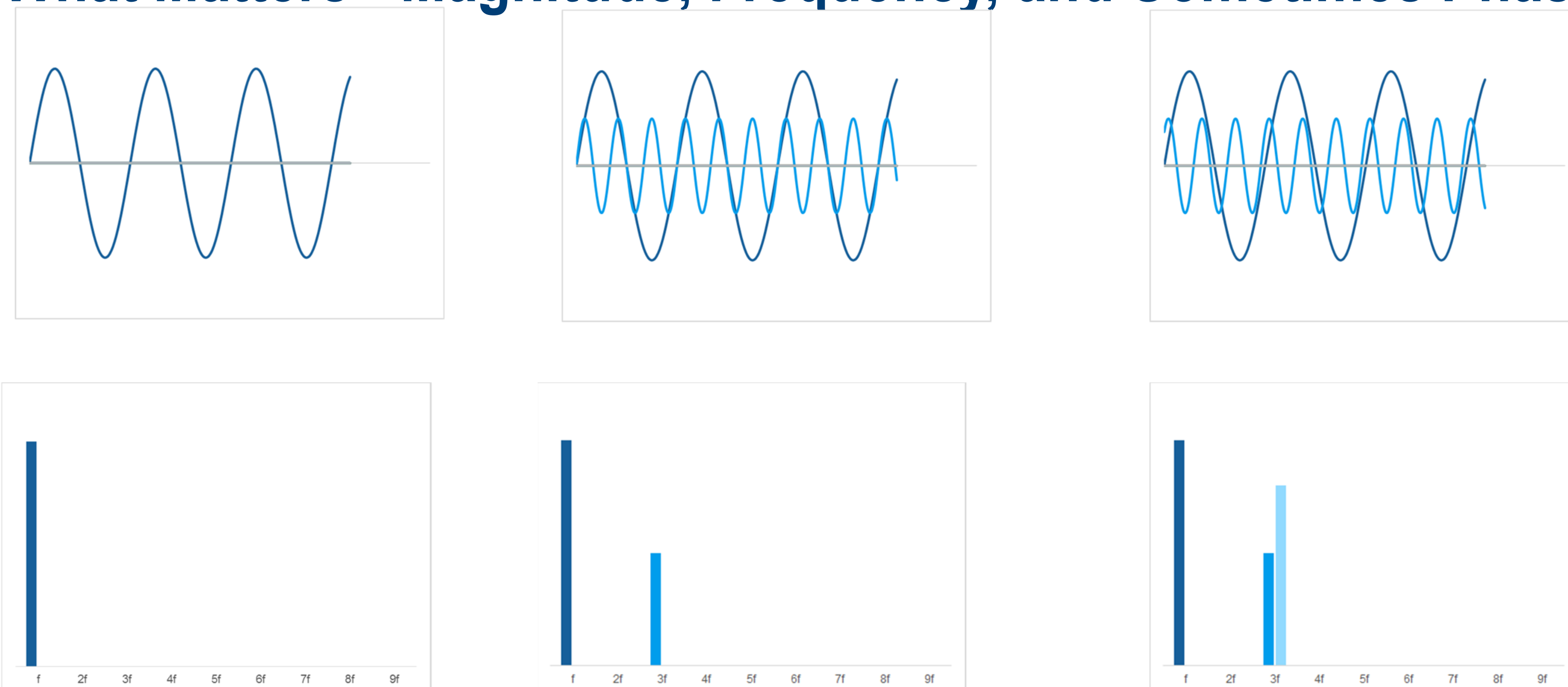
- Maxwell's Equations
- Electromagnetic Waves & Propagation

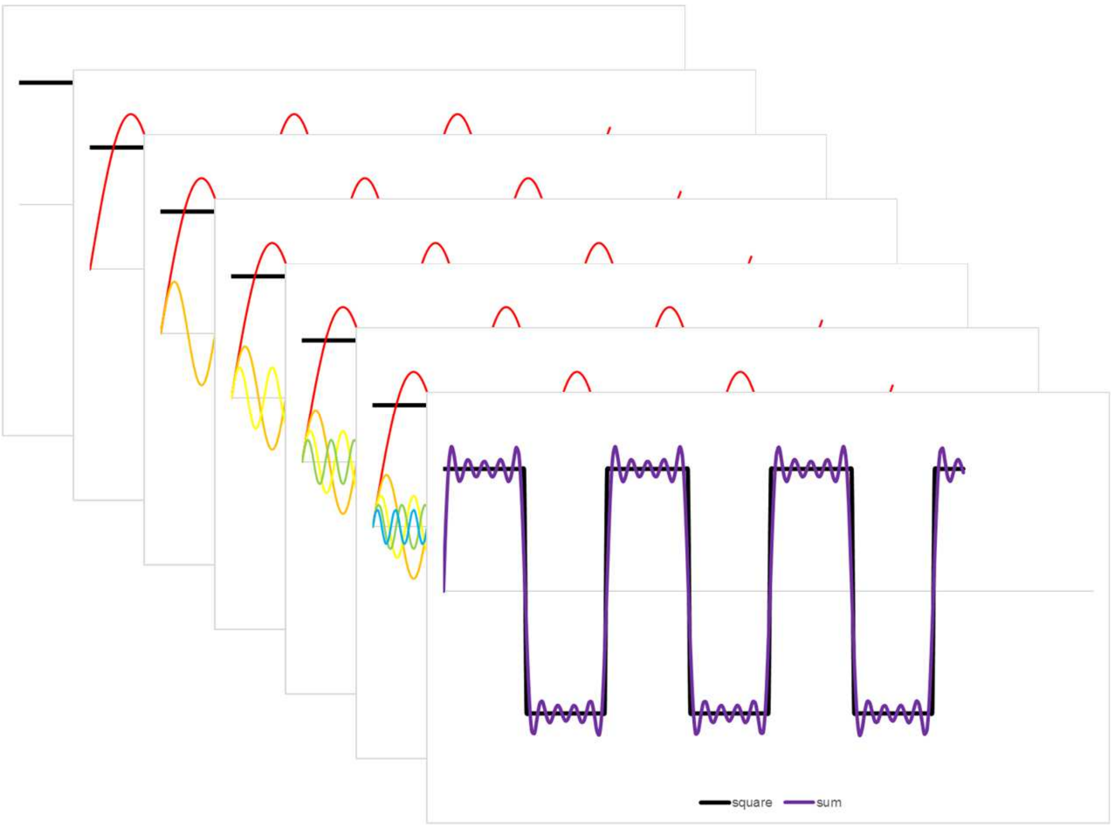
Time Domain and Frequency Domain

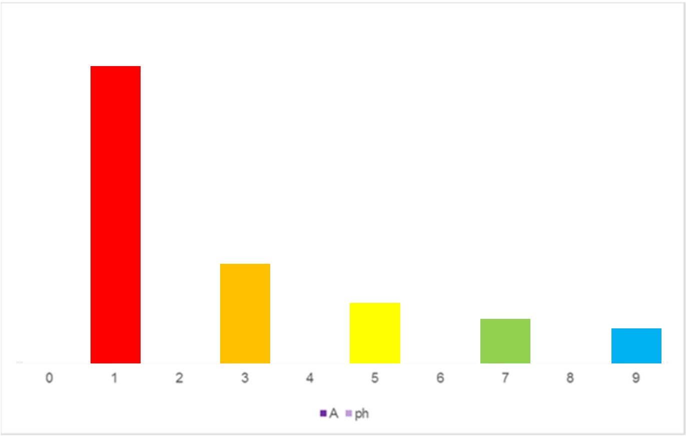


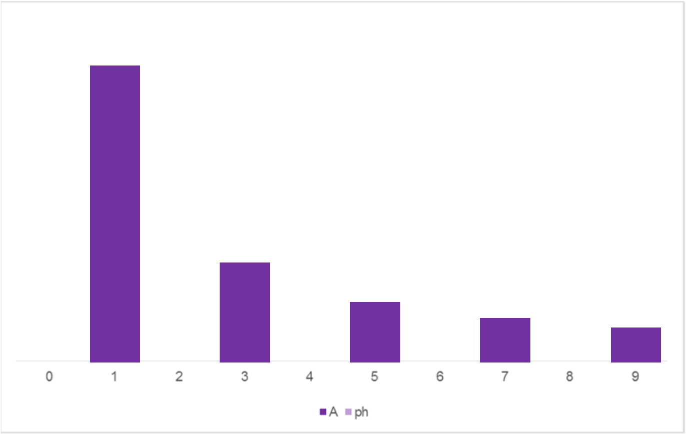
What Matters - Magnitude, Frequency, and Sometimes Phase



Representing a Square Wave







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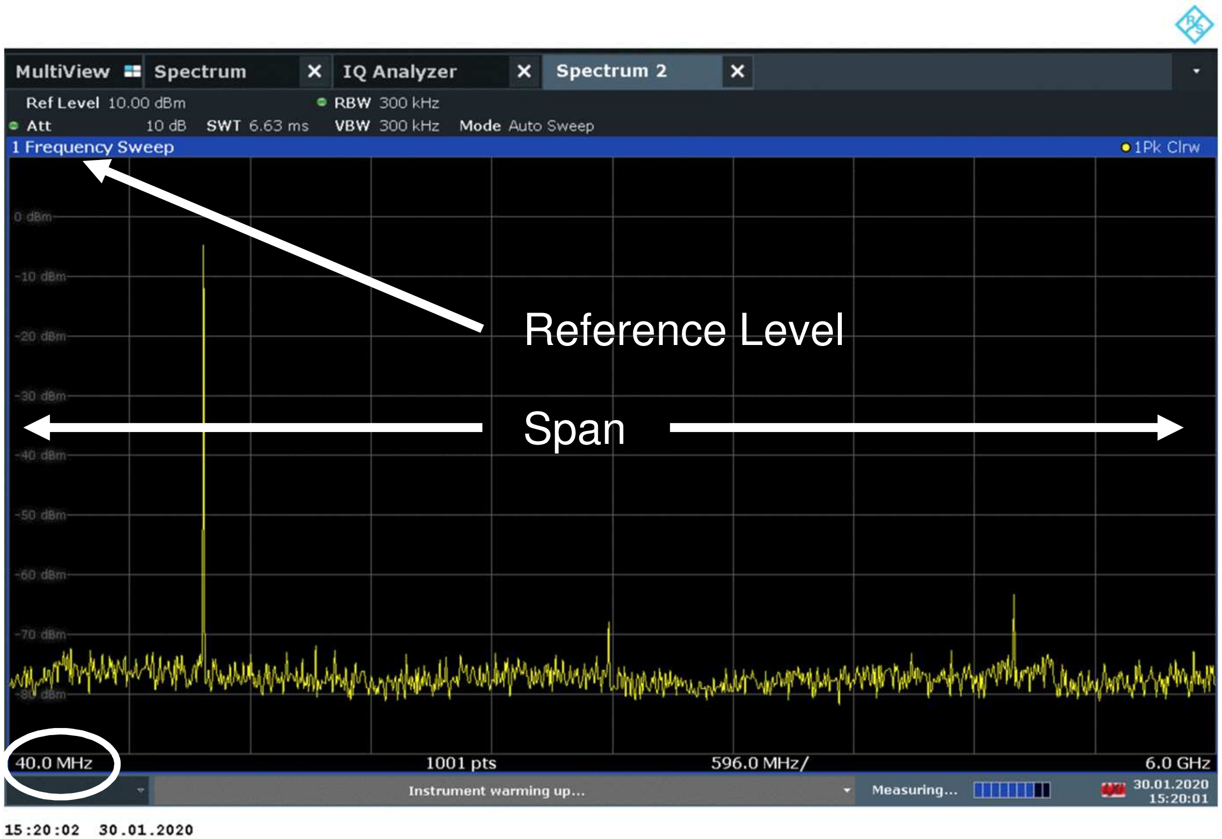
Spectrum as seen by a Spectrum Analyzer



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Maxwell's Equations

$$\nabla \cdot \mathbf{E} = 4\pi\rho$$

Gauss's Law

$$\nabla \cdot \mathbf{B} = 0$$

Gauss's Law for Magnetism

$$\nabla \times \mathbf{E} = -\frac{1}{c}\frac{\partial \mathbf{B}}{\partial t}$$

Faraday's Law

$$\nabla \times \mathbf{B} = \frac{1}{c}\left(4\pi\mathbf{J} + \frac{\partial \mathbf{E}}{\partial t}\right)$$

Ampere's Law

Maxwell's addition

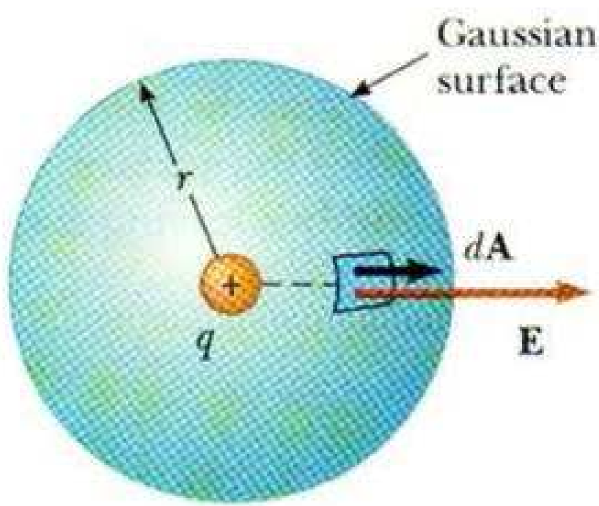
James Clerk Maxwell
(1831–1879)

http://en.wikipedia.org/wiki/Maxwell's_equations

Maxwell's Equations – Gauss's Law

► The electric field flux emanating from an enclosed surface is proportional to the electric charge within the surface

$$\nabla \cdot \mathbf{E} = 4\pi\rho$$

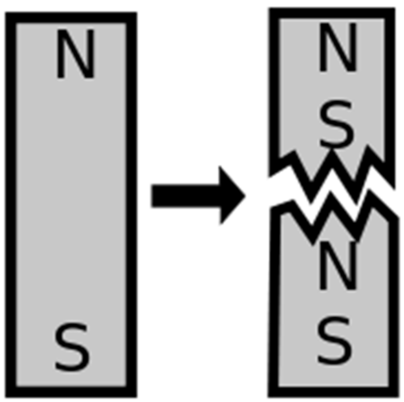


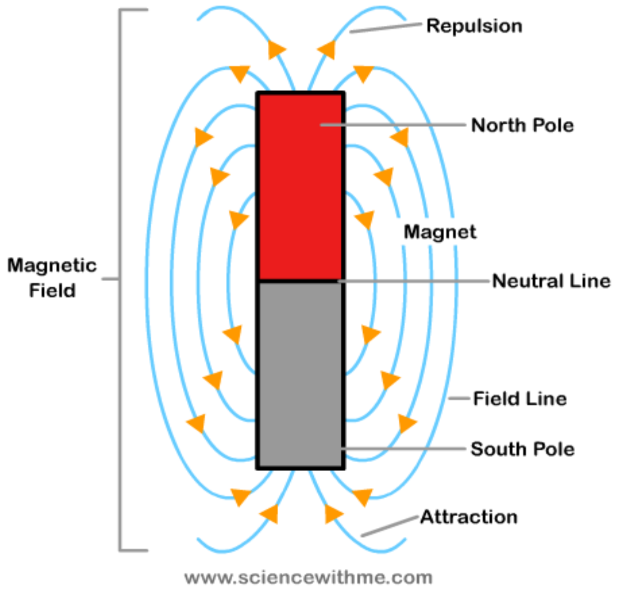
Carl Friedrich Gauss
1777 - 1855

Maxwell's Equations – Gauss's Law of Magnetism

- the magnetic field flux emanating from an enclosed surface is zero
- magnetic monopoles do not exist; every North has a South

$$\nabla \cdot \mathbf{B} = 0$$

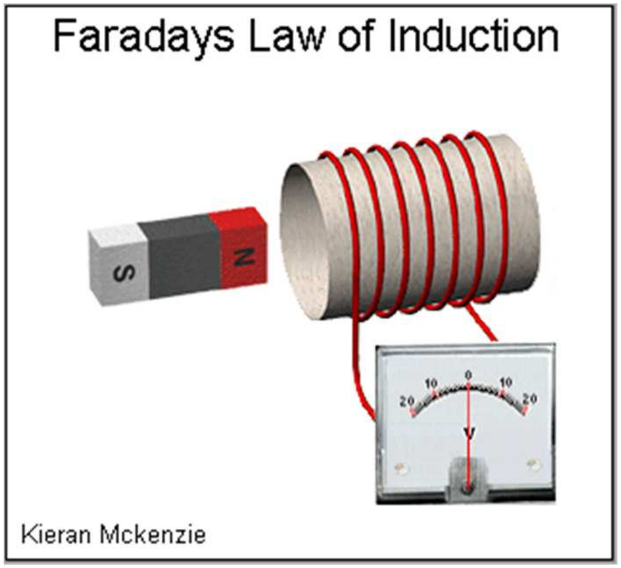




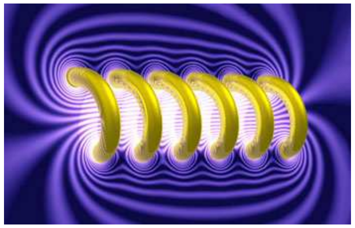
Maxwell's Equations – Faraday's Law

- A changing magnetic field induces an electric field

$$\nabla \times \mathbf{E} = -\frac{1}{c}\frac{\partial \mathbf{B}}{\partial t}$$



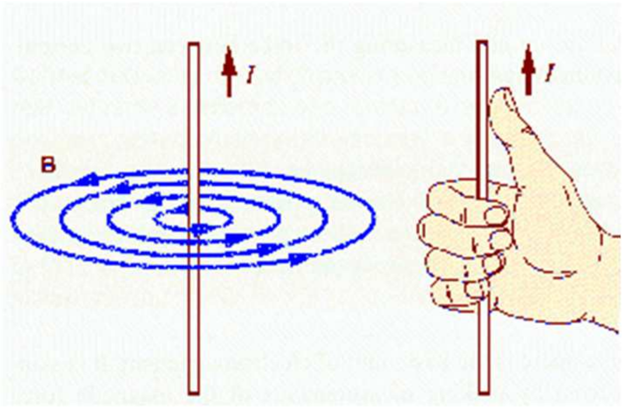
Michael Faraday
1791-1867



Maxwell's Equations – Ampere's Law

- An electric current creates a magnetic field
- A changing electric field also creates a magnetic field

$$\nabla \times \mathbf{B} = \frac{1}{c}\left(4\pi\mathbf{J} + \frac{\partial\mathbf{E}}{\partial t}\right)$$



Andre-Marie Ampere
1775-1836

Laws of Faraday and Ampere (with Maxwell's Observation)

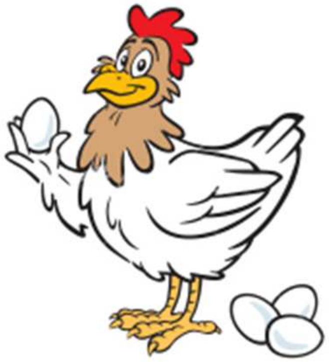
$$\nabla \times \mathbf{E} = -\frac{1}{c}\frac{\partial \mathbf{B}}{\partial t}$$

A changing magnetic field creates a perpendicular electric field

$$\nabla \times \mathbf{B} = \frac{1}{c}\left(4\pi \mathbf{J} + \frac{\partial \mathbf{E}}{\partial t}\right)$$

A changing electric field creates a perpendicular magnetic field

Oh, and an electric current will also create a magnetic field

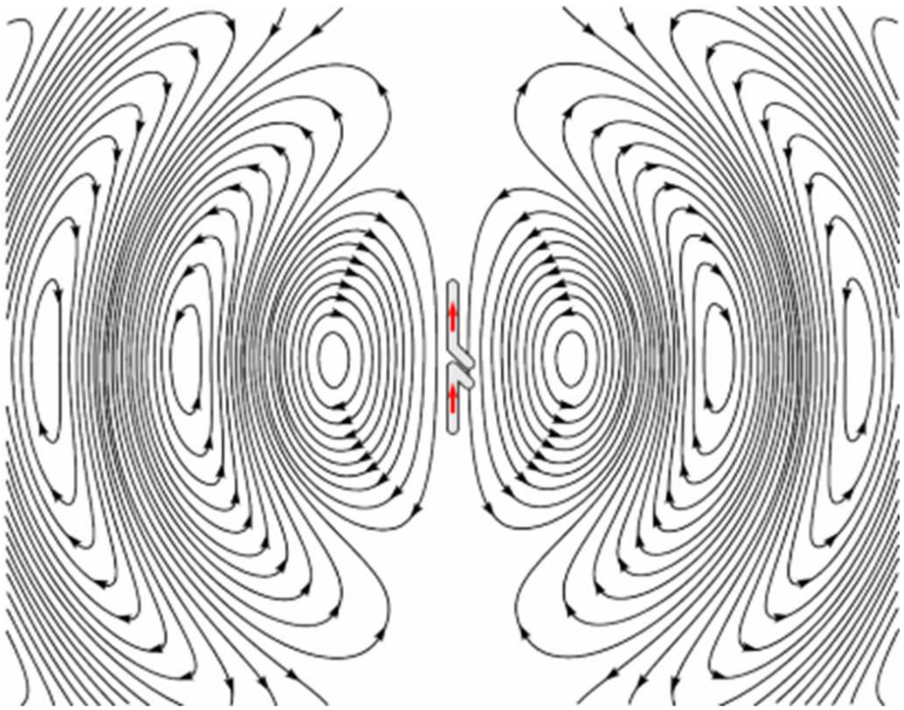


Creating ElectroMagnetic Fields and Waves

An electric current in a wire creates a magnetic field in the space around it

A *changing* electric current creates a *changing* magnetic field

An antenna converts conducted RF into electromagnetic waves and vice-versa.



Antenna Basics

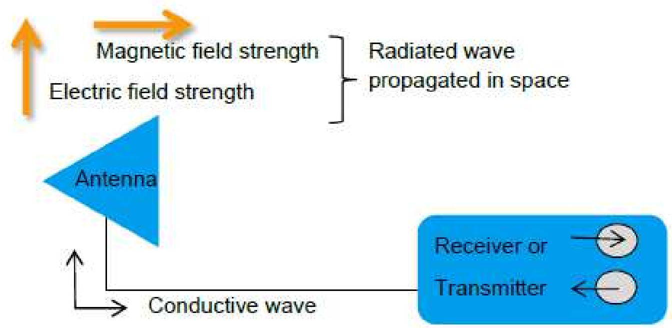


Figure 1: Basic antenna functionality

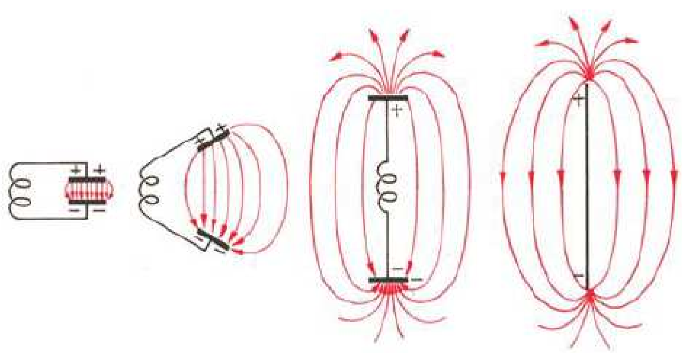
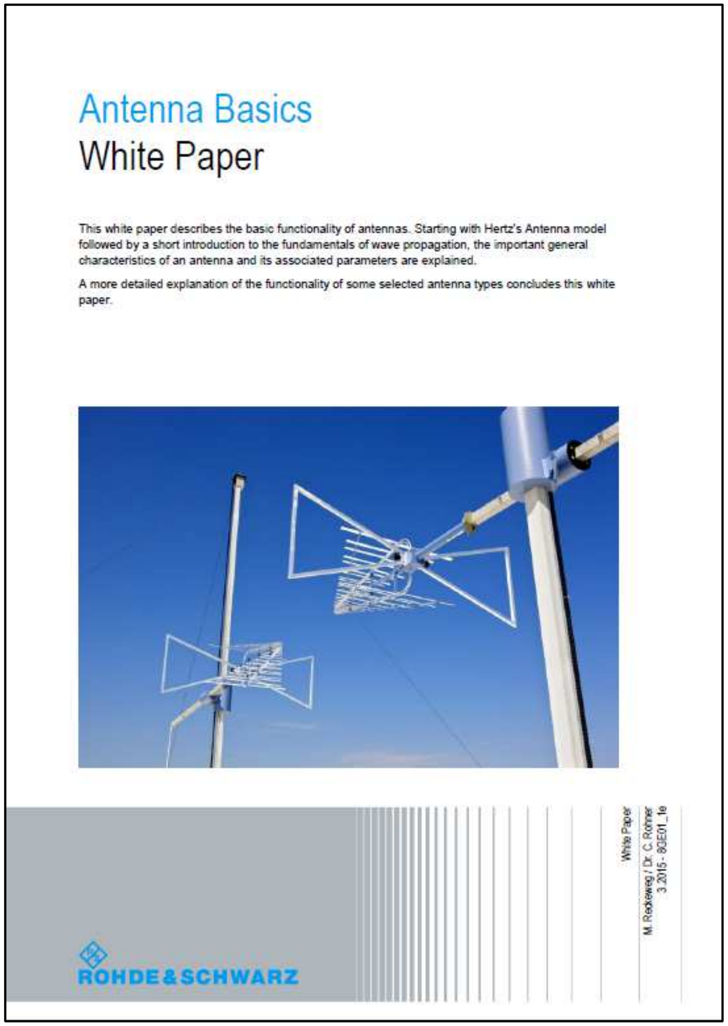


Figure 2: Heinrich Hertz's antenna model

R&S White Paper 8GE01



Antenna Basics
White Paper

This white paper describes the basic functionality of antennas. Starting with Hertz's Antenna model followed by a short introduction to the fundamentals of wave propagation, the important general characteristics of an antenna and its associated parameters are explained.

A more detailed explanation of the functionality of some selected antenna types concludes this white paper.

White Paper
M. Reckeweg / Dr. C. Rohner
3.2015 - 8GE01_1e

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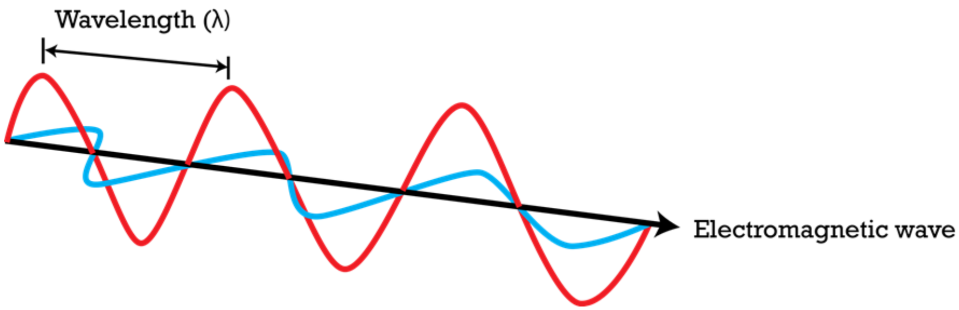
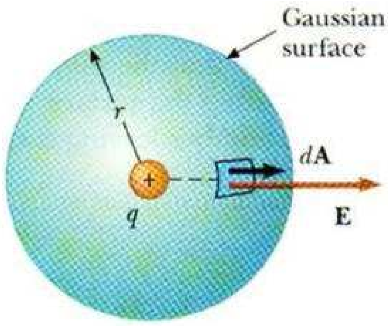
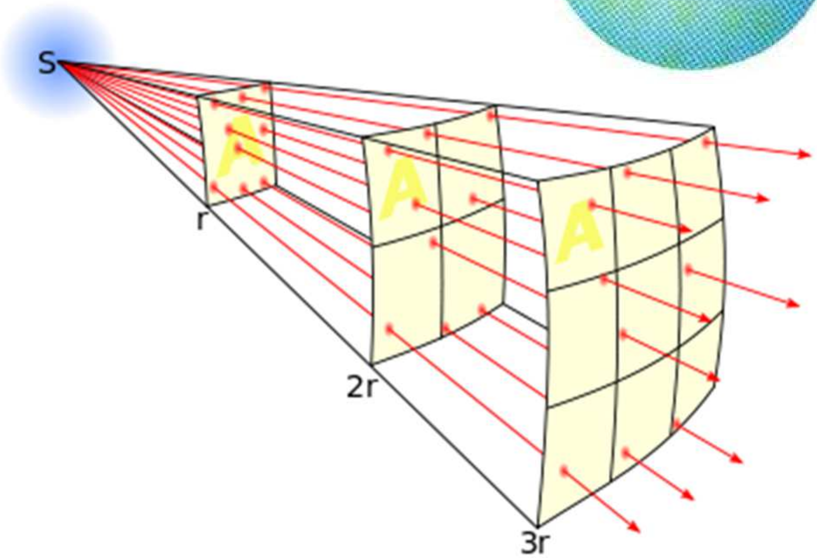
Transverse Waves and Polarization



Free Space Path Loss

- A signal transmitted by an isotropic radiator into free space will propagate outwards in the form of a sphere ($A = 4\pi d^2$)
- As the sphere expands, the intensity of the signal over the surface area of the sphere decreases as per the inverse square law
- Thus, FSPL increases with increasing distance





$$S = P_{TX} \frac{1}{4\pi d^2}$$

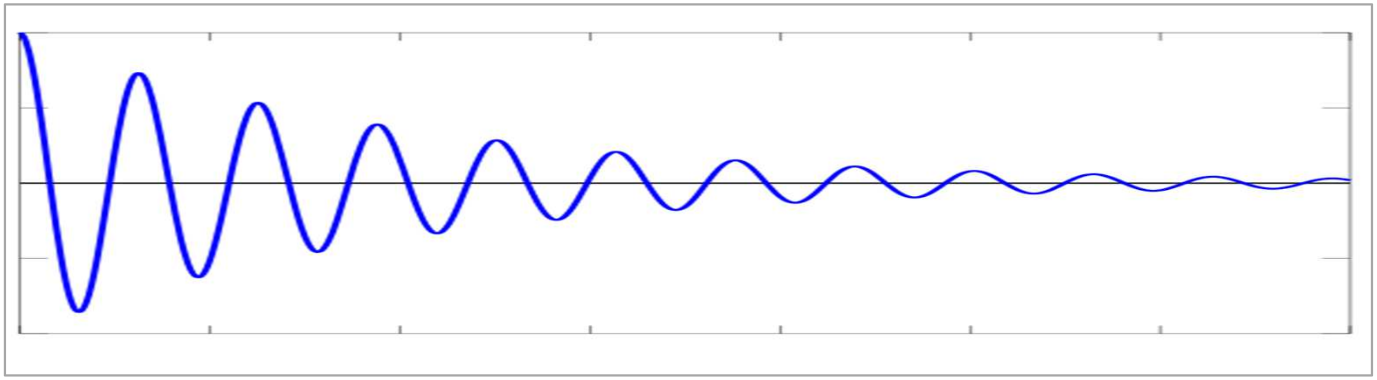
S = power density
P_{TX} = total radiated power
d = distance from antenna (radius of sphere)

Attenuation

All objects will absorb (or attenuate) RF. The amount of absorption depends primarily on the frequency of the signal and the composition and density of the object.

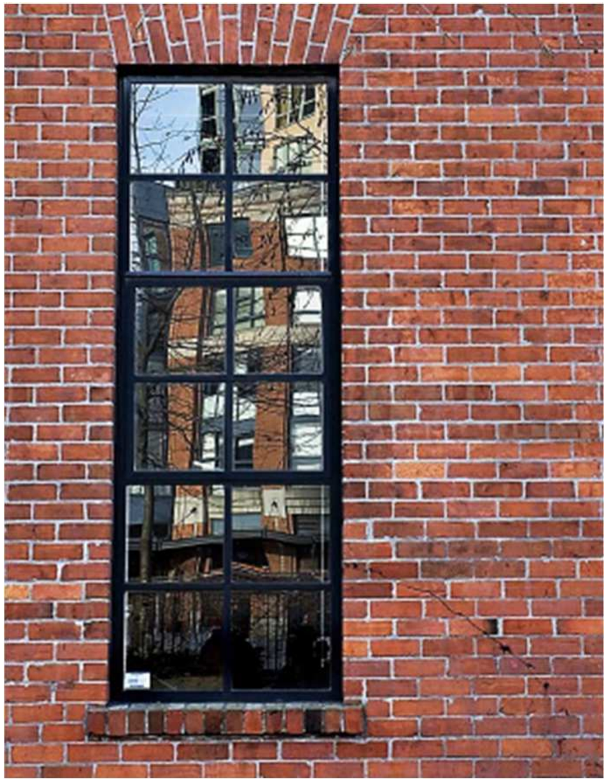
- Wood, plastic, (non-tinted) glass : low attenuation
- Bricks, organic material, liquids : medium attenuation
- Concrete, metal, tinted glass, soil : high attenuation

Note that RF signals can propagate through very small openings in these materials.



Reflection

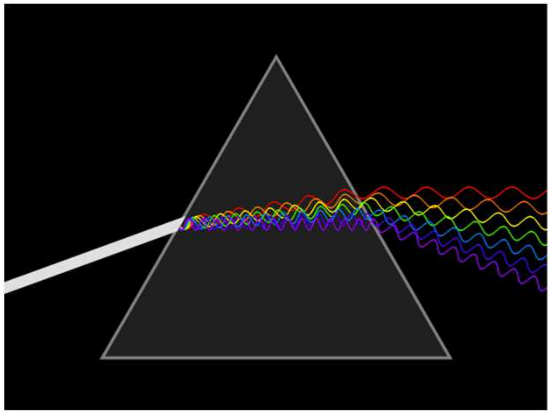
- Highly radio-opaque objects such as concrete and metal will also reflect RF signals.



Diffraction and Refraction

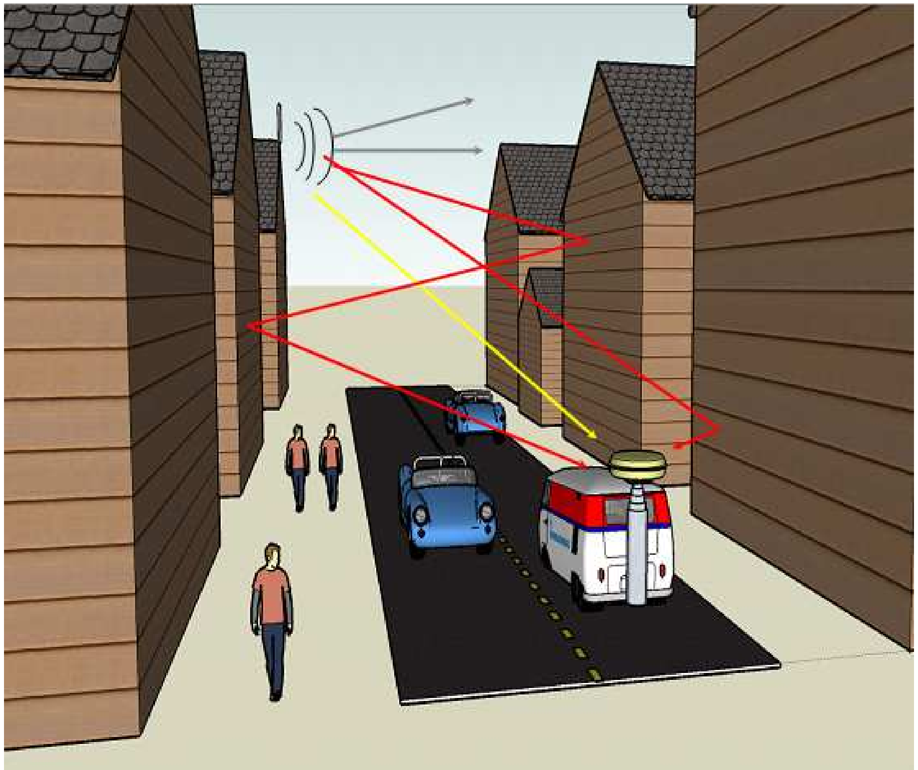
► RF signals can be refracted or bent by objects in their path.

► At lower frequency this causes signals to “wrap around” objects.



Multipath

- Particularly in urban environments, reflections can cause a signal to be received from different directions simultaneously – this is referred to as multipath.
- Multiple signals can add together constructively or destructively to create peaks and nulls known as fading
- Have you ever had bad FM reception sitting at a stoplight and fixed it by rolling forward a few inches?



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