Master Degree in Information Technology Engineering for Health and Communication: Health Curriculum

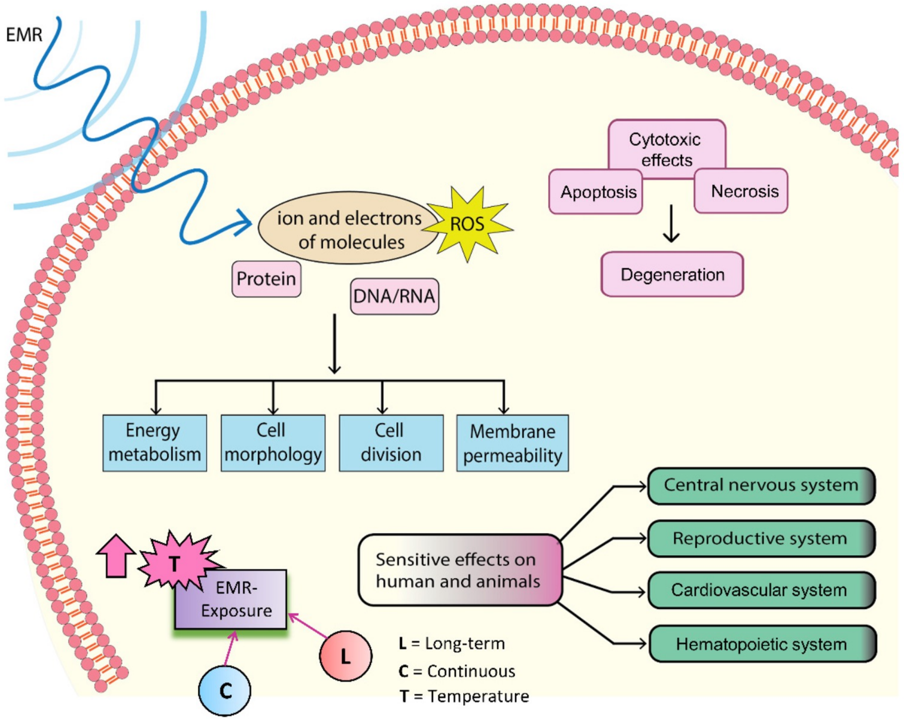
Electromagnetic interactions and diagnostics

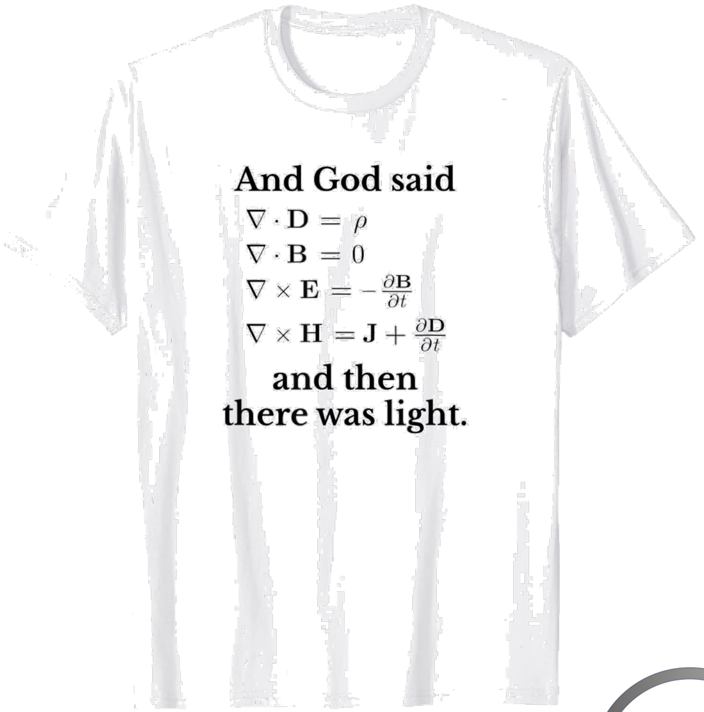
BASIS

Table of contents:

Forward modeling:

Any EM problem can be addressed by solving the complete set of Maxwell's equations





BASIS

Forward modeling:

Full-wave

$$\begin{cases} \nabla \times \mathbf{E} = -\dfrac{\partial \mathbf{B}}{\partial t} \\ \nabla \times \mathbf{H} = \mathbf{J} + \dfrac{\partial \mathbf{D}}{\partial t} \\ \nabla \cdot \mathbf{D} = \rho \\ \nabla \cdot \mathbf{B} = 0 \\ \nabla \cdot \mathbf{J} + \dfrac{\partial \rho}{\partial t} = 0 \end{cases}$$

Q. S. - Electric

$$\begin{cases} \nabla \times \mathbf{E} = 0 \\ \nabla \times \mathbf{H} = \mathbf{J} + \dfrac{\partial \mathbf{D}}{\partial t} \\ \nabla \cdot \mathbf{D} = \rho \\ \nabla \cdot \mathbf{B} = 0 \\ \nabla \cdot \mathbf{J} + \dfrac{\partial \rho}{\partial t} = 0 \end{cases}$$

Q. S. - Magnetic

$$\begin{cases} \nabla \times \mathbf{E} = -\dfrac{\partial \mathbf{B}}{\partial t} \\ \nabla \times \mathbf{H} = \mathbf{J} \\ \nabla \cdot \mathbf{D} = \rho \\ \nabla \cdot \mathbf{B} = 0 \\ \nabla \cdot \mathbf{J} = 0 \end{cases}$$

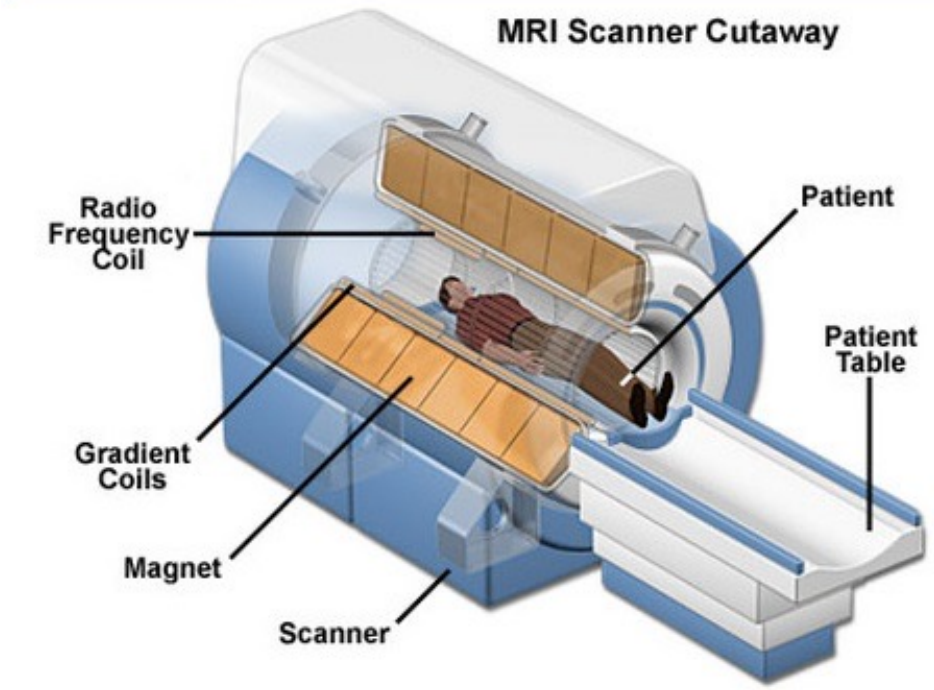
Stationary

$$\begin{cases} \nabla \times \mathbf{E} = 0 \\ \nabla \times \mathbf{H} = \mathbf{J} \\ \nabla \cdot \mathbf{D} = \rho \\ \nabla \cdot \mathbf{B} = 0 \\ \nabla \cdot \mathbf{J} = 0 \end{cases}$$

Propagation

BASIS

Forward modeling:



A static magnetic field (1.5 T or 3 T) is used in Magnetic Resonance Imaging

BASIS

Forward modeling:

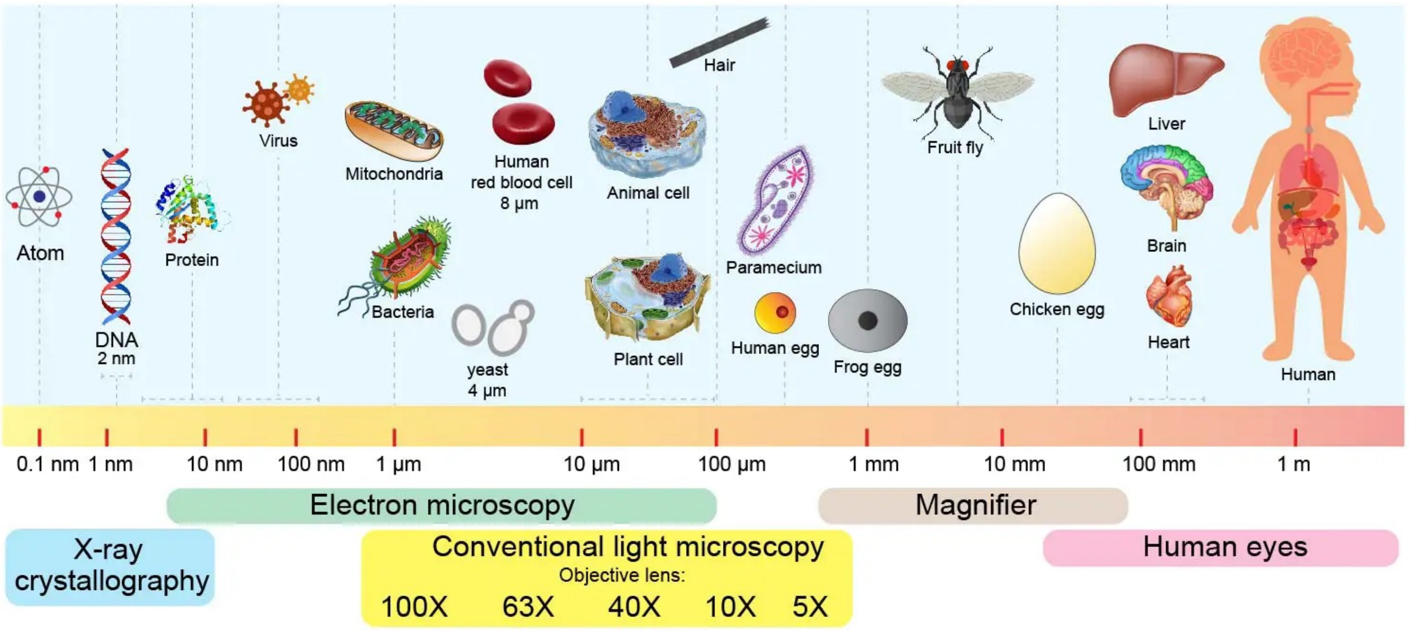
Cell type	Power Supply	Electric Field Strength (V/cm)	Stimulation Duration (h)	Preferred Direction	Major Result
Chondrocytes	DC, Keithley Instruments (USA)	6	3	Bidirectional (dependent on passage of cells)	EF directed migration was influenced by passage [27]
Keratinocytes	DC & AC PASCO Scientific (USA)	0.4 at 1.6 or 160 Hz (AC) / 1 (DC)	1	Cathode	Verification of electromechanical model for migration [93]
Mammary epithelial cells	DC, Pine (USA)	0.13–1.0	6	Anode	Clustered cells were more sensitive to alignment, but migrated slower than isolated cells [83]
Osteoblasts	DC, Biometra (Germany)	0.15–0.45	7	Anode	Upregulation of ion channel gene, associating Ca^{2+} with migration speed [96]
Peripheral blood lymphocytes	DC, Agilent Technologies (USA)	0.15–2	0.5–2.0	Cathode	Directed migration in vitro and in vivo and activated intracellular kinase pathways [37]
Neuroblastoma cells	DC, AMPI (Israel)	0.045–4.5	4	Anode	Enhancement of cell mobility [61]
Bone marrow stem cells	DC, Glassman FC (USA)	0.2–5	15	Cathode	Donor did not influence migration direction and morphological changes but affected response time to EF, migration speed and cell viability [22]

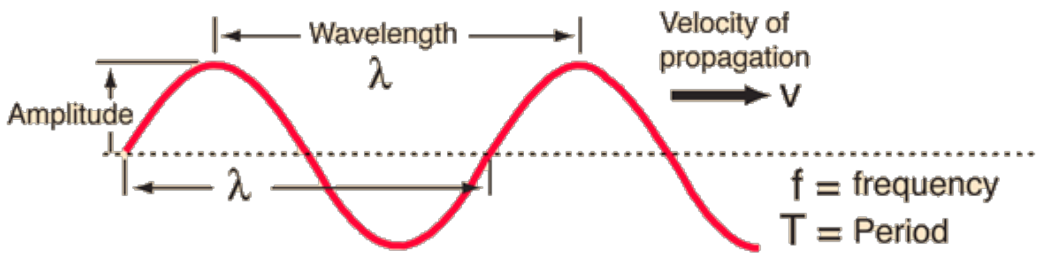
Endogenous electric fields are involved in the organisation and development of tissues, as well as in their regeneration following injury. They are stimulated using static electric fields.

BASIS

Forward modeling:

The coupling capability between EM waved and biological tissues does not **depend on the tissue physical dimension** (L) but **<u>on their electrical dimensions</u>** (k)

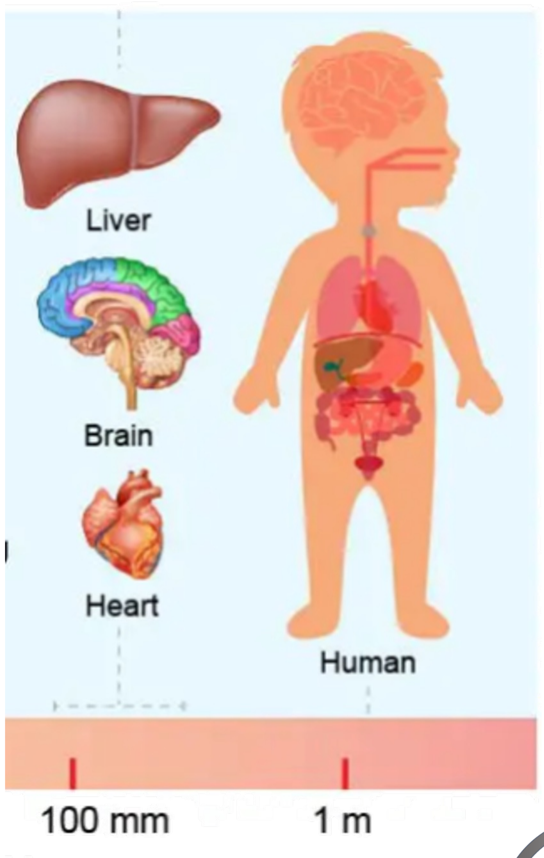


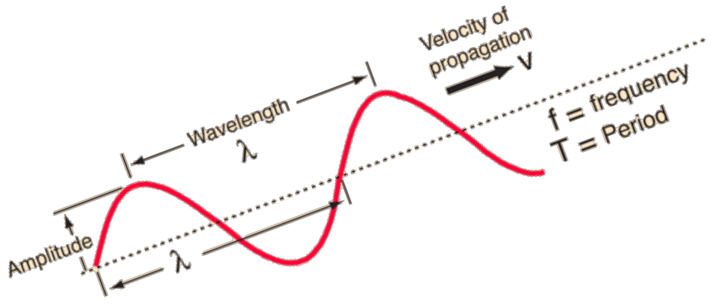


Forward modeling:

A tissue or an EM radiating source is termed to be "***electrically small***" if its largest physical dimension is "significantly" smaller than the shortest wavelength:

$$k = \frac{L}{\lambda} \longrightarrow \boxed{L \ll \lambda \text{ or } k \ll 1}$$



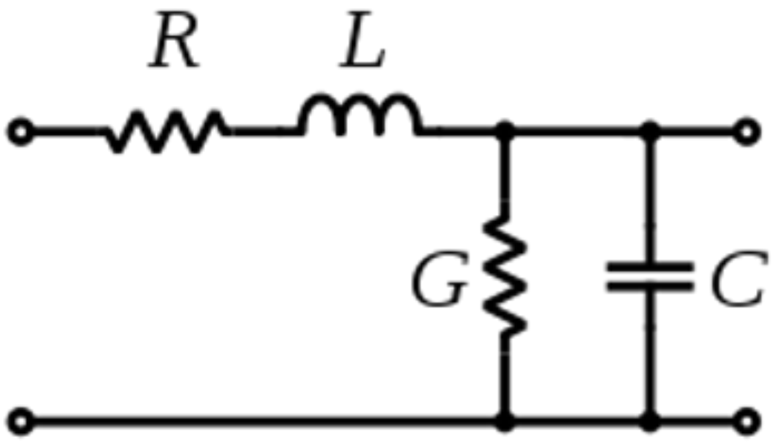


BASIS

Forward modeling:

When the EM problem is electrically small, lumped-circuit models together with Kirchhoff's laws can be used for solving rather than Maxwell's equations.

$$\begin{cases} \nabla \cdot \mathbf{D} = \rho \\ \nabla \cdot \mathbf{B} = 0 \\ \nabla \times \mathbf{E} = -\dfrac{\partial \mathbf{B}}{\partial t} \\ \nabla \times \mathbf{H} = \mathbf{J} + \dfrac{\partial \mathbf{D}}{\partial t} \end{cases}$$

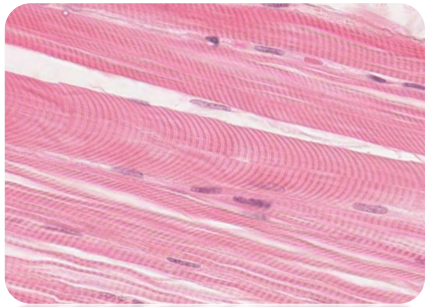


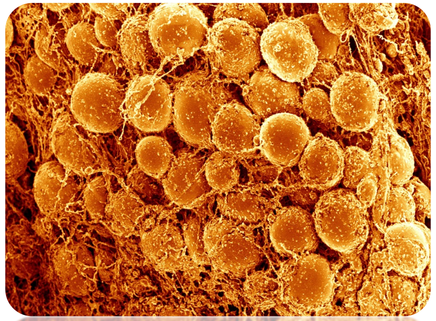
BASIS

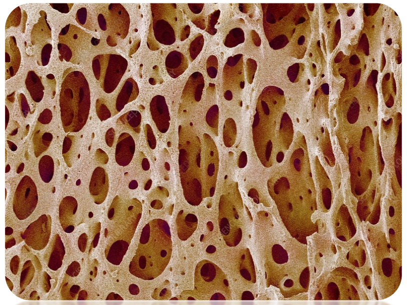
Forward modeling:

It must be pointed out that *k* depends on the dielectric properties of the medium:

$$k = g(L, \lambda) \longrightarrow \lambda = \frac{v}{f} \longrightarrow v = \frac{1}{\sqrt{\varepsilon\mu}} = \frac{v_0}{\sqrt{\varepsilon_r \mu_r}}$$





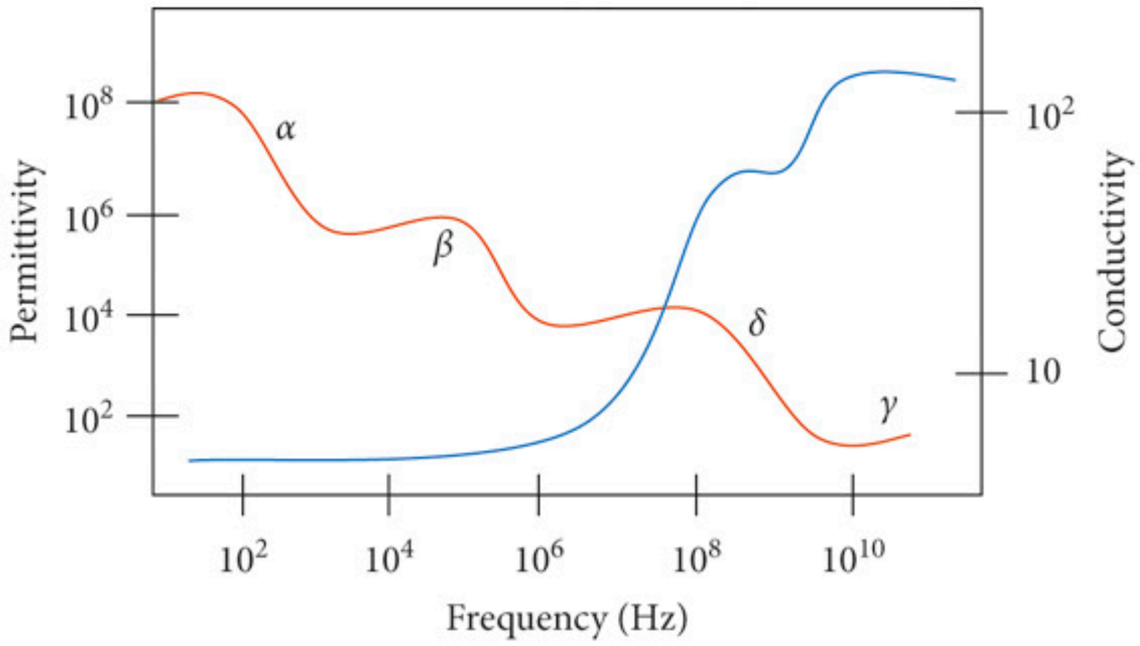


$$v_{\text{Muscle}}(f = 100\ \text{MHz}) = \frac{3 \times 10^8\ \text{m/s}}{\sqrt{12.7 \times 1}} = 84{,}182{,}029\ \text{m/s} = 0.28\ v_0$$

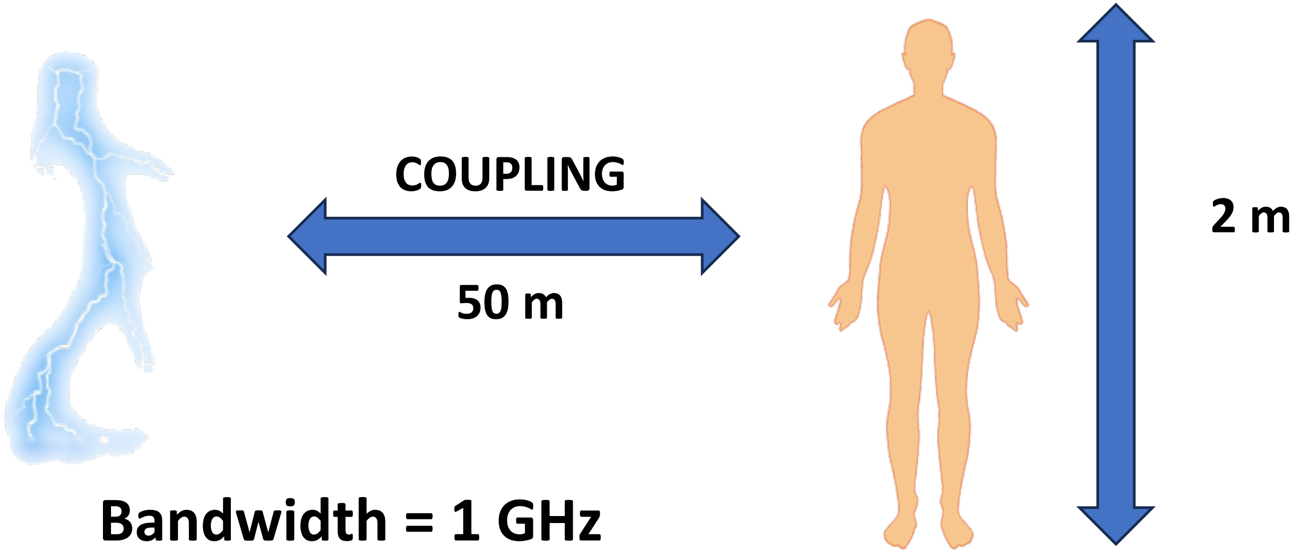
Forward modeling: dielectric properties of tissues

Tissue Type	Relative Permittivity ε_r ($\times 10^3$)	Conductivity σ (S/m)
Bone	0.28	0.0144
Liver	9.8–14	0.15–0.16
Spleen	3.3	0.62
Blood	2.7–4.0	0.55–0.68
Kidney	10.9–12.5	0.24–0.25
Retina	4.75	0.52
Bone (cancellous)	0.47	0.09
Bone (cortical)	0.23	0.02
Bone (marrow)	0.11	0.003
Cartilage	2.57	0.18
Skeletal muscle	14.4–27.3	0.38–0.65
Fat	0.09	0.02
Cerebrospinal fluid	0.1	2
Brain (grey matter)	3.8	0.17
Brain (white matter)	1.9–3.4	0.12–0.15

[1] Measured *ex vivo* at 100 kHz, adapted from [92–94].

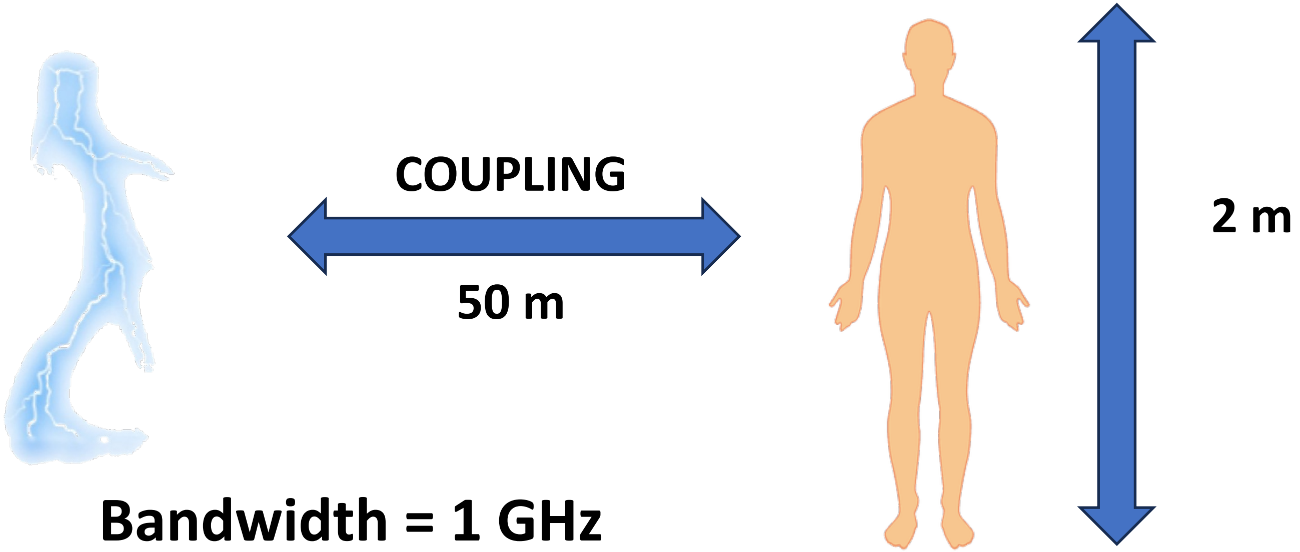


Forward modeling: showcase



Bandwidth = 1 GHz

Forward modeling: showcase



Bandwidth = 1 GHz

The problem is «electronically large» and, hence, the complete set of Maxwell's equations is needed.

Forward modeling: showcase

- Signal frequency = 20 GHz
- $v = 2.1 \times 10^8$ m/s

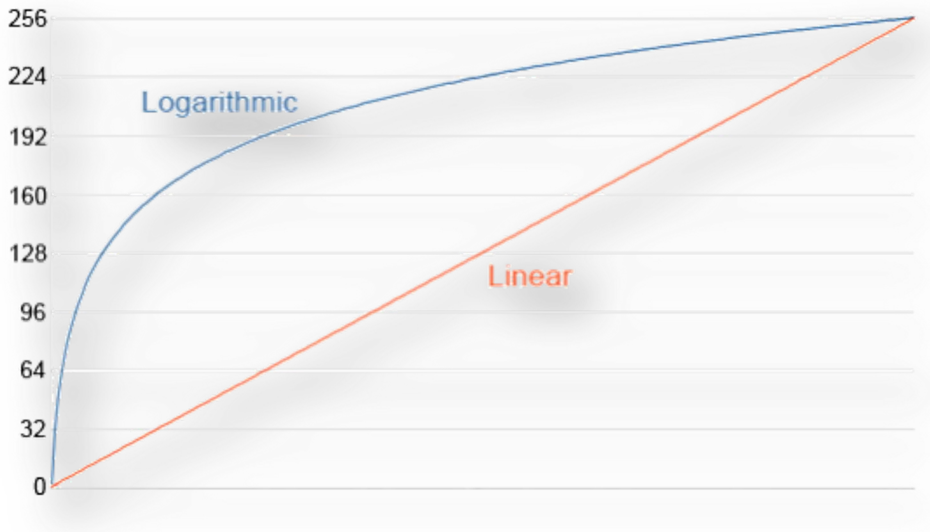
Forward modeling: showcase

The problem is «electronically small» and, hence, lumped-circuit models can be used.

- Signal frequency = 20 GHz
- $v = 2.1 \times 10^8$ m/s

BASIS

Decibels:



- ✓ Human ears feel noise according to a logarithmic scale
- ✓ To exploit math properties of log function
- ✓ To compress the large dynamic range of signals involved in bioEM
- ✓ To express SNR or measurement/reference signals

BASIS

Decibels:

$$\text{dB} \equiv 10\log_{10}\left(\frac{P_2}{P_1}\right) \text{ (power)}$$

$$\text{dB} \equiv 20\log_{10}\left(\frac{v_2}{v_1}\right) \text{ (voltage)}$$

$$\text{dB} \equiv 20\log_{10}\left(\frac{i_2}{i_1}\right) \text{ (current)}$$

$$\text{dB}\mu\text{V} \equiv 20\log_{10}\left(\frac{\text{volts}}{1\ \mu\text{V}}\right)$$

$$\text{dBmV} \equiv 20\log_{10}\left(\frac{\text{volts}}{1\ \text{mV}}\right)$$

$$\text{dB}\mu\text{A} \equiv 20\log_{10}\left(\frac{\text{amperes}}{1\ \mu\text{A}}\right)$$

$$\text{dBmA} \equiv 20\log_{10}\left(\frac{\text{amperes}}{1\ \text{mA}}\right)$$

$$\text{dB}\mu\text{W} \equiv 10\log_{10}\left(\frac{\text{watts}}{1\ \mu\text{W}}\right)$$

$$\text{dBm} \equiv \text{dBmW} \equiv 10\log_{10}\left(\frac{\text{watts}}{1\ \text{mW}}\right)$$

$$\text{dB}\mu\text{V/m} \equiv 20\log_{10}\left(\frac{\text{V/m}}{1\ \mu\text{V/m}}\right) \quad \text{dB}\mu\text{A/m} \equiv 20\log_{10}\left(\frac{\text{A/m}}{1\ \mu\text{A/m}}\right)$$

BASIS

Decibels:

- 1 V → dBµV ?
- 350 mV → dBµV ?
- 630 mA → dBmA ?
- 250 mW → dBµW ?

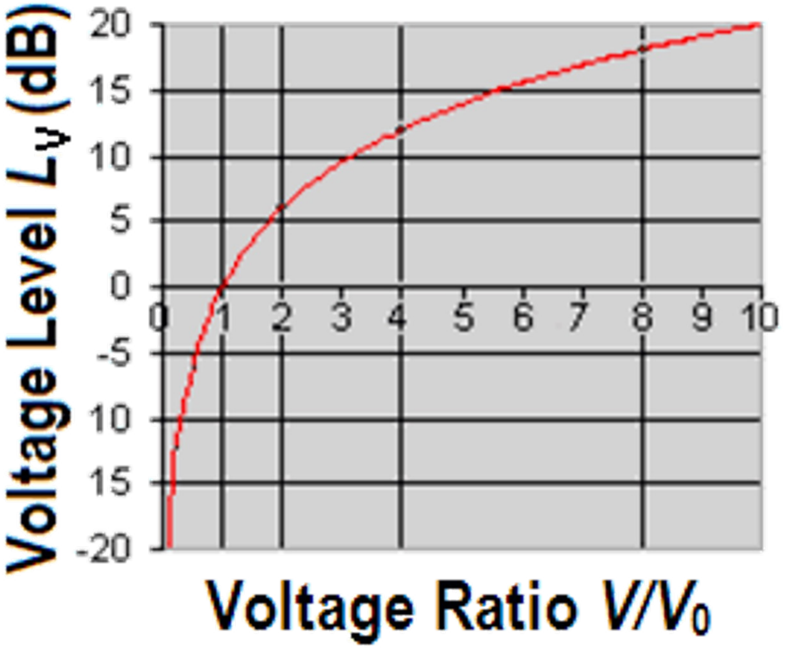
BASIS

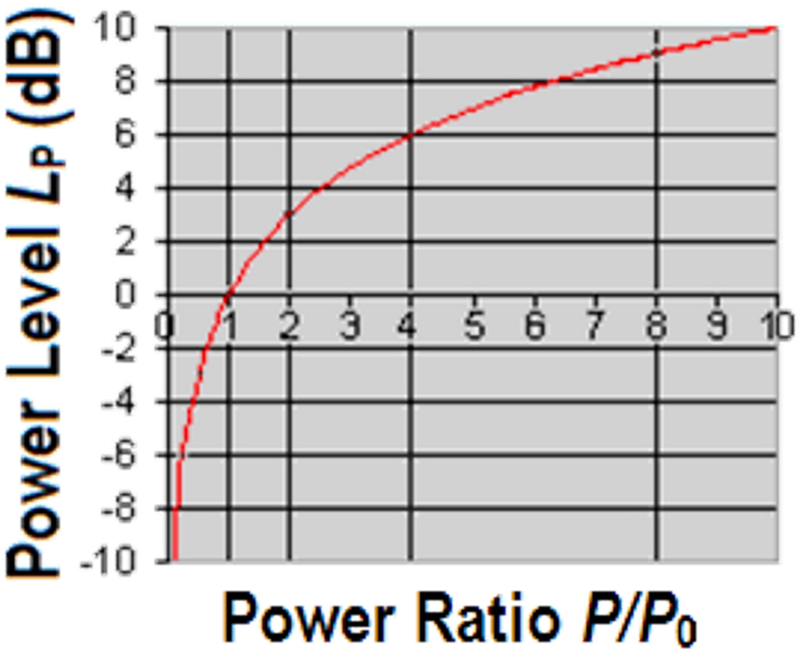
Decibels:

- 1 V → 120.00 dBμV
- 350 mV → 110.88 dBμV
- 630 mA → 55.99 dBmA
- 250 mW → 53.98 dBμW

BASIS

Decibels:





Ratio	V or I in dB	P in dB
10^6	120	60
10^5	100	50
10^4	80	40
10^3	60	30
10^2	40	20
10	20	10
9	19.08	9.54
8	18.06	9.03
7	16.9	8.45
6	15.56	7.78
5	13.98	6.99
4	12.04	6.02
3	9.54	4.77
2	6.02	3.01
1	0	0
10^{-1}	−20	−10
10^{-2}	−40	−20
10^{-3}	−60	−30

BASIS

Decibels:

- 108 dBμV $\rightarrow$ V ?
- 44 dBμV/m $\rightarrow$ μV/m ?
- 56 dBm $\rightarrow$ W ?

BASIS

Decibels:

- 108 dBμV → 0.2512 V
- 44 dBμV/m → 158.49 μV/m
- 56 dBm → 398.107 W

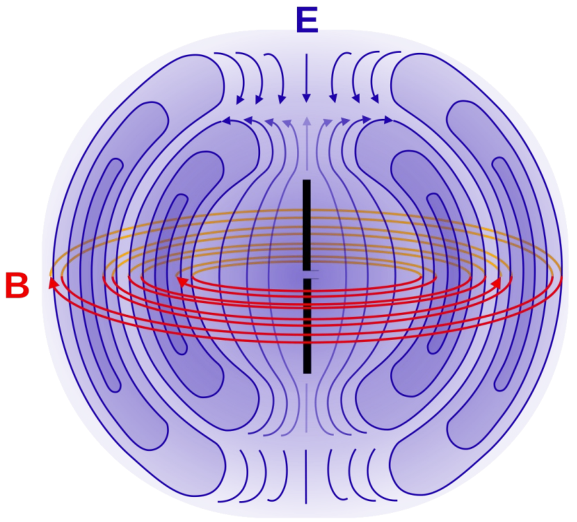
BASIS

Near and far field:

$\max(3\lambda, 2\frac{D^2}{\lambda})$

$$\begin{cases} \hat{E}_r = 2\frac{\hat{I}dl}{4\pi}\eta_0{\beta_0}^2 cos\theta(j\frac{1}{{\beta_0}^2r^2} - j\frac{1}{{\beta_0}^3r^3})e^{-j\beta_0 r} \\ \hat{E}_\theta = \frac{\hat{I}dl}{4\pi}\eta_0{\beta_0}^2 sin\theta(j\frac{1}{\beta_0 r} + \frac{1}{{\beta_0}^2r^2} - j\frac{1}{{\beta_0}^3r^3})e^{-j\beta_0 r} \\ \hat{E}_\phi = 0 \end{cases}$$

$$\vec{\hat{E}}_{\mathrm{FF}} = j\eta_0\beta_0\frac{\hat{I}dl}{4\pi}sin\theta\frac{e^{-j\beta_0 r}}{r}\hat{\theta}$$



Distance from source

NEAR FIELD **FAR FIELD**

BASIS

Near and far field:

Antenna factor Antenna pattern

$$\hat{E}_\theta = \hat{M}\hat{I}\,\frac{e^{-j\beta_0 r}}{r}\,F(\theta)$$

- $\hat{I}$ is current at the center of the antenna
- $0 < F(\theta) < 1$
- $\hat{M}$ depends on the antenna type

Hertzian dipole:

$$\hat{M} = j\frac{\eta_0\beta_0}{4\pi}L = j2\pi\cdot 10^{-7} f L \qquad F(\theta) = \sin(\theta)$$

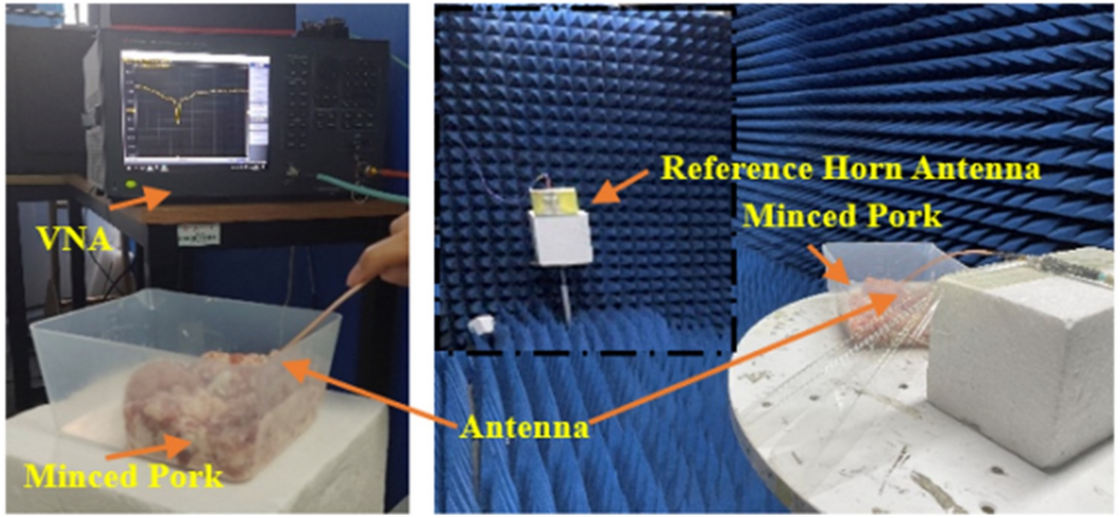
Half-wave dipole:

$$\hat{M} = j\frac{\eta_0}{2\pi} = j60 \qquad F(\theta) = \frac{\cos\left(\frac{1}{2}\pi\cos\theta\right)}{\sin\theta}$$

BASIS

Near and far field:

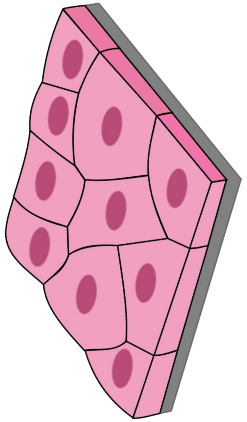
The incident EM field onto a tissue can be thought as generated by a far-field antenna. As a result, it can be evaluated using the Friis link equation:



P_T

G

$$\begin{cases} \left|\widehat{E^i}\right| = \dfrac{\sqrt{60 P_T G}}{d} \\ \left|\widehat{H^i}\right| = \dfrac{\left|\widehat{E^i}\right|}{\eta_0} \end{cases}$$



d

Near and far field:

Considering the Hertzian dipole as the elementary electric field source, it was shown that in the far field:

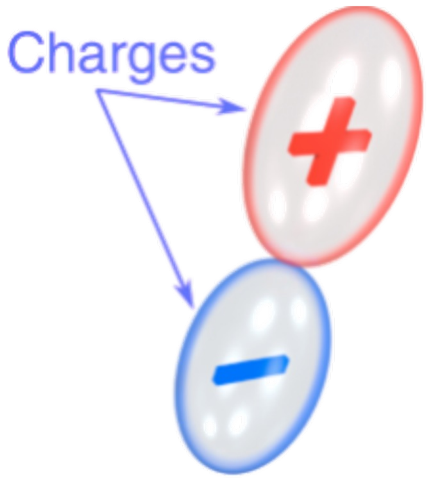
1) E_ϑ and H_ϕ are mutually orthogonal.
2) $|E_\vartheta|/|H_\phi|$ is the free-space intrinsic impedance, η_0.

This is no longer true for near fields.

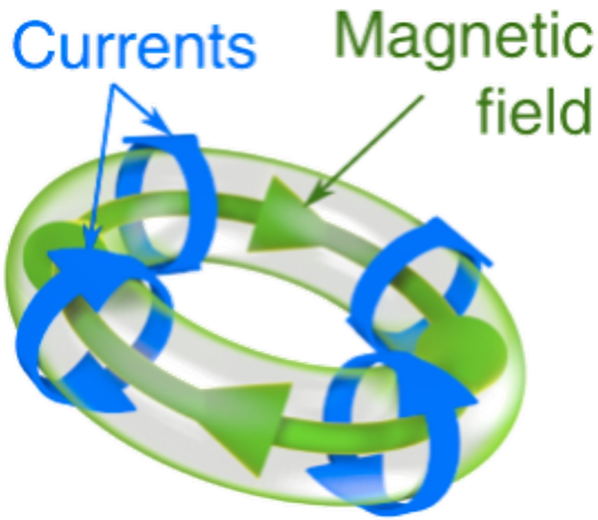
A further reasonable criterion to determine the near-/far-field region boundary is to find the distance from the source where the ratio $|E_\vartheta|/|H_\phi|$ is about η_0.

BASIS

Near and far field:



$$\hat{Z}_w = \frac{\hat{E}_\phi}{\hat{H}_\theta} = -\eta_0 \frac{j\frac{\beta_0}{r} + \frac{1}{(\beta_0 r)^2}}{j\frac{\beta_0}{r} + \frac{1}{(\beta_0 r)^2} - \frac{j}{(\beta_0 r)^3}}$$

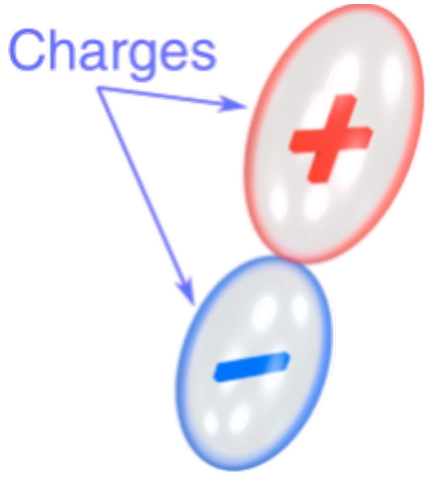


$$\hat{Z}_w = \frac{\hat{E}_\theta}{\hat{H}_\phi} = \eta_0 \frac{j\frac{\beta_0}{r} + \frac{1}{(\beta_0 r)^2} - \frac{j}{(\beta_0 r)^3}}{j\frac{\beta_0}{r} + \frac{1}{(\beta_0 r)^2}}$$

$\hat{Z}_w$ is termed as **wave impedance** (“intrinsic impedance” in the far field case).

BASIS

Near and far field:

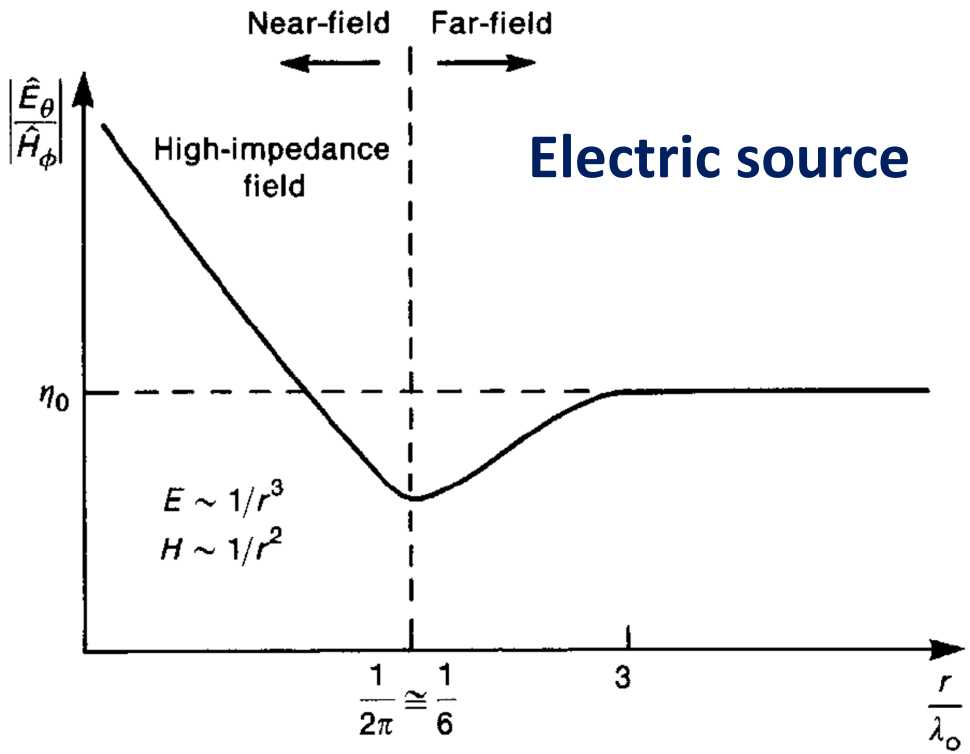


$$\hat{Z}_w = \frac{\hat{E}_\theta}{\hat{H}_\phi} = \eta_0 \frac{j\frac{\beta_0}{r} + \frac{1}{(\beta_0 r)^2} - \frac{j}{(\beta_0 r)^3}}{j\frac{\beta_0}{r} + \frac{1}{(\beta_0 r)^2}}$$

$\hat{Z}_w \cong \eta_0$ **Far-field ($\beta_0 r >> 1$)**

$\hat{Z}_w \cong \eta_0 \left(-j\frac{1}{\beta_0 r}\right)$ **Near-field ($\beta_0 r << 1$)**

Near and far field:



Near-field
Hertzian dipole

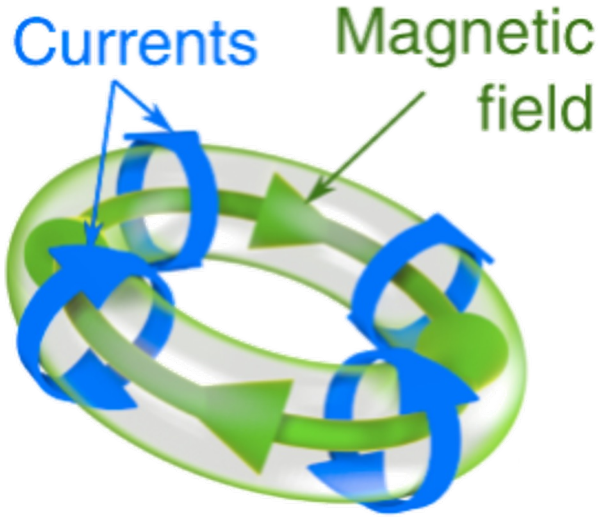
$$\begin{cases} \hat{E}_\theta \sim \dfrac{1}{r^3} \\ \hat{H}_\phi \sim \dfrac{1}{r^2} \end{cases}$$

$$|\hat{Z}_w|_e = \frac{1}{2\pi f \varepsilon_0 r} = 60\frac{\lambda_0}{r}$$

Hence, in the near field, the electric dipole is termed as **high impedance source** since its wave impedance is larger than the intrinsic one.

BASIS

Near and far field:

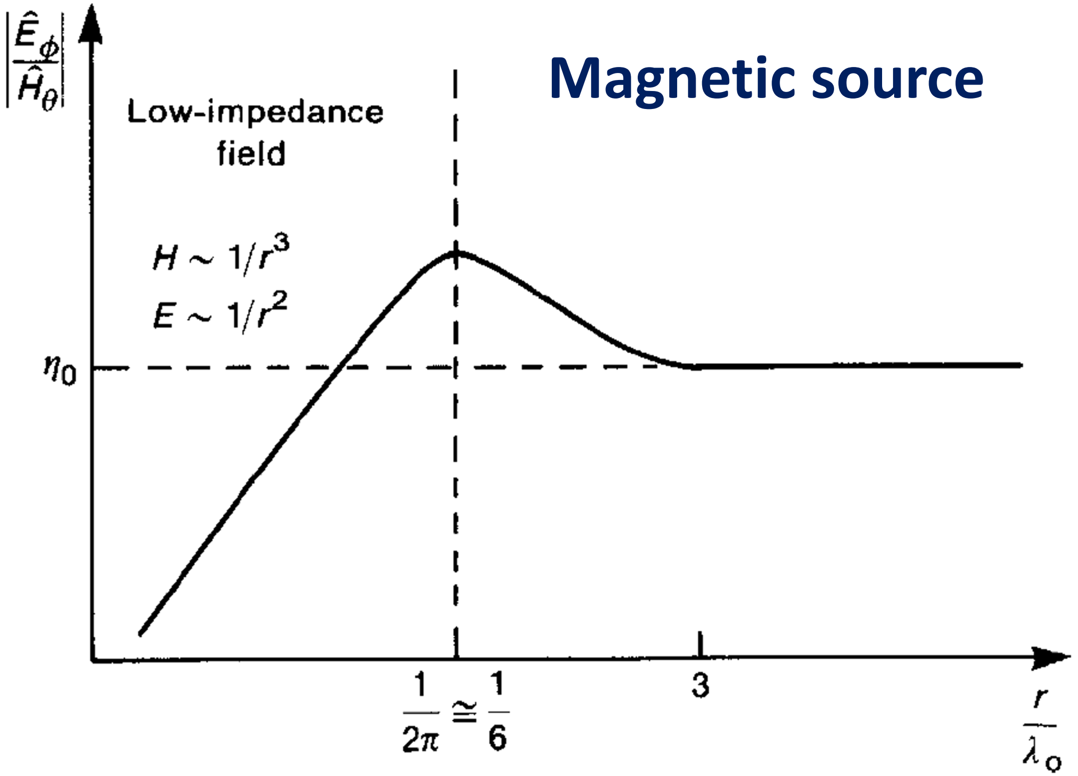


$$\hat{Z}_w = \frac{\hat{E}_\phi}{\hat{H}_\theta} = -\eta_0 \frac{j\frac{\beta_0}{r} + \frac{1}{(\beta_0 r)^2}}{j\frac{\beta_0}{r} + \frac{1}{(\beta_0 r)^2} - \frac{j}{(\beta_0 r)^3}}$$

$\left|\hat{Z}_w\right| \cong \eta_0$ **Far-field ($\beta_0 r >> 1$)**

$\hat{Z}_w \cong -j\eta_0\beta_0 r$ **Near-field ($\beta_0 r << 1$)**

Near and far field:



Magnetic source

Near-field
Current loop

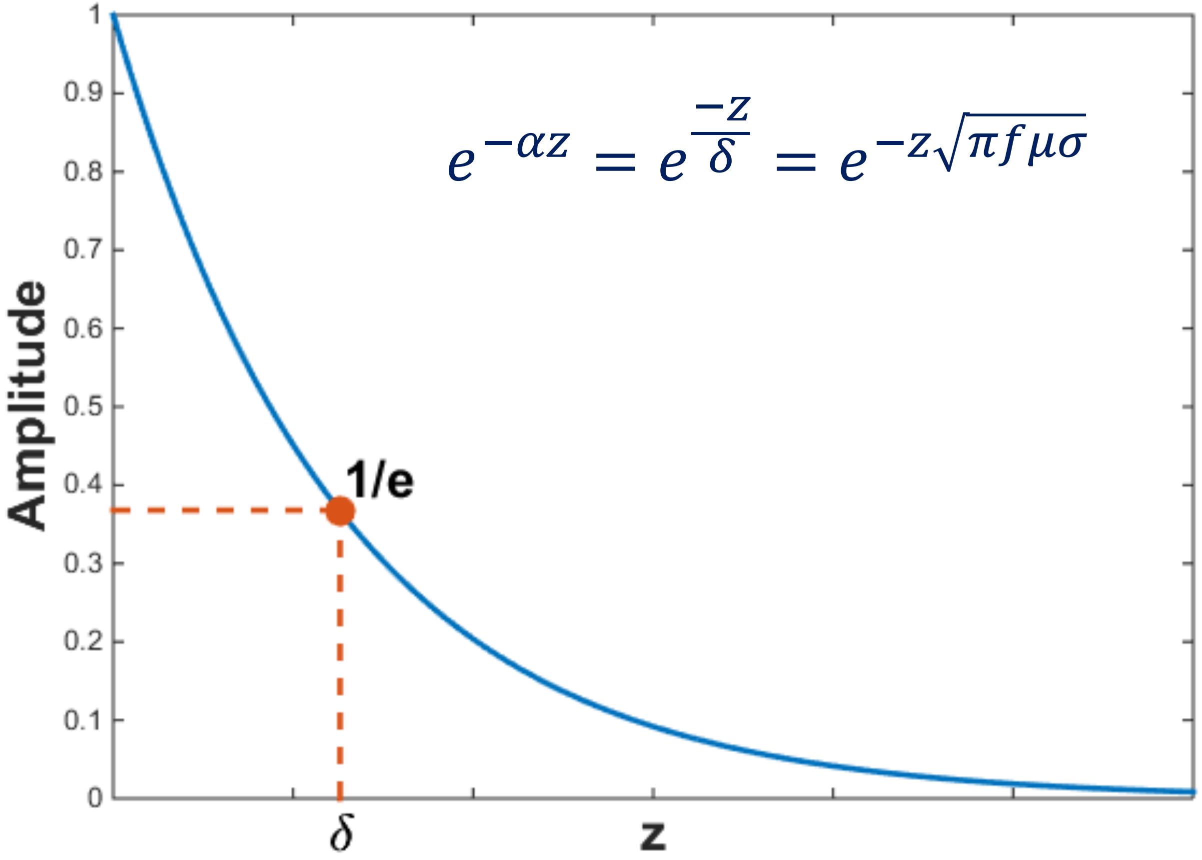
$$\begin{cases} \hat{H}_\theta \sim \dfrac{1}{r^3} \\ \hat{E}_\phi \sim \dfrac{1}{r^2} \end{cases}$$

$$\left|\hat{Z}_w\right|_m = 2\pi f \mu_0 r = 2369 \frac{r}{\lambda_0}$$

Hence, in the near field, the current loop is termed as **low impedance source** since its wave impedance is lower than the intrinsic one.

BASIS

Penetration depth:



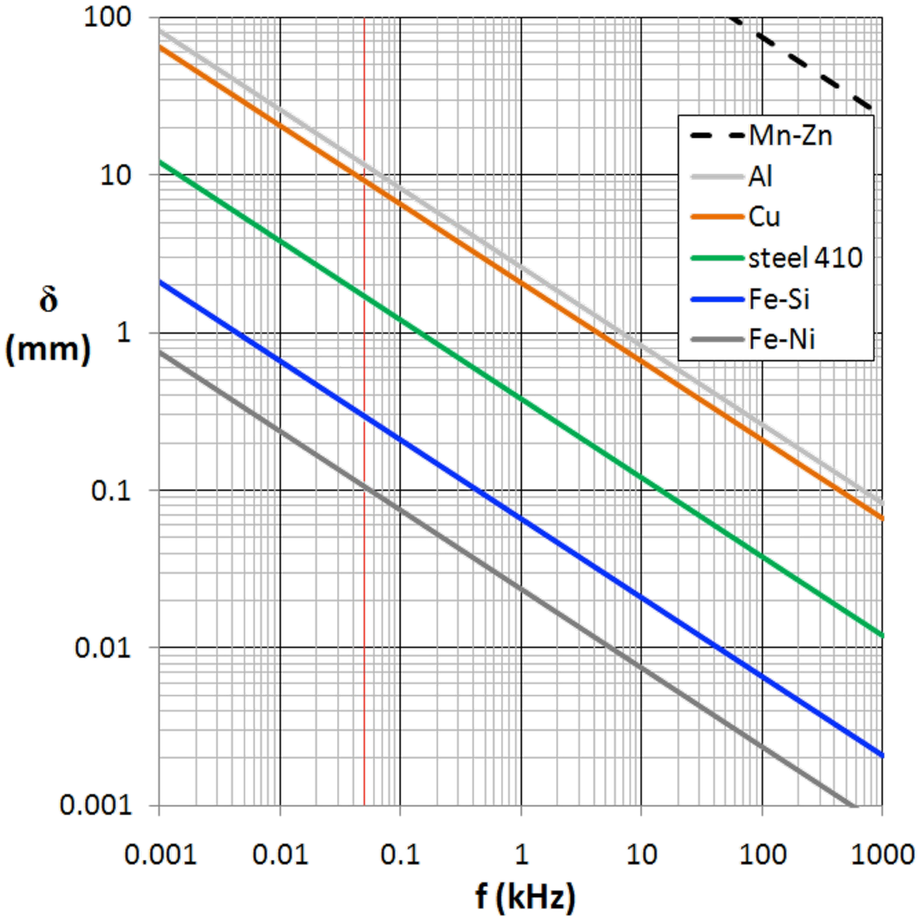
The penetration depth δ is defined as the depth where the power density is just 1/e (about 37%) of the surface value.

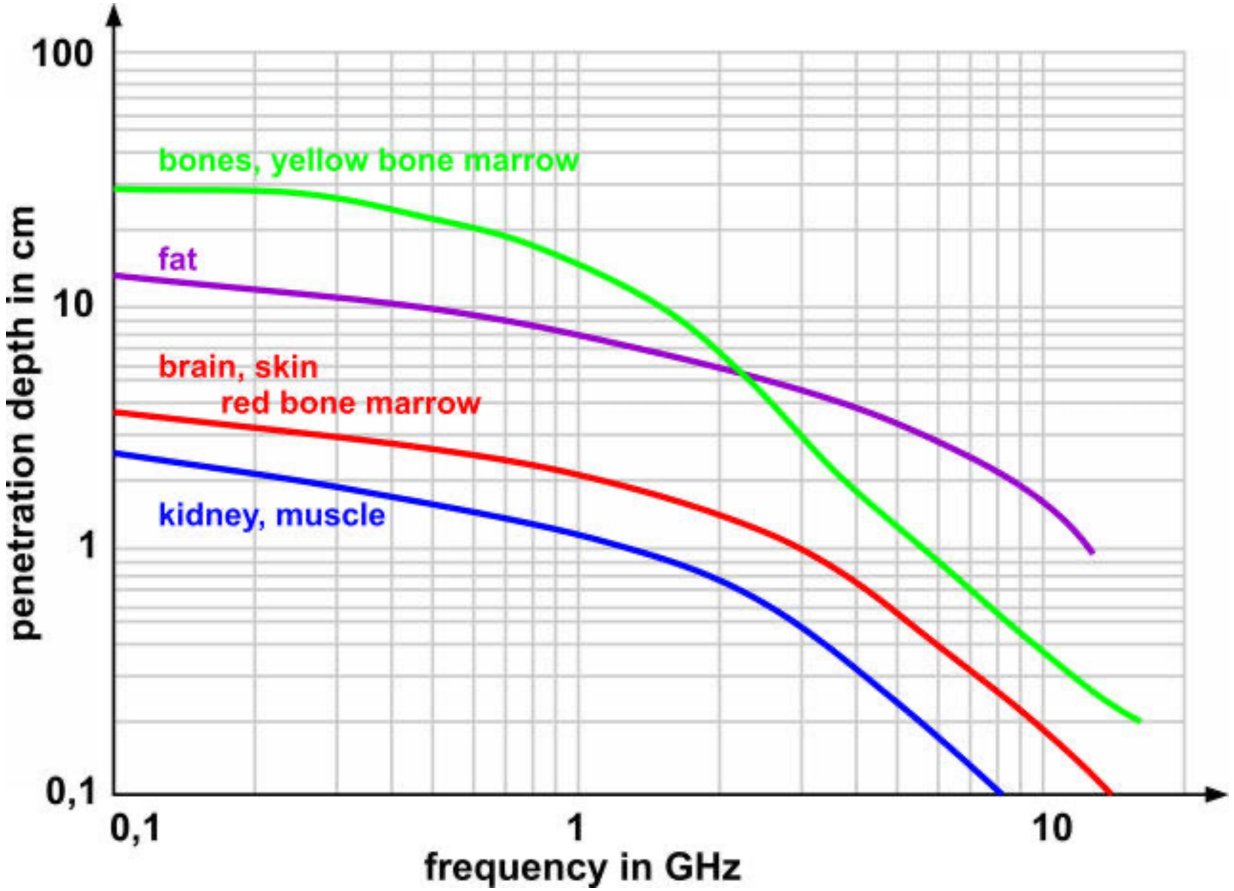
$$\delta = \frac{1}{\sqrt{\pi f \mu \sigma}} \ \ \mathrm{m}$$

Media with higher loss factor ε_r'' (imaginary part of the complex electric permittivity) show faster microwave energy absorption.

BASIS

Penetration depth:

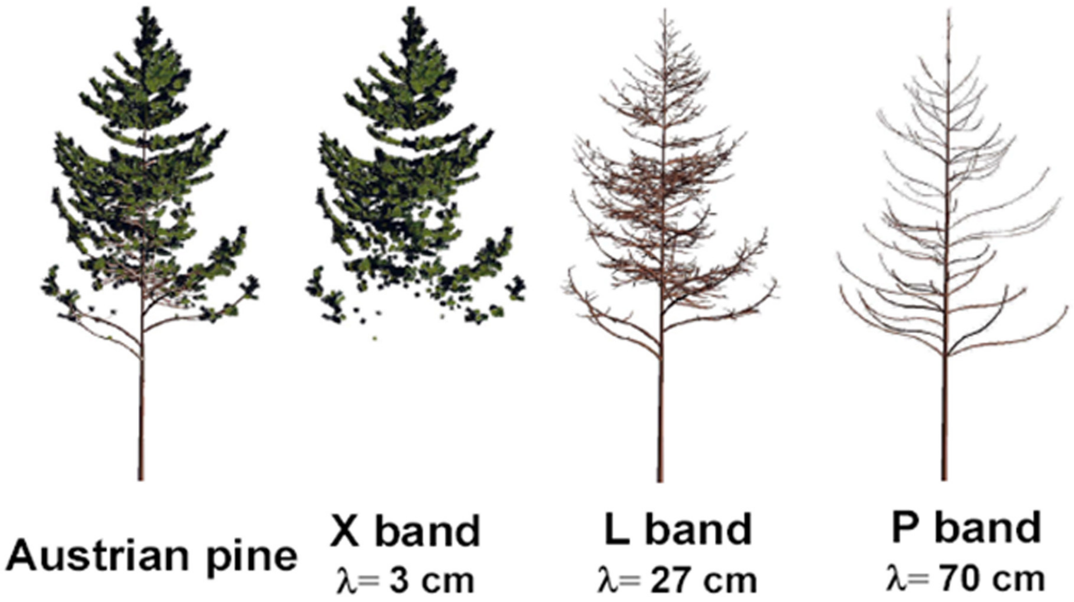


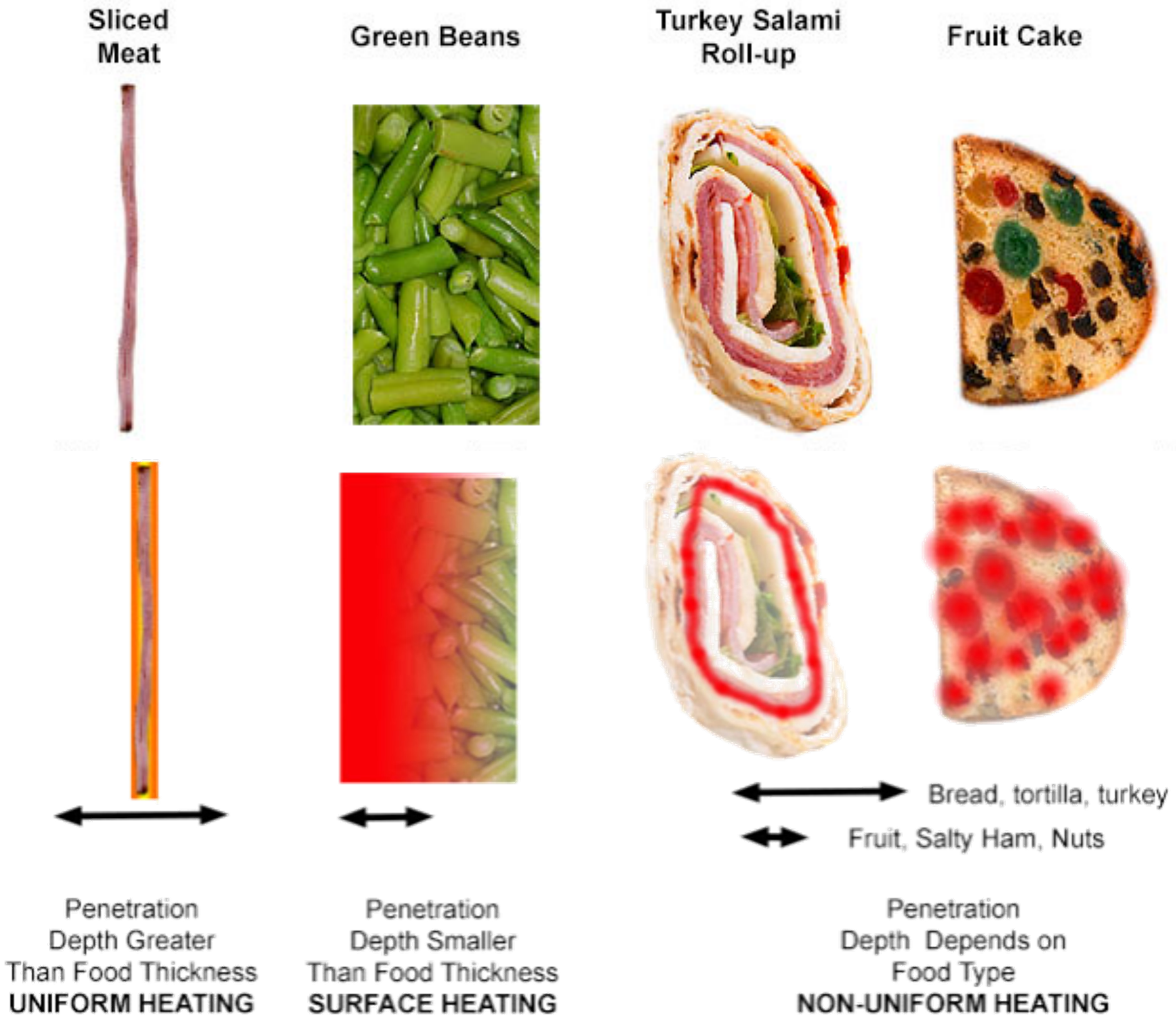


Note that δ depends on both tissue (conductivity) and EM wave (frequency) properties.

BASIS

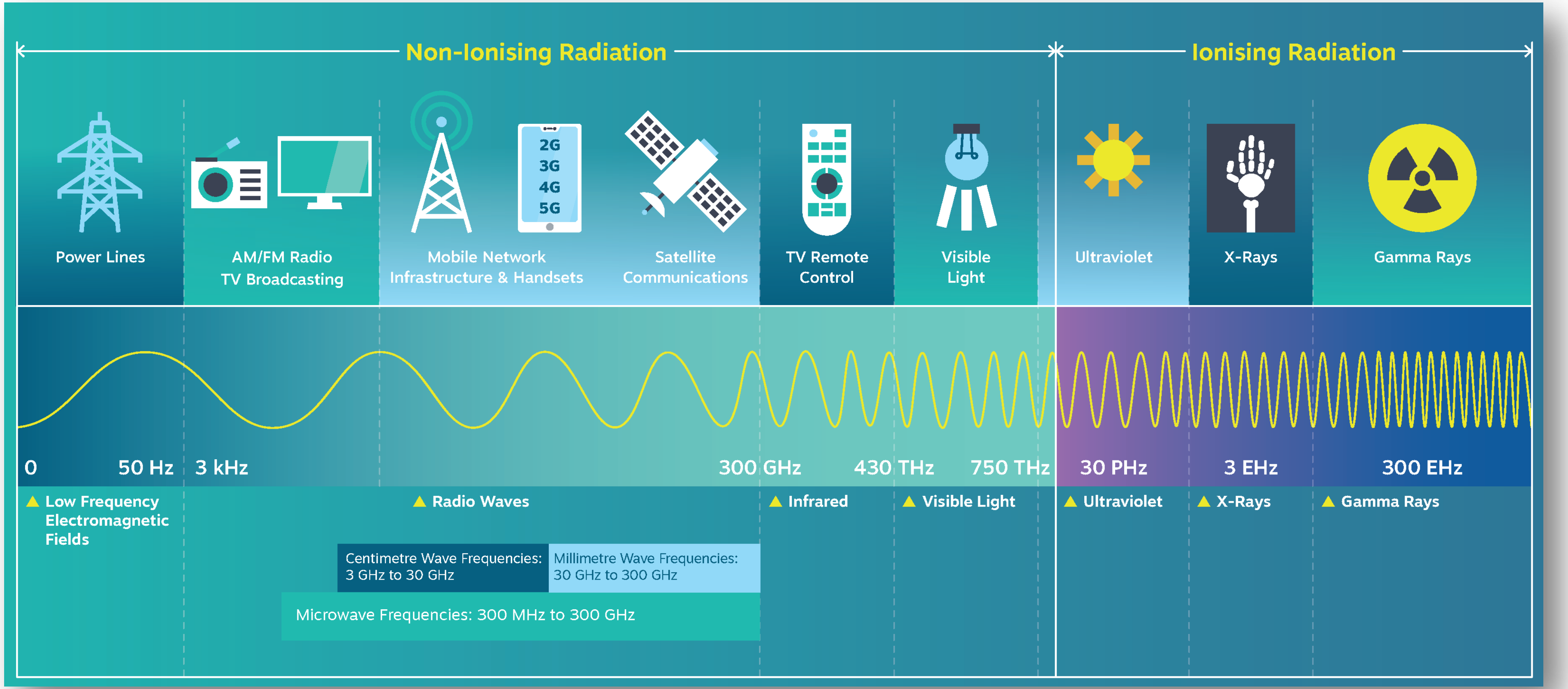
Penetration depth:





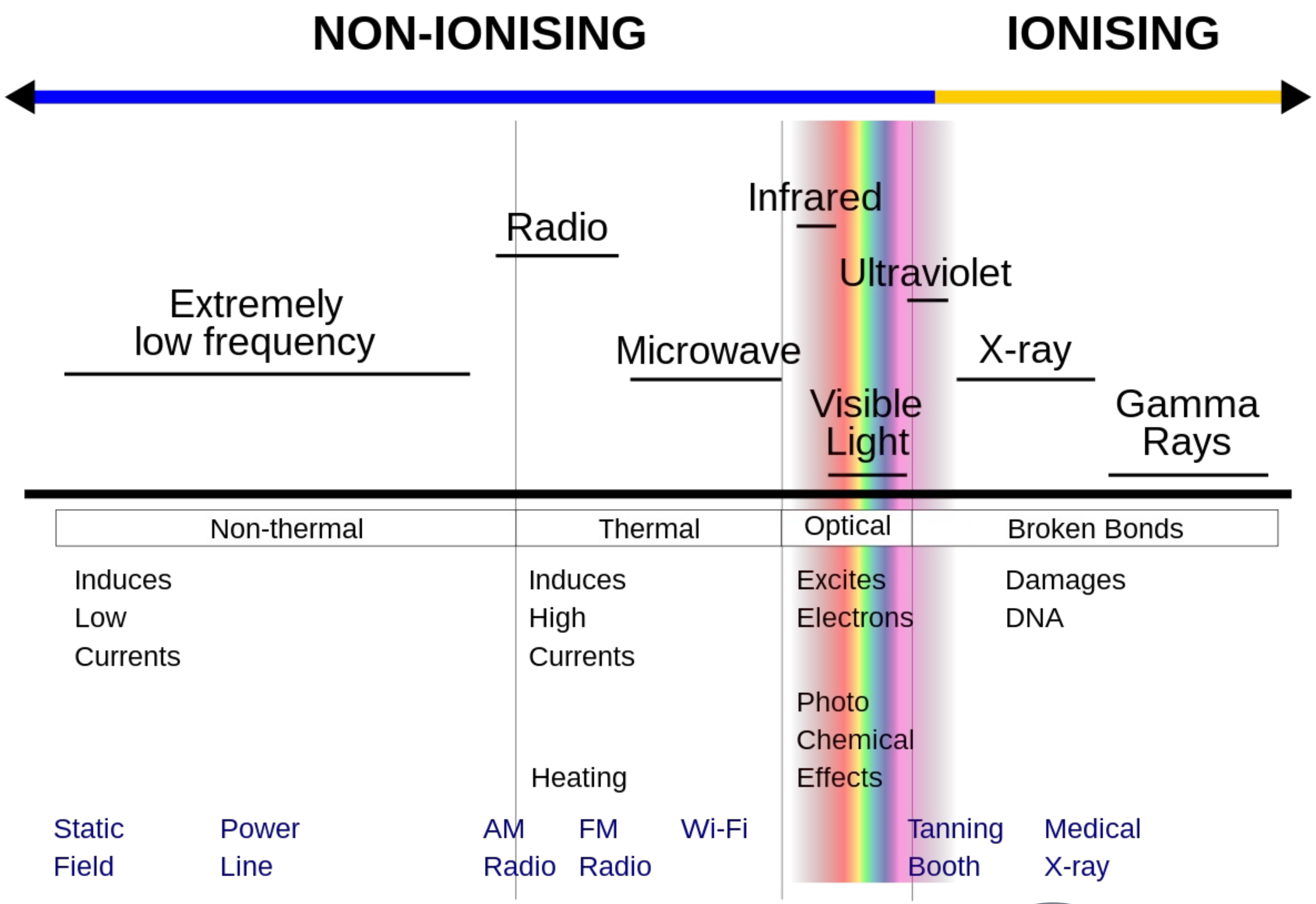
BASIS

EM spectrum:



BASIS

EM spectrum:



BASIS

EM spectrum: