The Antenna - Our Window to the Radio Universe

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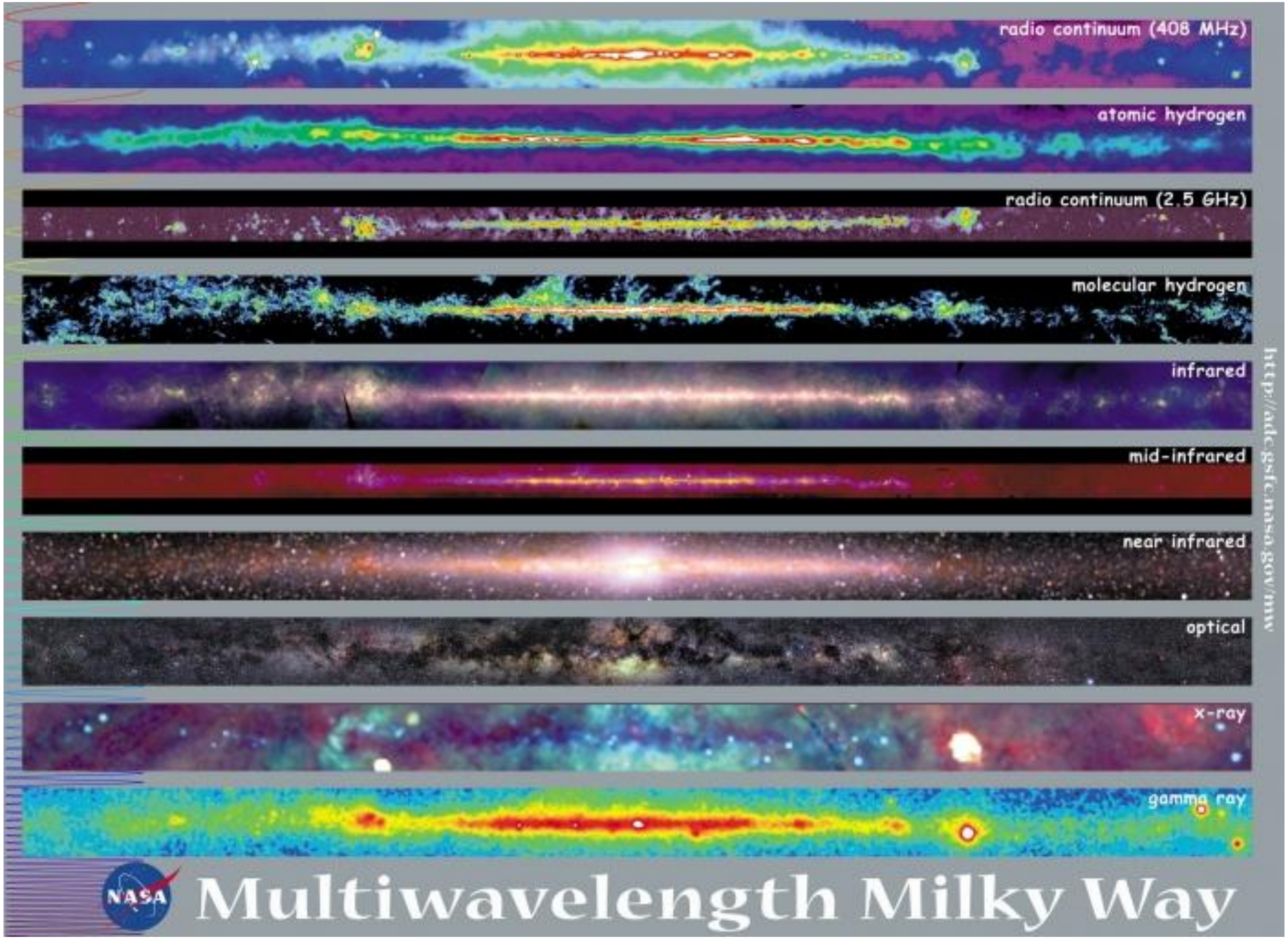
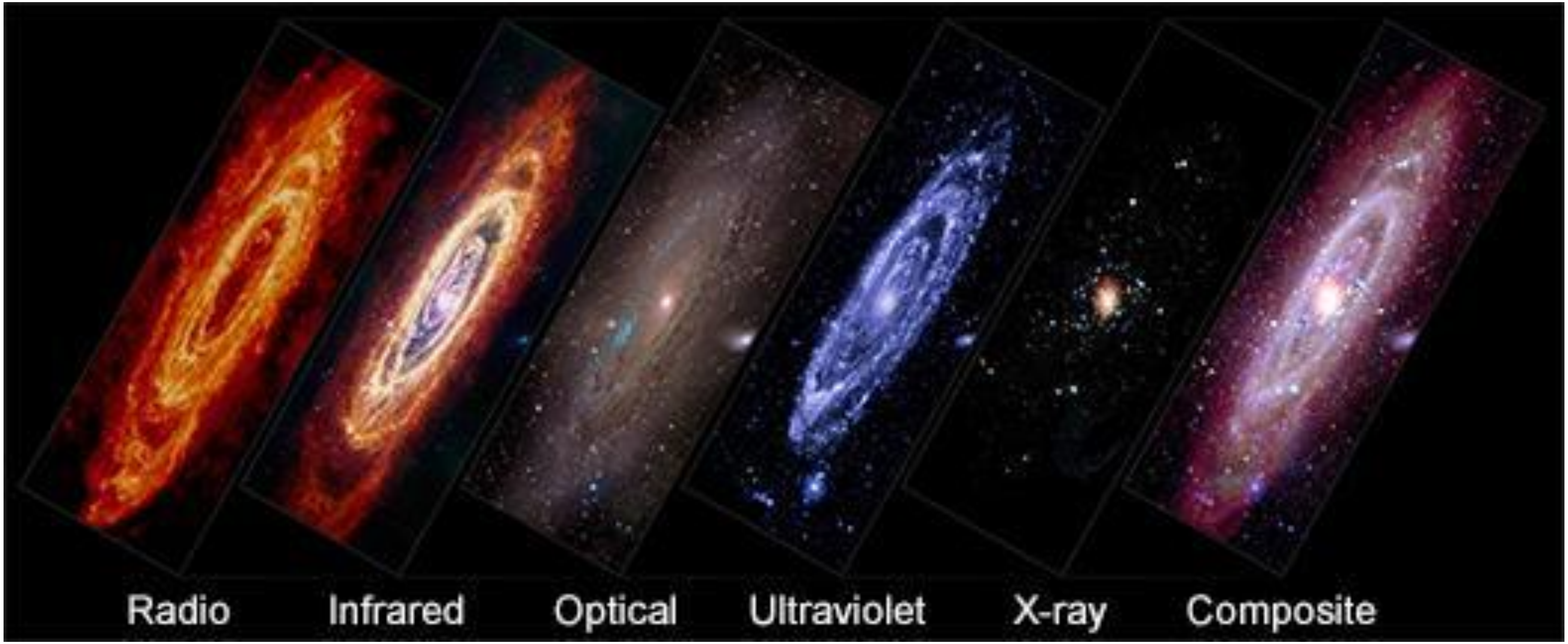
Objective

To understand what an antenna is, how it works, and what its most important properties are for radio astronomy.

Giấc mộng đêm hè. Tác giả: Hoàng Duy. Địa điểm: Hòa Bình, Việt Nam.

Dải Ngân Hà Trên Đỉnh Núi Tuyết. Tác giả: Lưu Hoài Nam. Địa điểm: Gunma, Nhật Bản.


radio continuum (408 MHz)
atomic hydrogen
radio continuum (2.5 GHz)
molecular hydrogen
infrared
mid-infrared
near infrared
optical
x-ray
gamma ray
http://adc.gsfc.nasa.gov/mw
NASA
Multiwavelength Milky Way

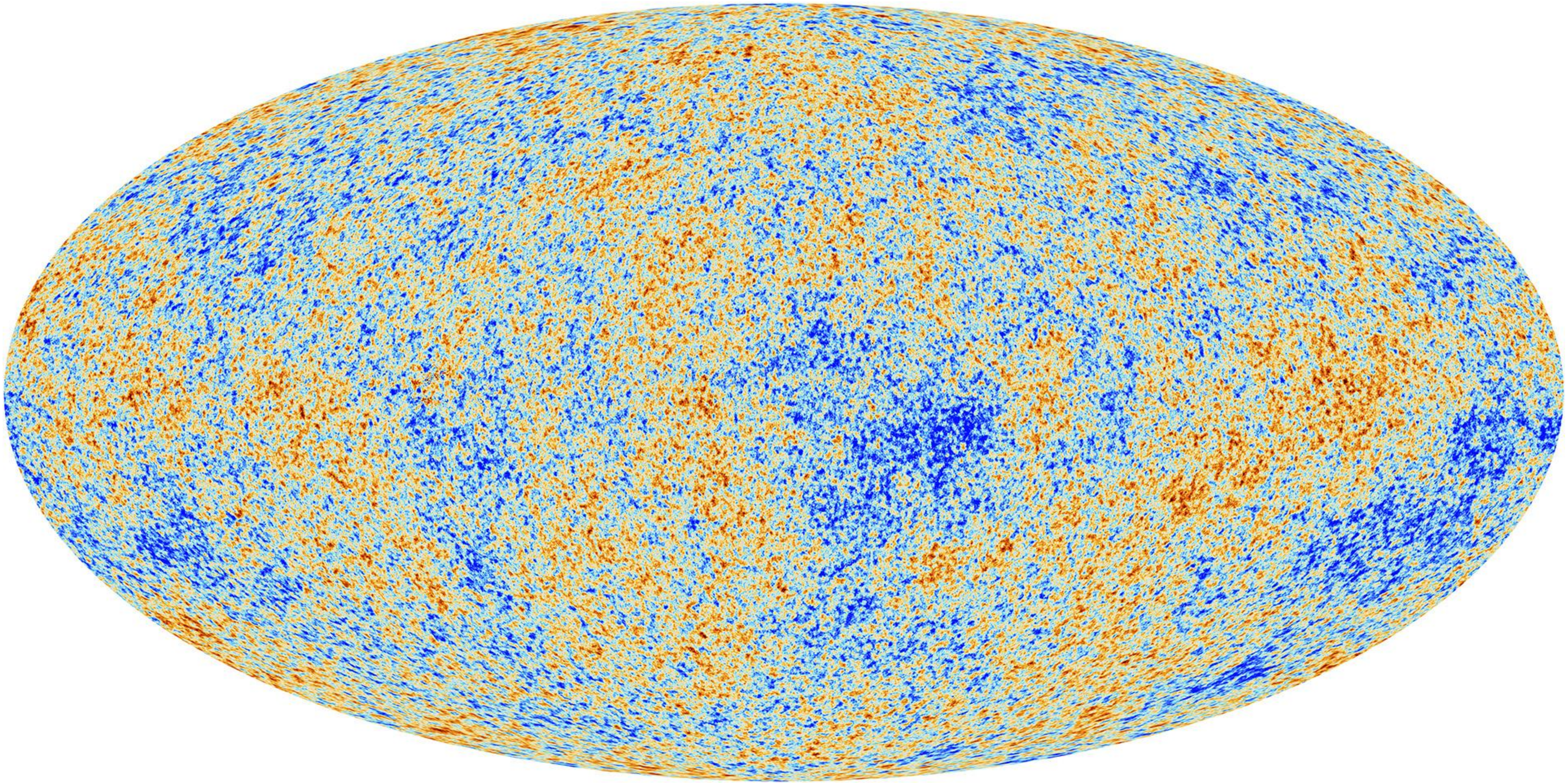


The Andromeda Galaxy (M31) in Different Types of Light.

X-ray: NASA/CXO/UMass/Z. Li & Q.D. Wang, ESA/XMM-Newton; Infrared: NASA/JPL-Caltech/WISE, Spitzer, NASA/JPL-Caltech/K. Gordon (U. Az), ESA/Herschel, ESA/Planck, NASA/IRAS, NASA/COBE; Radio: NSF/GBT/WSRT/IRAM/C. Clark (STScI); Ultraviolet: NASA/JPL-Caltech/GALEX; Optical: Andromeda, Unexpected © Marcel Drechsler, Xavier Strottner, Yann Sainty & J. Sahner, T. Kottary. Composite image processing: L. Frattare, K. Arcand, J.Major

What is Radio Astronomy?

- Radio astronomy is a branch of astronomy that studies celestial objects and phenomena by observing the radio waves they emit.
- Unlike optical astronomy, which uses visible light, radio astronomy utilizes radio telescopes to detect and analyze radio waves, allowing us to "see" a different part of the universe. These radio waves can pass through gas and dust clouds that block visible light, giving astronomers a clearer picture of certain objects and phenomena.



The Cosmic Microwave Background (CMB) - the oldest light in the universe.

CREDIT ESA and the Planck Collaboration

How to Make a Radio Wave?

$$
\begin{aligned}
\nabla \cdot \mathbf{E} &= \frac{\rho}{\varepsilon_0} \\
\nabla \cdot \mathbf{B} &= 0 \\
\nabla \times \mathbf{E} &= -\frac{\partial \mathbf{B}}{\partial t} \\
\nabla \times \mathbf{B} &= \mu_0 \left(\mathbf{J} + \varepsilon_0 \frac{\partial \mathbf{E}}{\partial t} \right)
\end{aligned}
$$

Radio waves are generated by accelerating charged particles, most commonly through alternating currents in an antenna. When electrons move back and forth, they create a changing electric field, which in turn generates a magnetic field, and these two fields propagate outward at the speed of light as a radio wave

1. Gauss's Law for Electricity

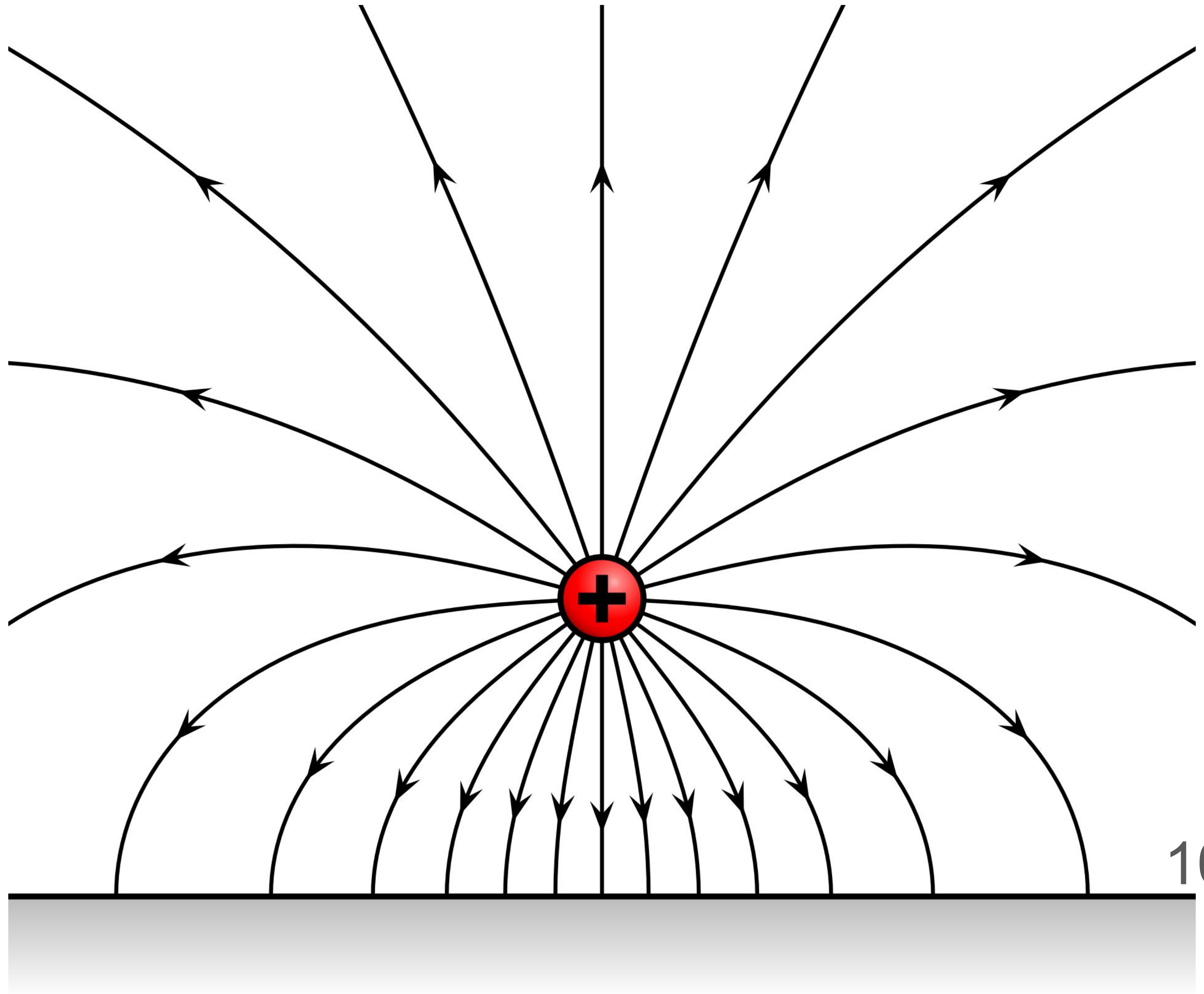
$$
\begin{aligned}
\nabla \cdot \mathbf{E} &= \frac{\rho}{\varepsilon_0} \\
\nabla \cdot \mathbf{B} &= 0 \\
\nabla \times \mathbf{E} &= -\frac{\partial \mathbf{B}}{\partial t} \\
\nabla \times \mathbf{B} &= \mu_0 \left(\mathbf{J} + \varepsilon_0 \frac{\partial \mathbf{E}}{\partial t} \right)
\end{aligned}
$$

Electric fields originate on electric charges. Field lines point away from positive charges and toward negative charges.

$$\nabla \cdot E = \rho_v / \varepsilon_0$$

where $\nabla \cdot E$ is the divergence of the electric field, ρ_v is the charge density, and ε_0 is the permittivity of free space.

=> This sets up the source of our disturbance.



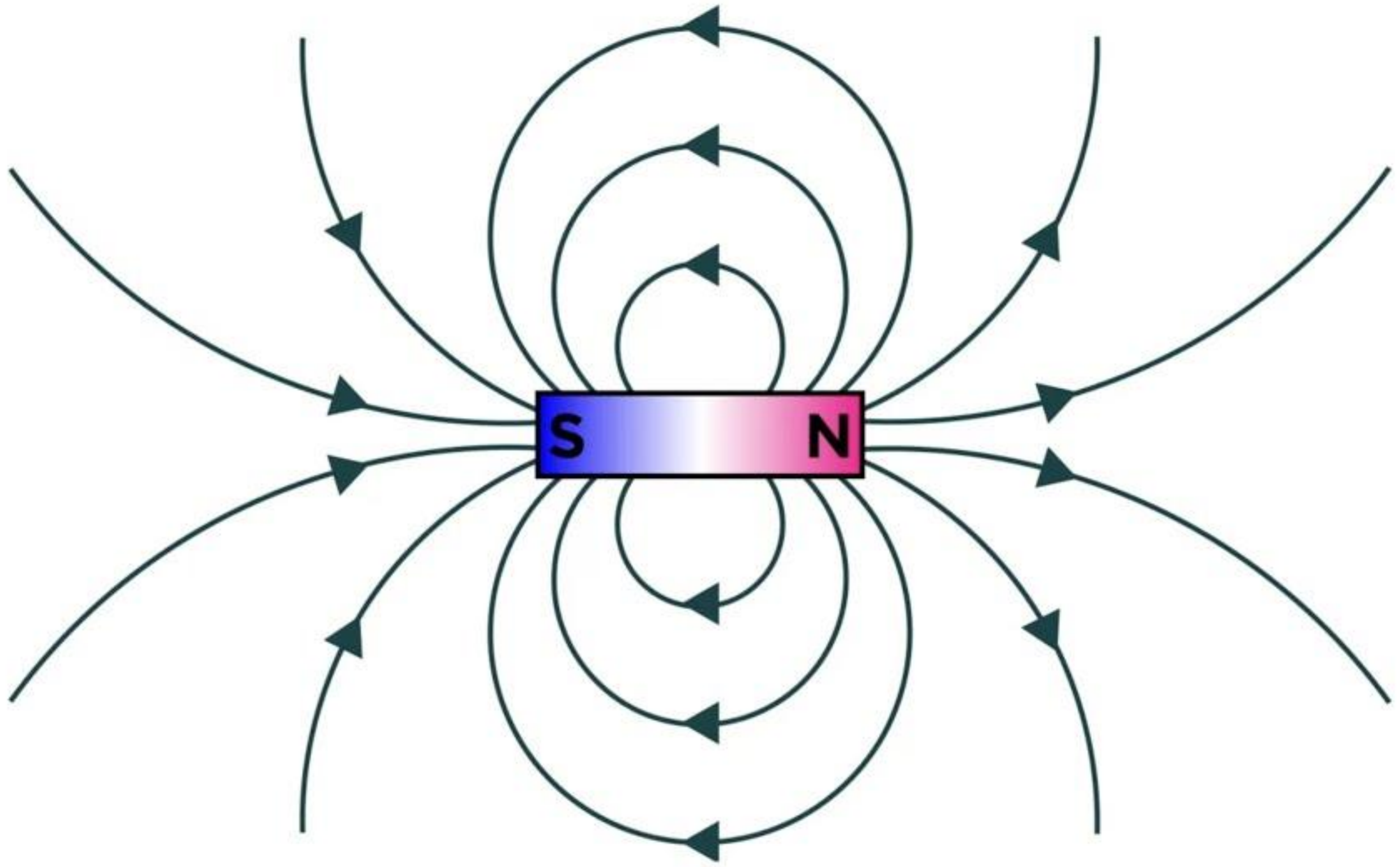
2. Gauss's Law for Magnetism

$$\begin{aligned}\nabla\cdot\mathbf{E} &= \frac{\rho}{\varepsilon_0}\\ \nabla\cdot\mathbf{B} &= 0\\ \nabla\times\mathbf{E} &= -\frac{\partial\mathbf{B}}{\partial t}\\ \nabla\times\mathbf{B} &= \mu_0\left(\mathbf{J}+\varepsilon_0\frac{\partial\mathbf{E}}{\partial t}\right)\end{aligned}$$

This law states that there are no magnetic monopoles (isolated north or south poles). The magnetic flux through any closed surface is always zero.

$$\nabla \cdot B = 0$$

where $\nabla \cdot B$ is the divergence of the magnetic field
=> This is a fundamental constraint, but not the main actor in creating the wave.



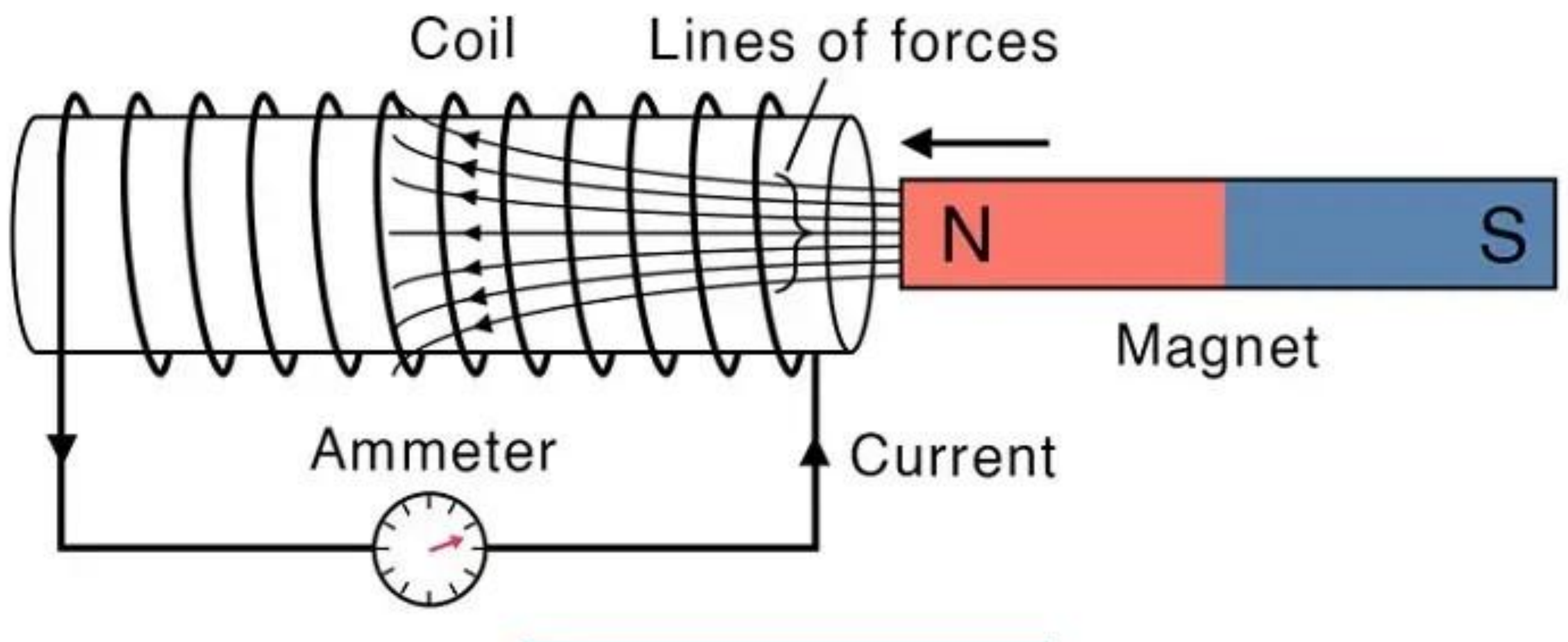
3. Faraday's Law of Induction

$$\nabla \cdot \mathbf{E} = \frac{\rho}{\varepsilon_0}$$
$$\nabla \cdot \mathbf{B} = 0$$
$$\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t}$$
$$\nabla \times \mathbf{B} = \mu_0 \left(\mathbf{J} + \varepsilon_0 \frac{\partial \mathbf{E}}{\partial t} \right)$$

This law describes how a changing magnetic field induces an electric field. It states that the electromotive force (voltage) around a closed loop is equal to the rate of change of magnetic flux through the loop.

$$\nabla \times E = -\partial B/\partial t$$

where $\nabla \times E$ is the curl of the electric field and $\partial B/\partial t$ is the time derivative of the magnetic field.



A **changing magnetic field** (the $\partial B/\partial t$ term) creates a **circulating electric field** (the $\nabla \times E$ or "curl of E" term).

4. Ampère-Maxwell's Law

This law describes how electric currents and changing electric fields create magnetic fields. It states that the magnetic field around a closed loop is proportional to the electric current passing through the loop and the rate of change of electric flux through the loop.

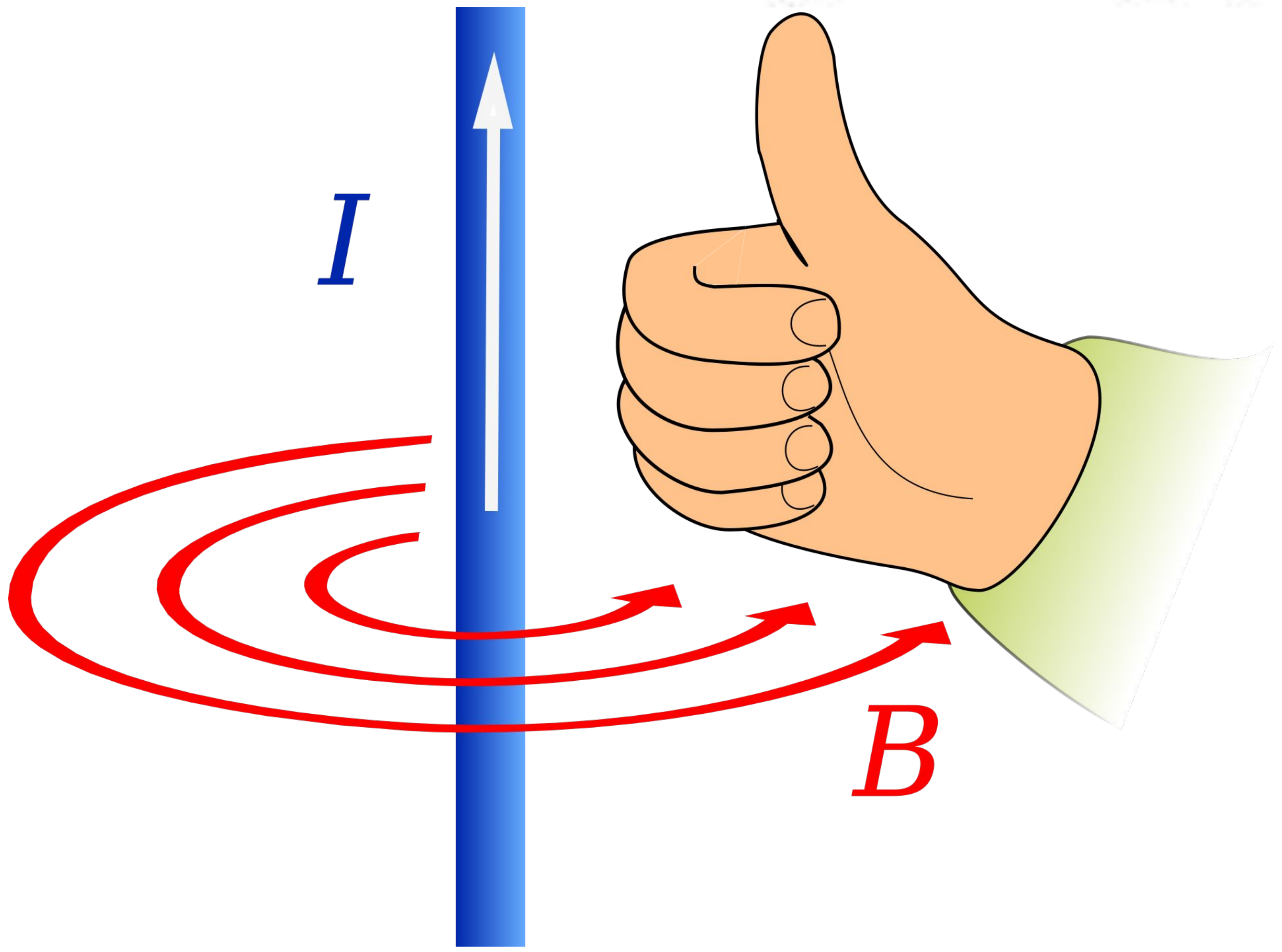
$$\nabla \times B = \mu_0(J + \varepsilon_0 \partial E/\partial t)$$

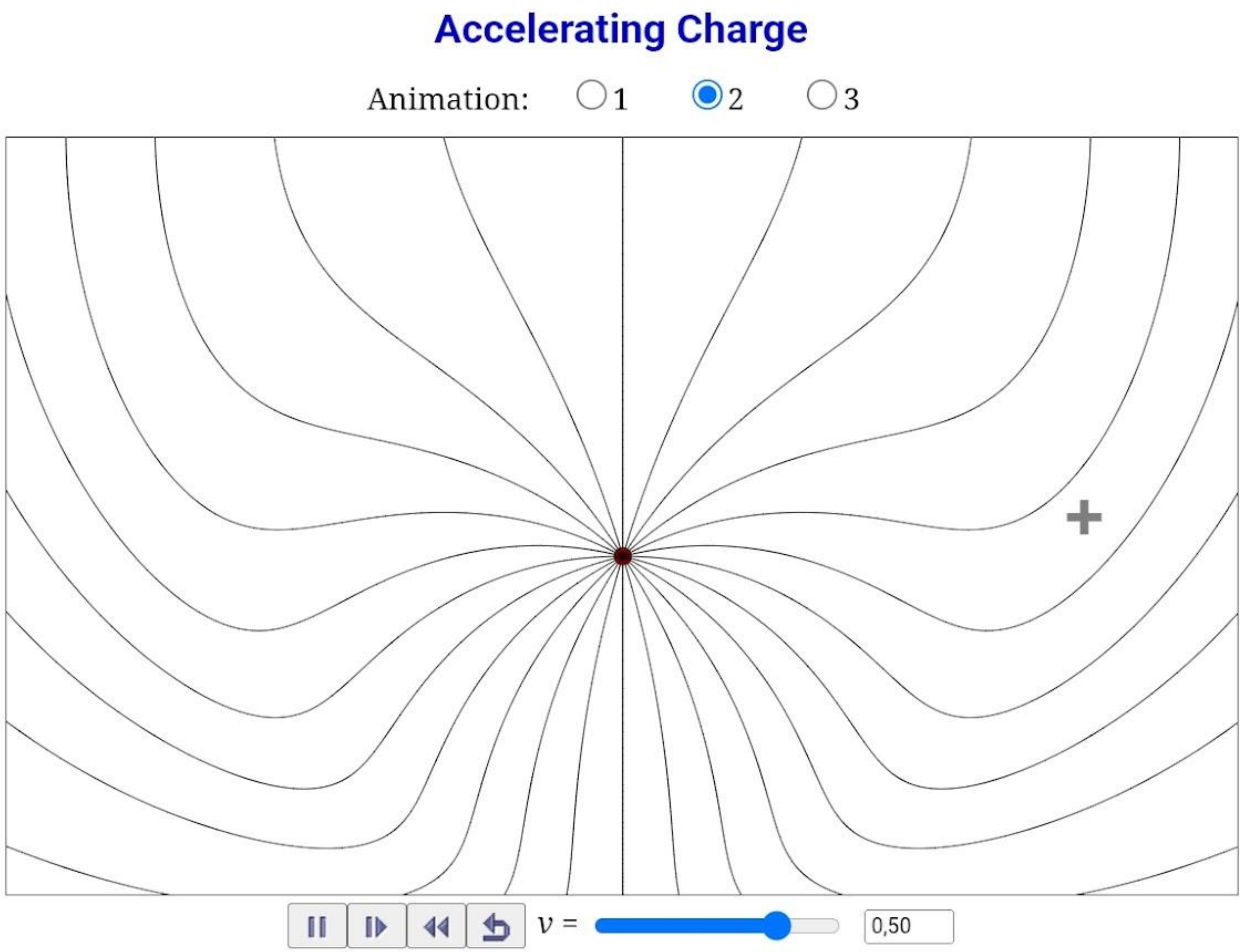
where $\nabla \times B$ is the curl of the magnetic field, J is the current density, and ε_0 is the permittivity of free space, μ_0 is the permeability of free space.

=> A circulating magnetic field ($\nabla \times B$) is created by an electric current (J).

=> **the displacement current** $\mu_0\varepsilon_0(\partial E/\partial t)$: a **changing electric field** also creates a circulating **magnetic field**, even in empty space where there is no current (J=0)!

$$\begin{aligned} \nabla \cdot \mathbf{E} &= \frac{\rho}{\varepsilon_0} \\ \nabla \cdot \mathbf{B} &= 0 \\ \nabla \times \mathbf{E} &= -\frac{\partial \mathbf{B}}{\partial t} \\ \nabla \times \mathbf{B} &= \mu_0 \left(\mathbf{J} + \varepsilon_0 \frac{\partial \mathbf{E}}{\partial t} \right) \end{aligned}$$





See simulation at: https://www.compadre.org/osp/EJSS/4126/154.htm

Antennas

An antenna is a device that converts a guided electrical signal (from a wire/cable) into a free-space electromagnetic wave, and vice-versa.

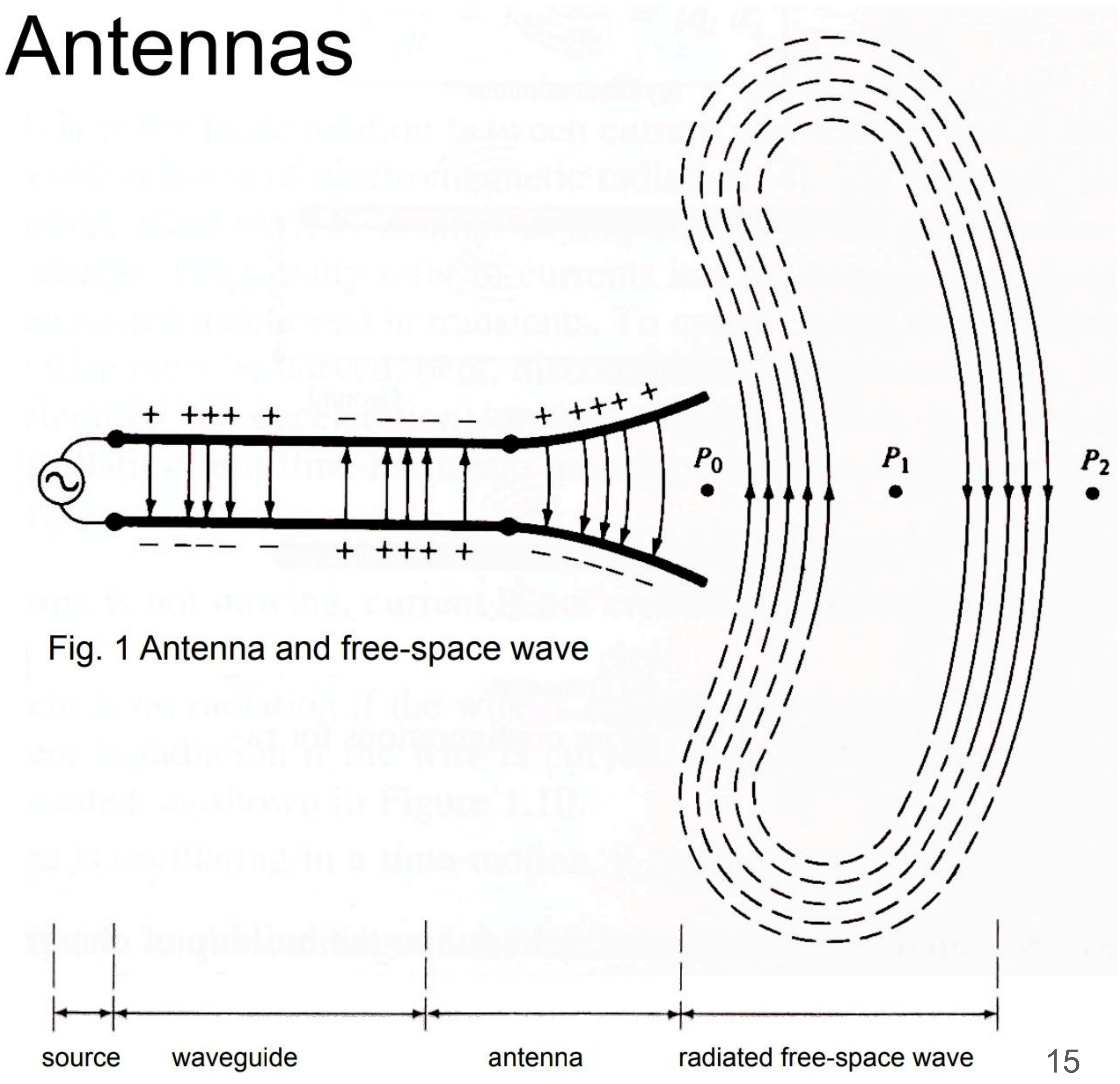
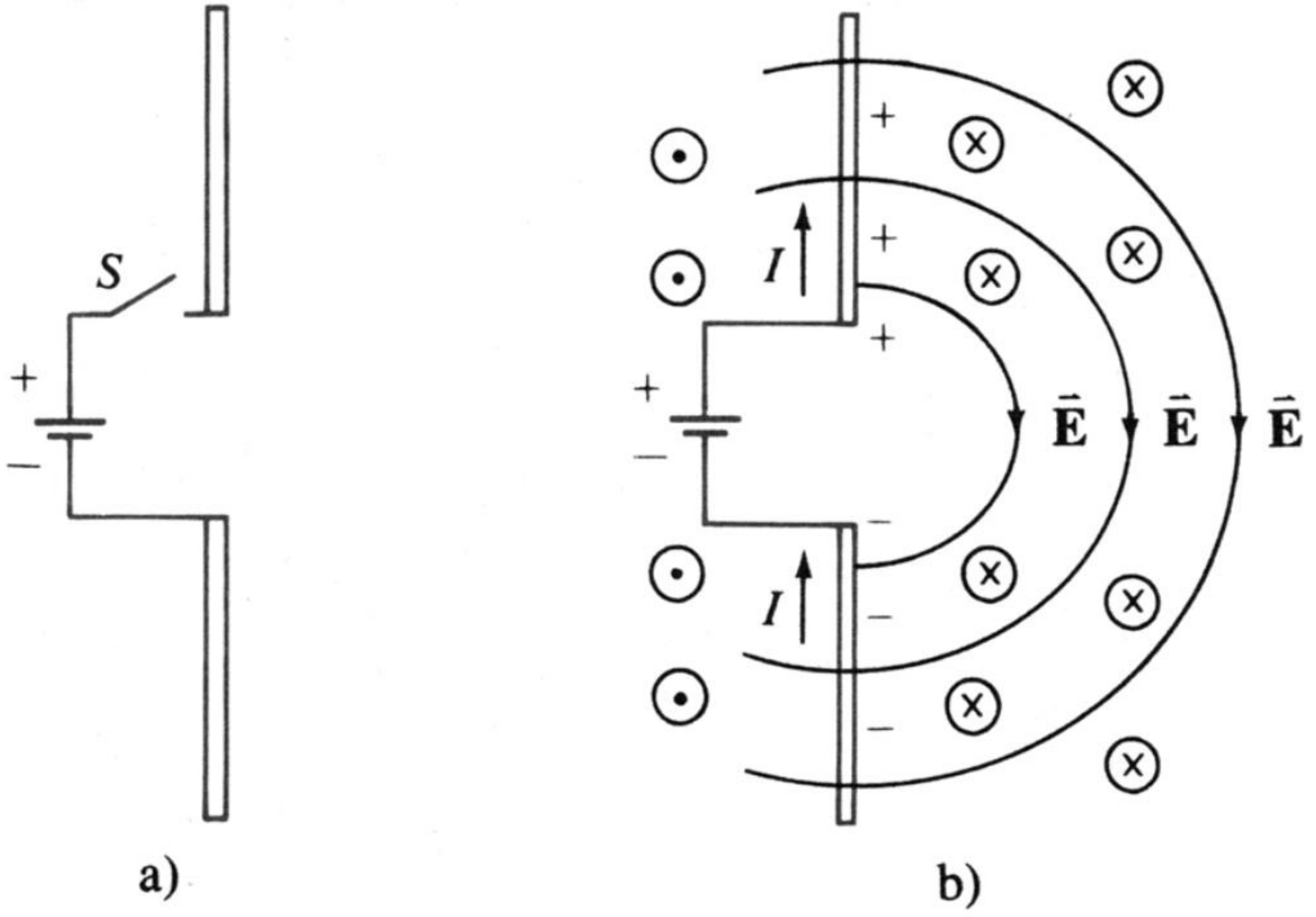


Fig. 1 Antenna and free-space wave

Principal of radiation

Imagine we have a simple dipole antenna: two metal rods connected to a voltage generator.

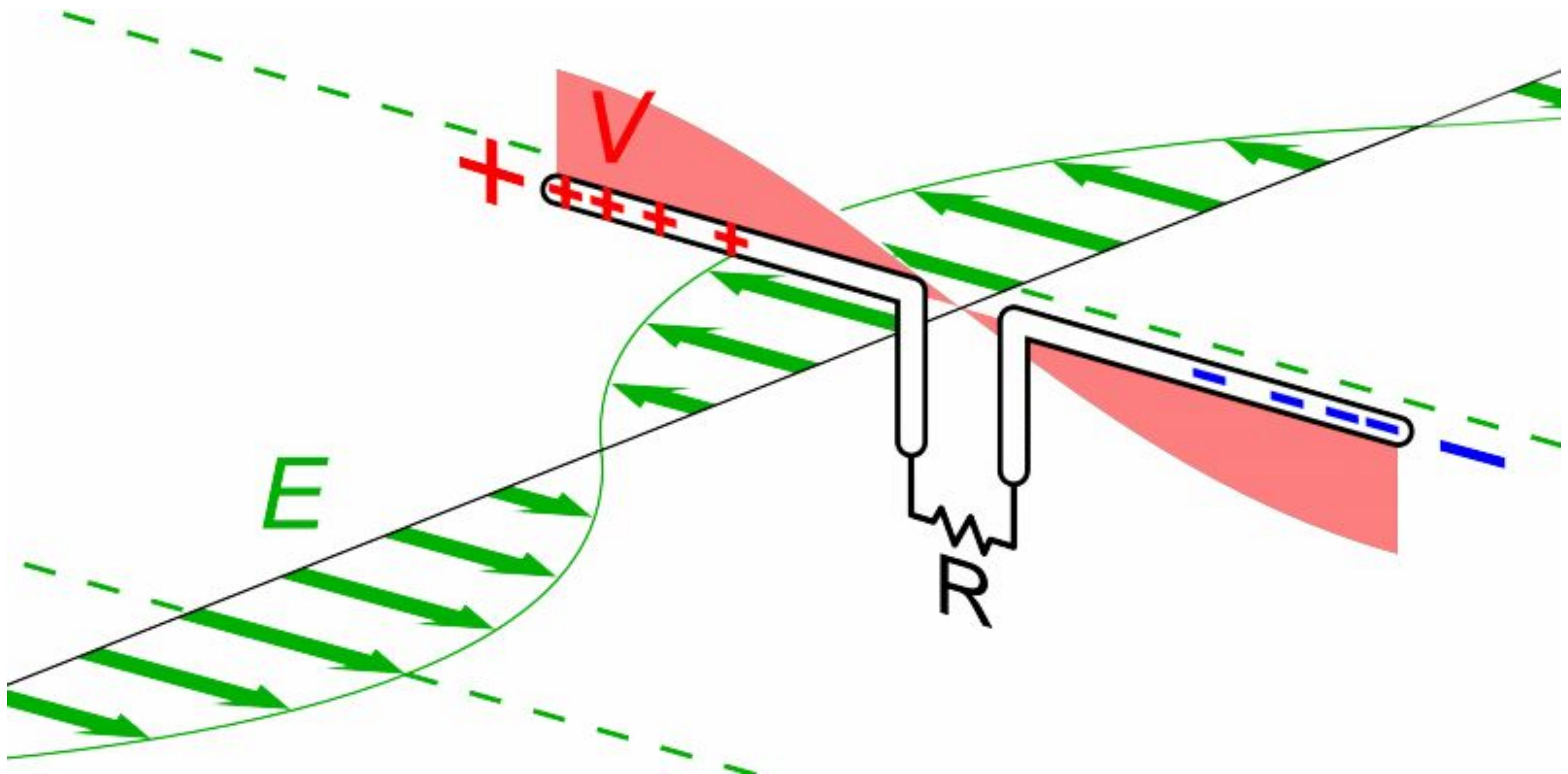
- If we consider the behavior of the device when starting the application of variable electric field, a current will propagate in both rods.
- This current therefore produces a magnetic field that surrounds the to conductors. The presence of charges in the two conductors simultaneously induces an electric field, which is itself in terms of both conductors.

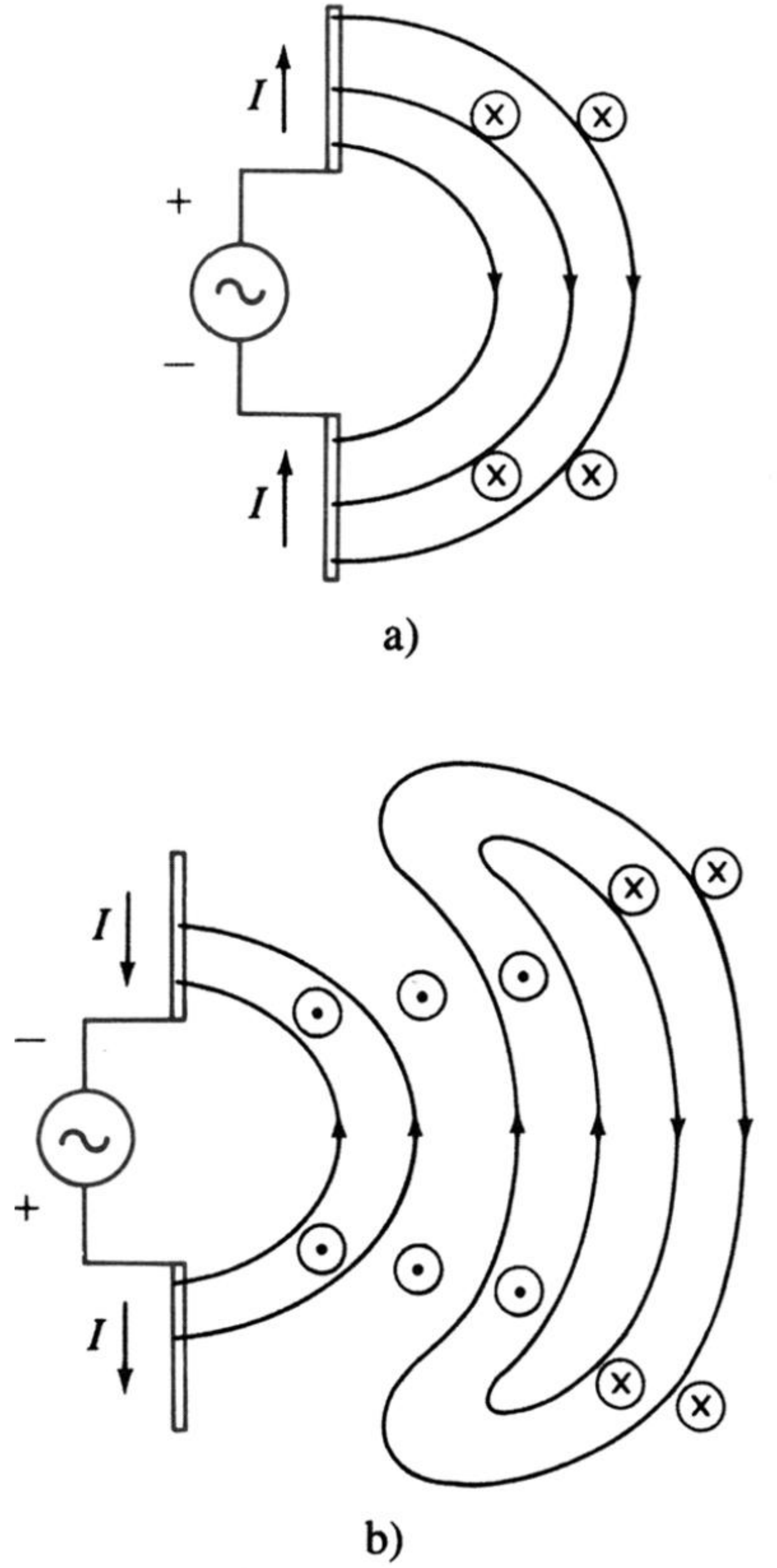


Principal of radiation

Create a Changing Electric Field (Applying Gauss's Law and Maxwell's Correction)

- The AC source pushes electrons up one rod, making its tip negative, and pulls them from the other rod, making its tip positive.
- According to **Gauss's Law**, this separation of charge creates an electric field (E) pointing from the positive tip to the negative tip.
- Because the AC source is oscillating, the amount of charge at the tips is constantly changing. This means the electric field is also constantly changing in strength and direction. We now have a **changing E-field (∂E/∂t)**.

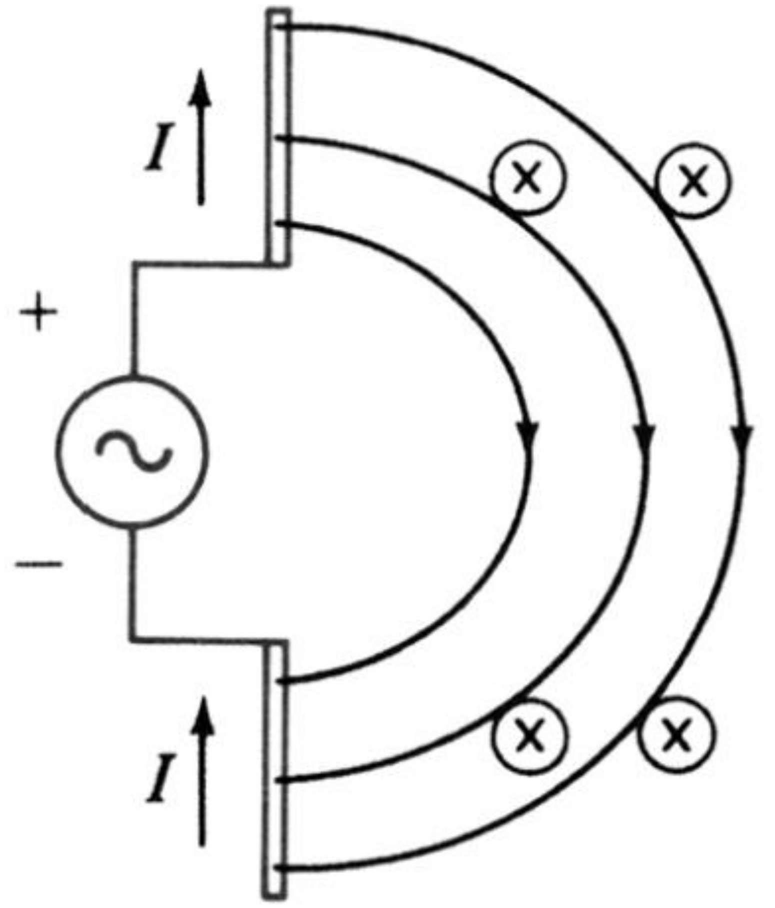




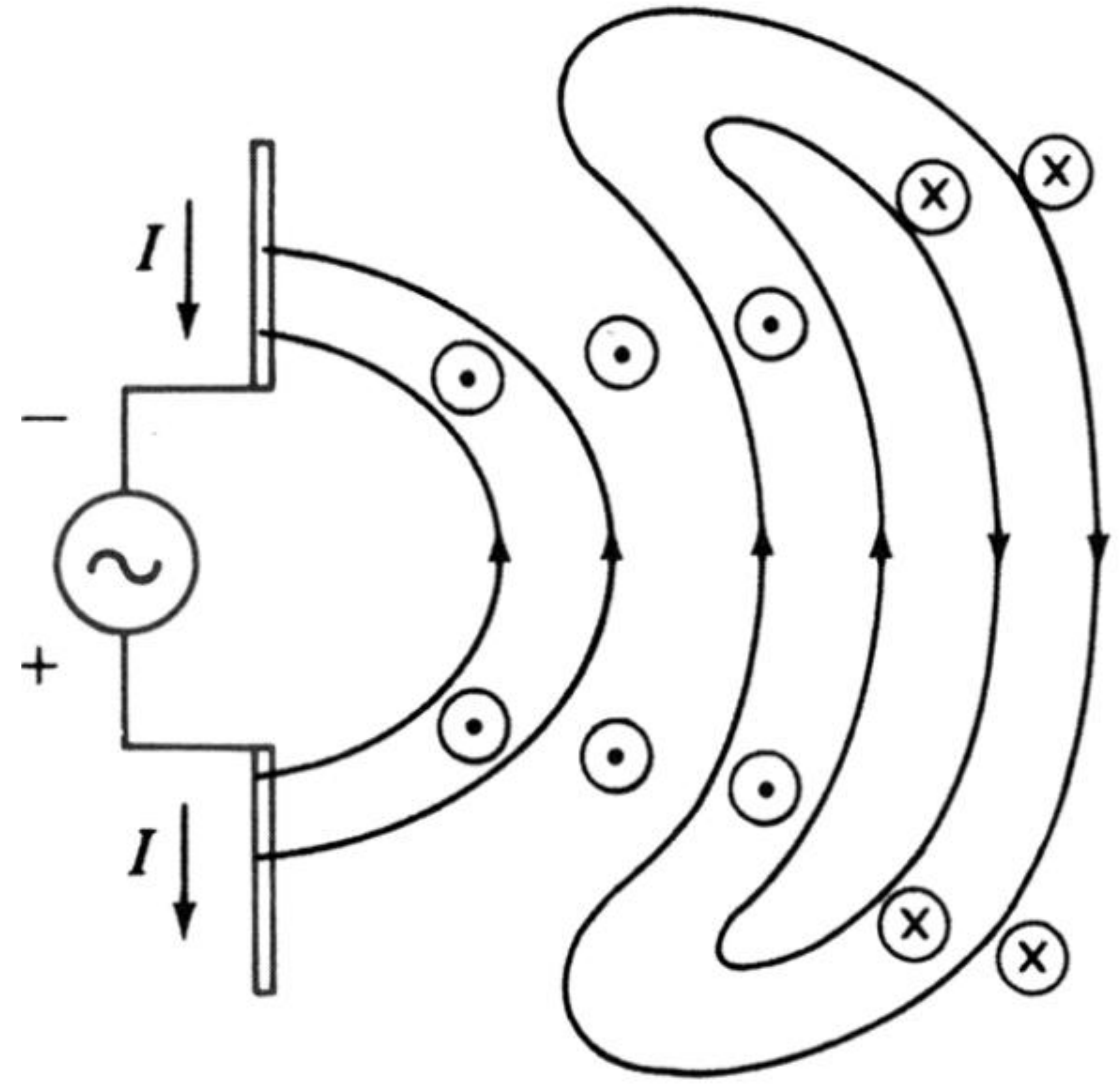
Principal of radiation

In the following alternations, the current flows in the opposite direction, and are therefore produced an electric field and a magnetic field in opposite directions to those of the previous rotation. Meanwhile, the electric field and magnetic field created by the previous alternation continues to spread to infinity, forming closed loops

Figure: Patterns of spread of electric and magnetic fields from oscillating loads on the two conductors connected to an AC source



a)

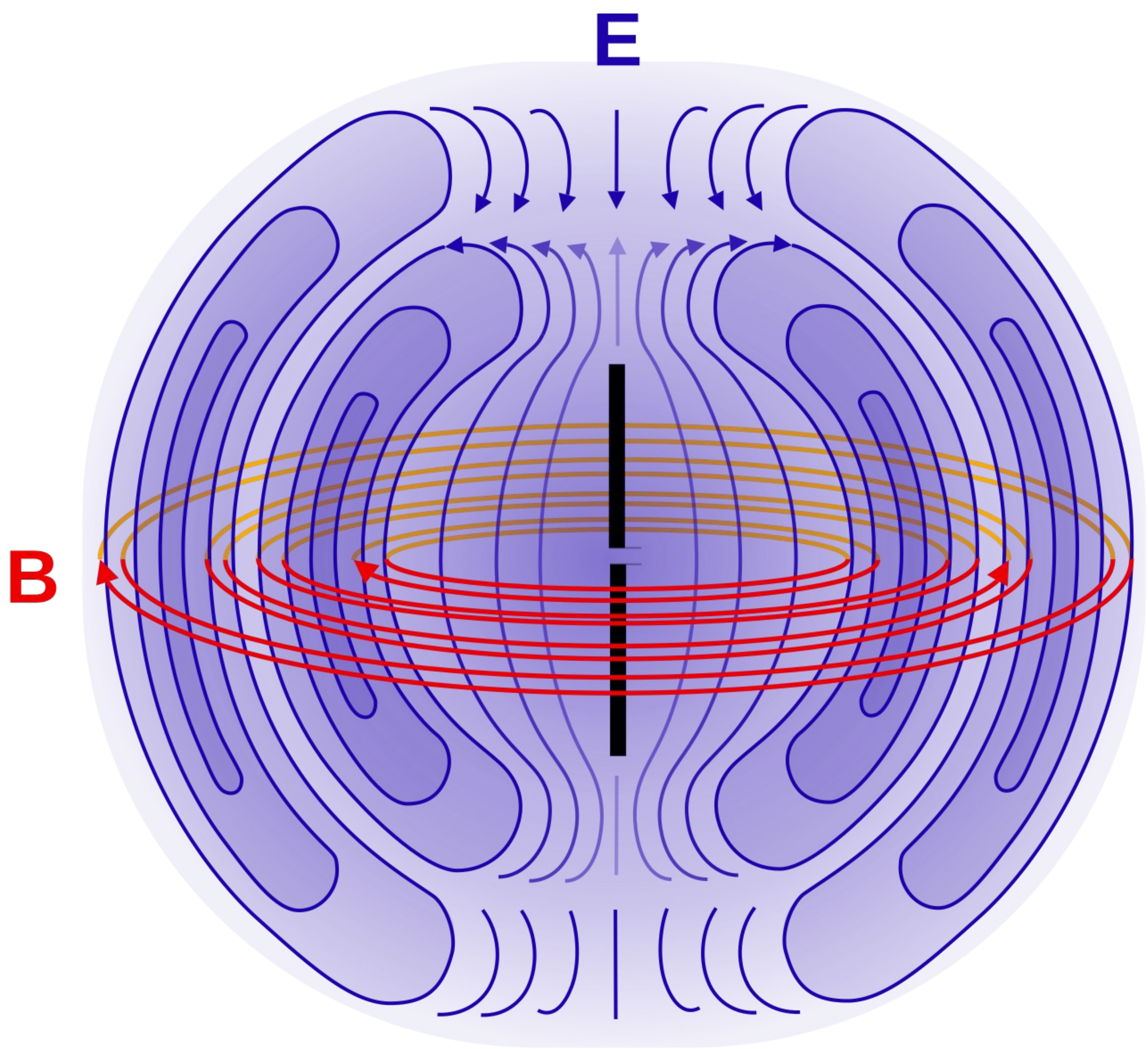


b)

Principal of radiation

The Changing E-Field Creates a Changing B-Field (Applying Maxwell's Correction)

- Ampere's Law: It says that this ∂E/∂t (our changing electric field) must create a **circulating magnetic field (∇ × B)** around it.
- This new magnetic field (B) wraps around the antenna like rings. Since the E-field is changing sinusoidally, the B-field it creates also changes sinusoidally. We now have a **changing B-field (∂B/∂t)**.



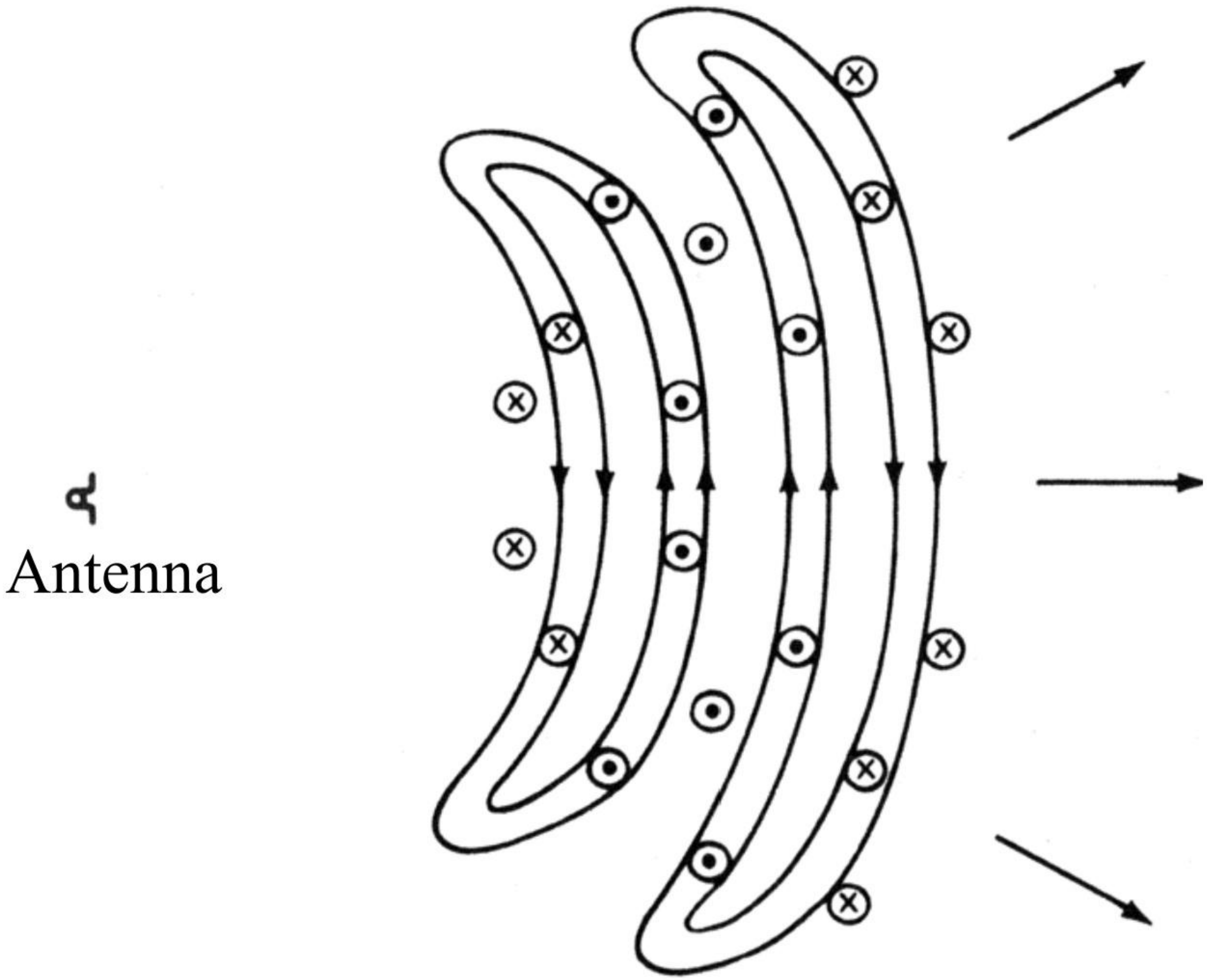
Principal of radiation

The Changing B-Field Creates a New E-Field (Applying Faraday's Law)

- According to Faraday's Law, our newly created changing magnetic field ($\partial B/\partial t$) must, in turn, induce a new circulating electric field ($\nabla \times E$) a little further out from the antenna.
- This new E-field is a consequence of the B-field, not the original charges on the antenna.

- This new changing E-field then creates another changing B-field a bit further out (by Maxwell's correction).
- That new changing B-field creates another new changing E-field a bit further out (by Faraday's Law).

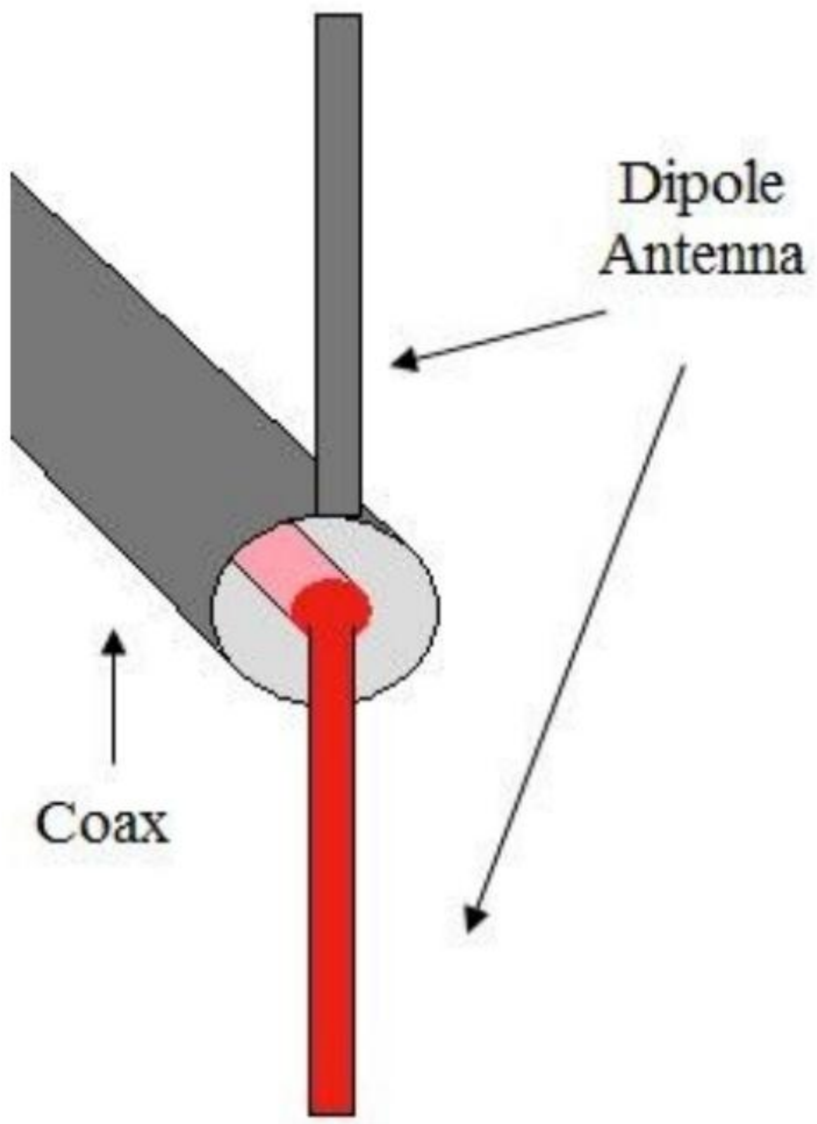
=> This process becomes a self-sustaining "leapfrog" between electric and magnetic fields. Each one creates the other a little further away in space.

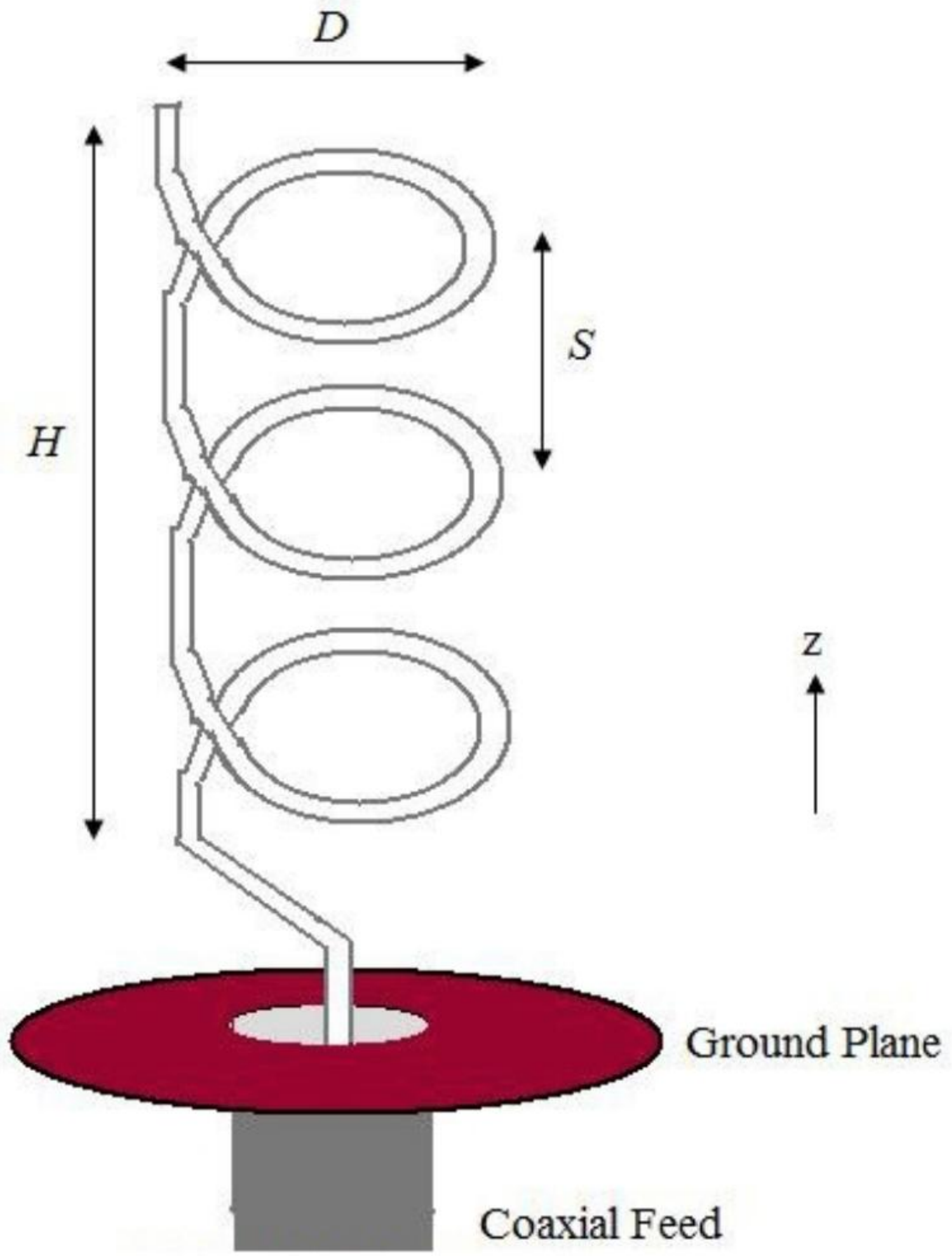


Principal of radiation

In summary, to make a radio wave, you simply need to accelerate charges (like wiggling them back and forth in an antenna). This initial disturbance creates a changing E-field, and Maxwell's equations dictate the inescapable, self-propagating chain reaction that follows, sending a wave of energy out into the cosmos.

Wire antennas

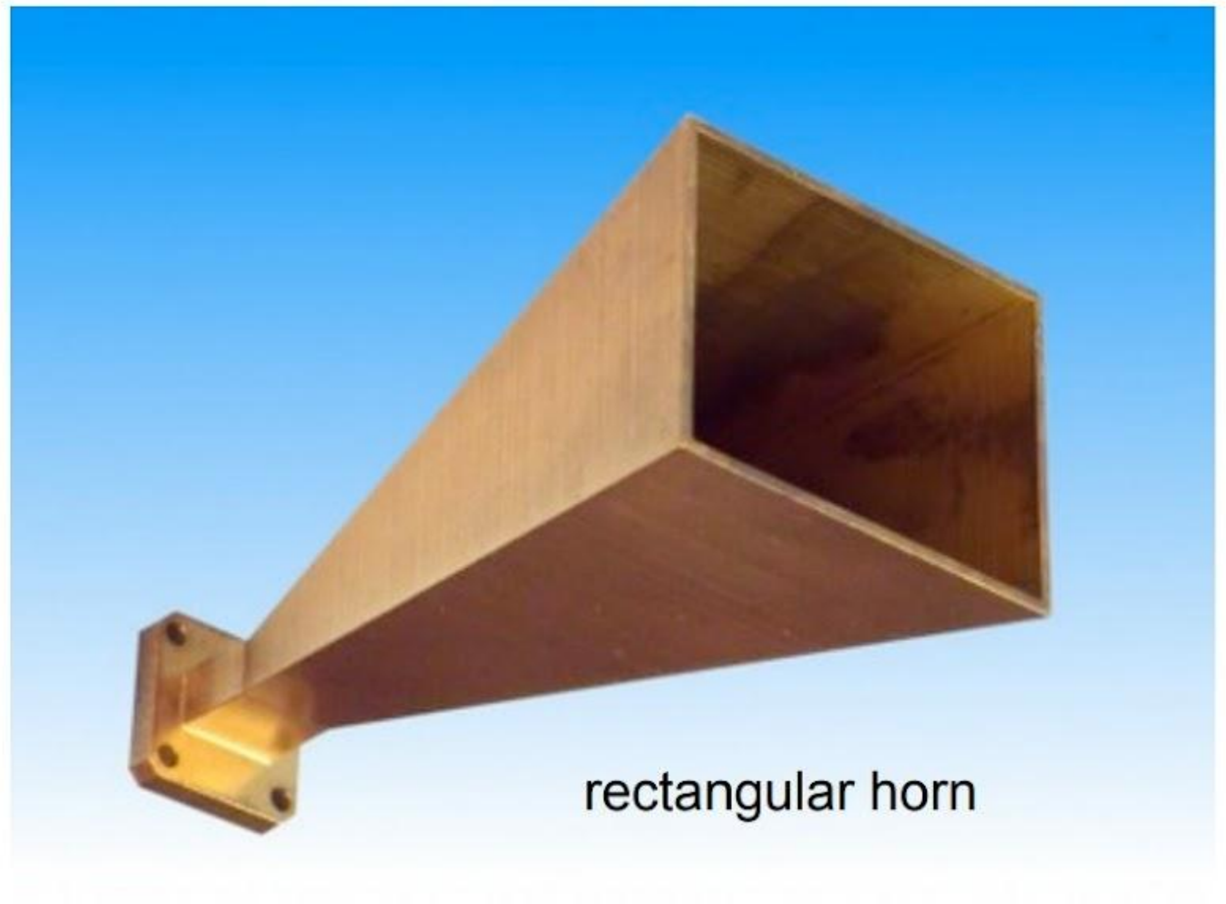




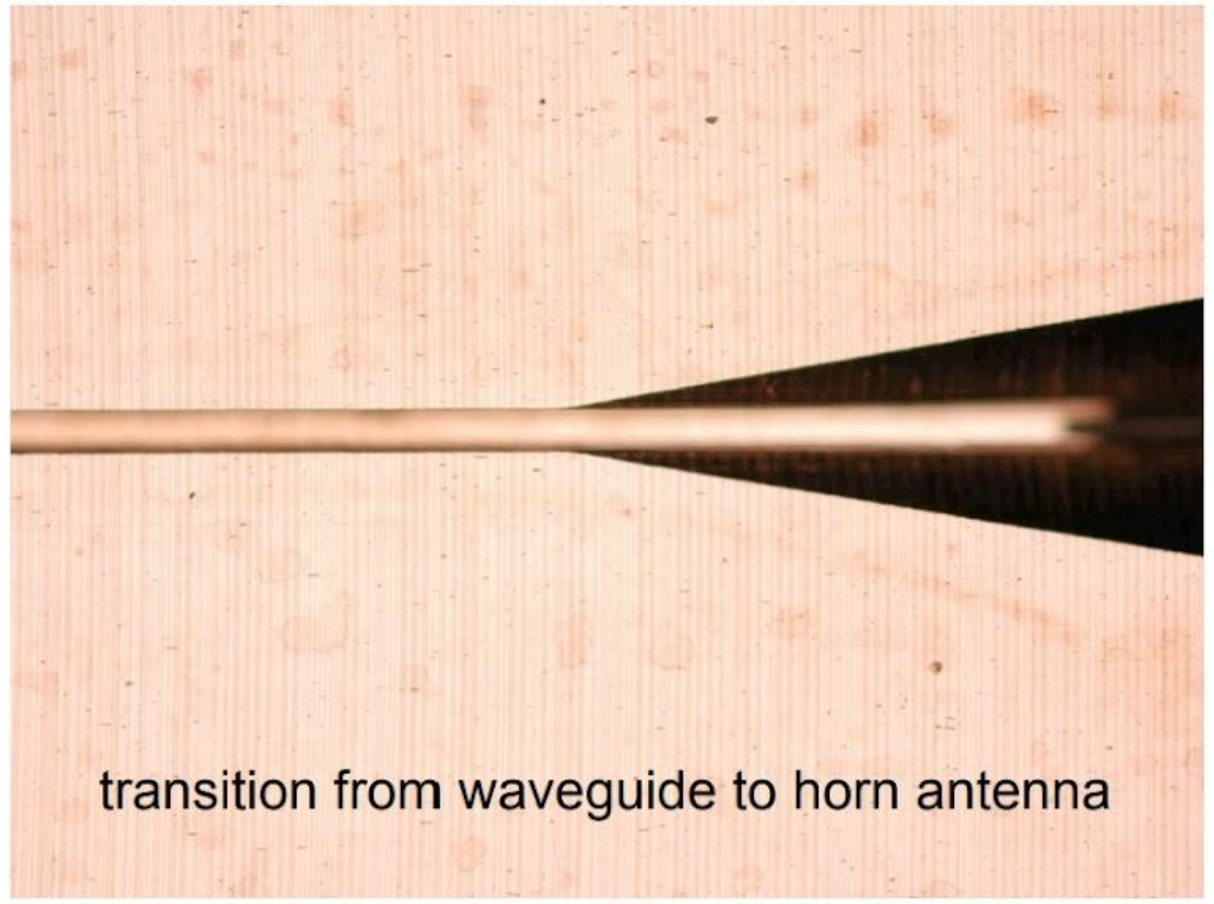
from www.antenna-theory.com

Aperture antennas

380 GHz -dual mode Potter horn

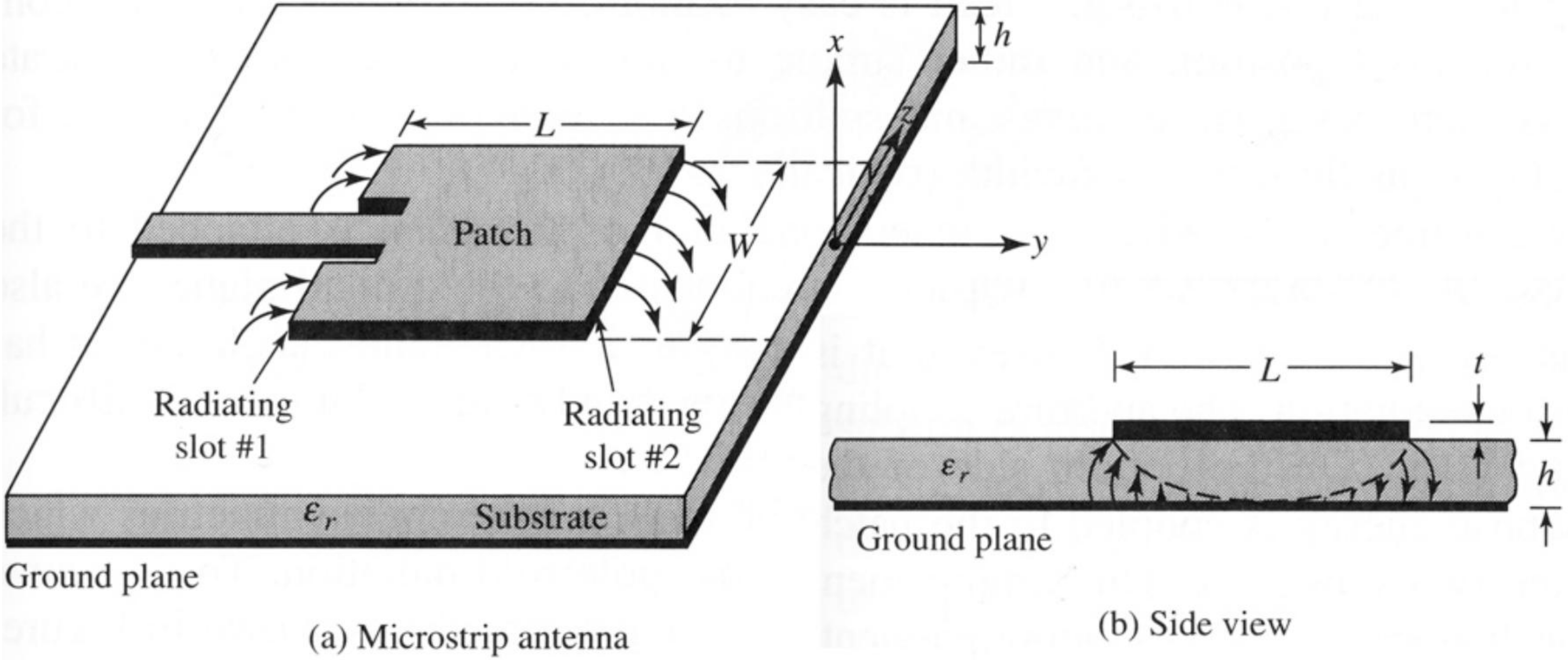


rectangular horn



transition from waveguide to horn antenna

Patch antennas



after Antenna Theory – Constantine A. Balanis

YAGI antennas

Hidetsugu Yagi Yagi Antenna

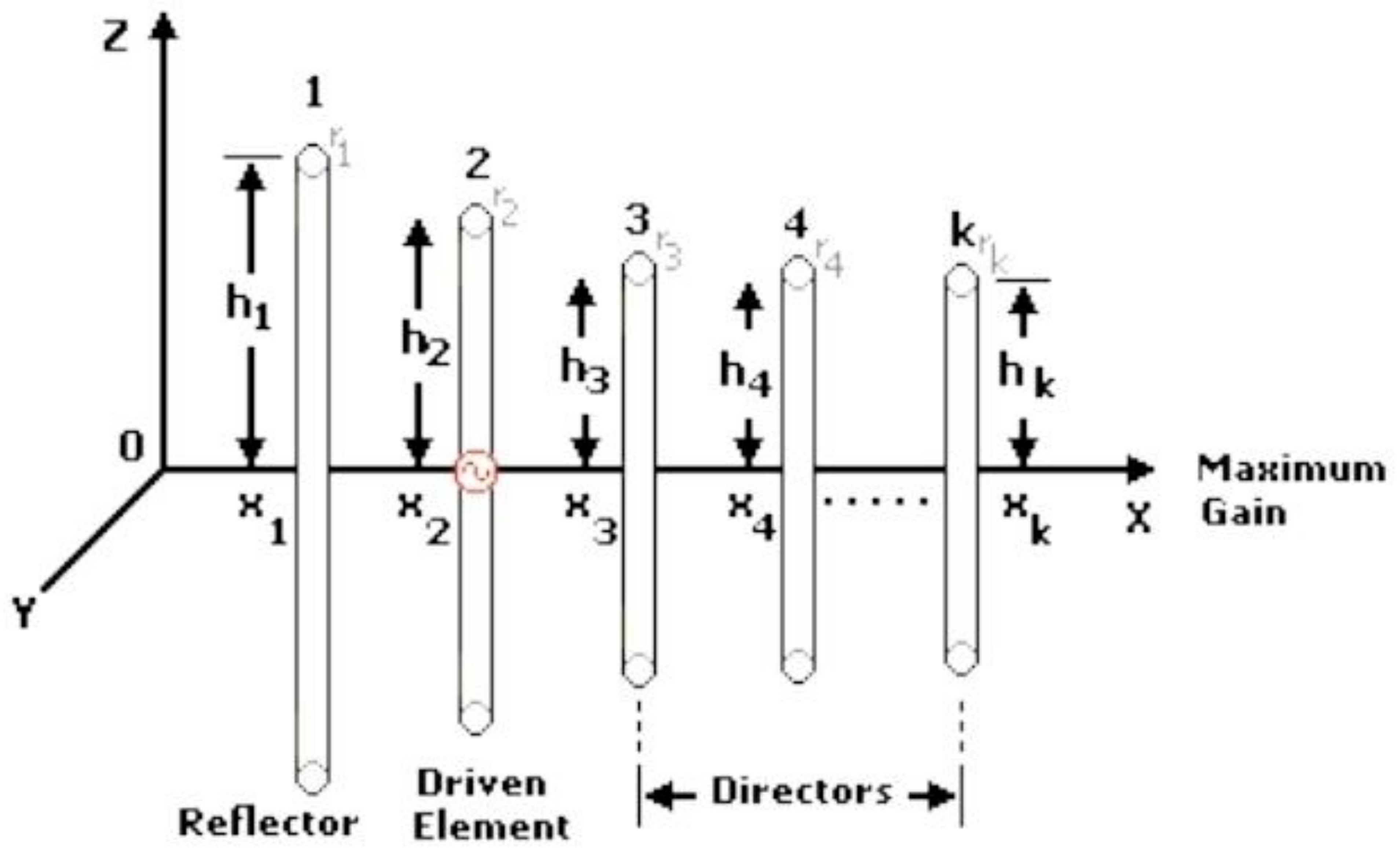
The Yagi Antenna is a directional antenna invented by Dr. Hidetsugu Yagi of Tohoku Imperial University and his assistant, Dr. Shintaro Uta. This groundbreaking invention combined a simple structure with high performance. Most ultra short or extremely shortwave receiving antennas, such as TV antennas, use this structure.

Dr. Yagi's invention was ahead of its time (patented in 1926) and therefore not understood in Japan. Its value was, however, accepted in Europe and North America, where it entered commercial production. It is said that people in Japan realized the true value of the Yagi Antenna in World War 2 when it was discovered that the invention was used as a radar antenna by the Allies.

YAGI antennas

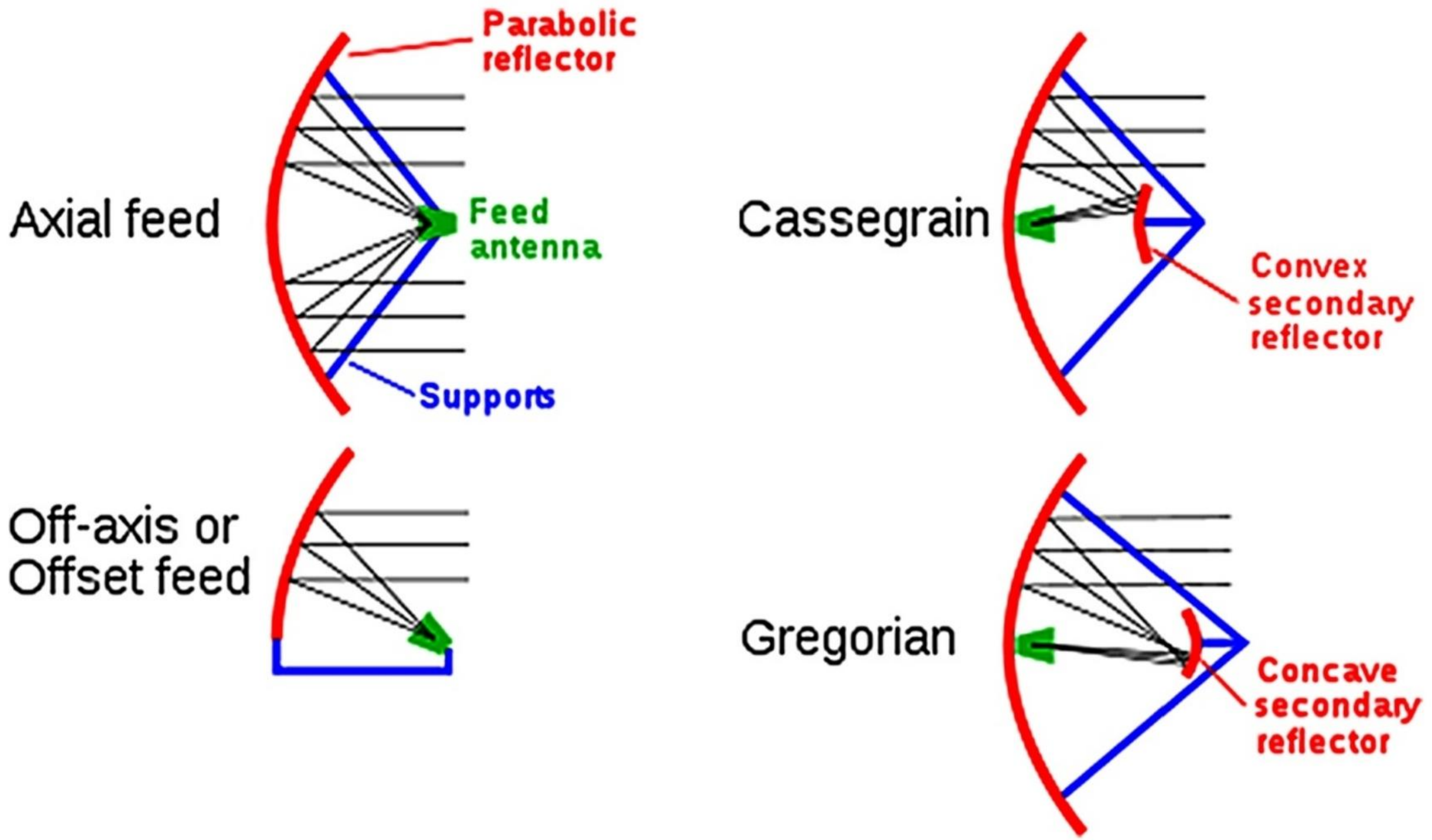
- The second dipole in the Yagi-Uda array is the only driven elemen
  with applied input/output source feed.
- All the others interact by mutual coupling since receive and
  reradiate electromagnetic energy

=> they act as parasitic elements by induced current. It is assumed th
an antenna is a passive reciprocal device, then may used either for
transmission or for reception of the electromagnetic energy.

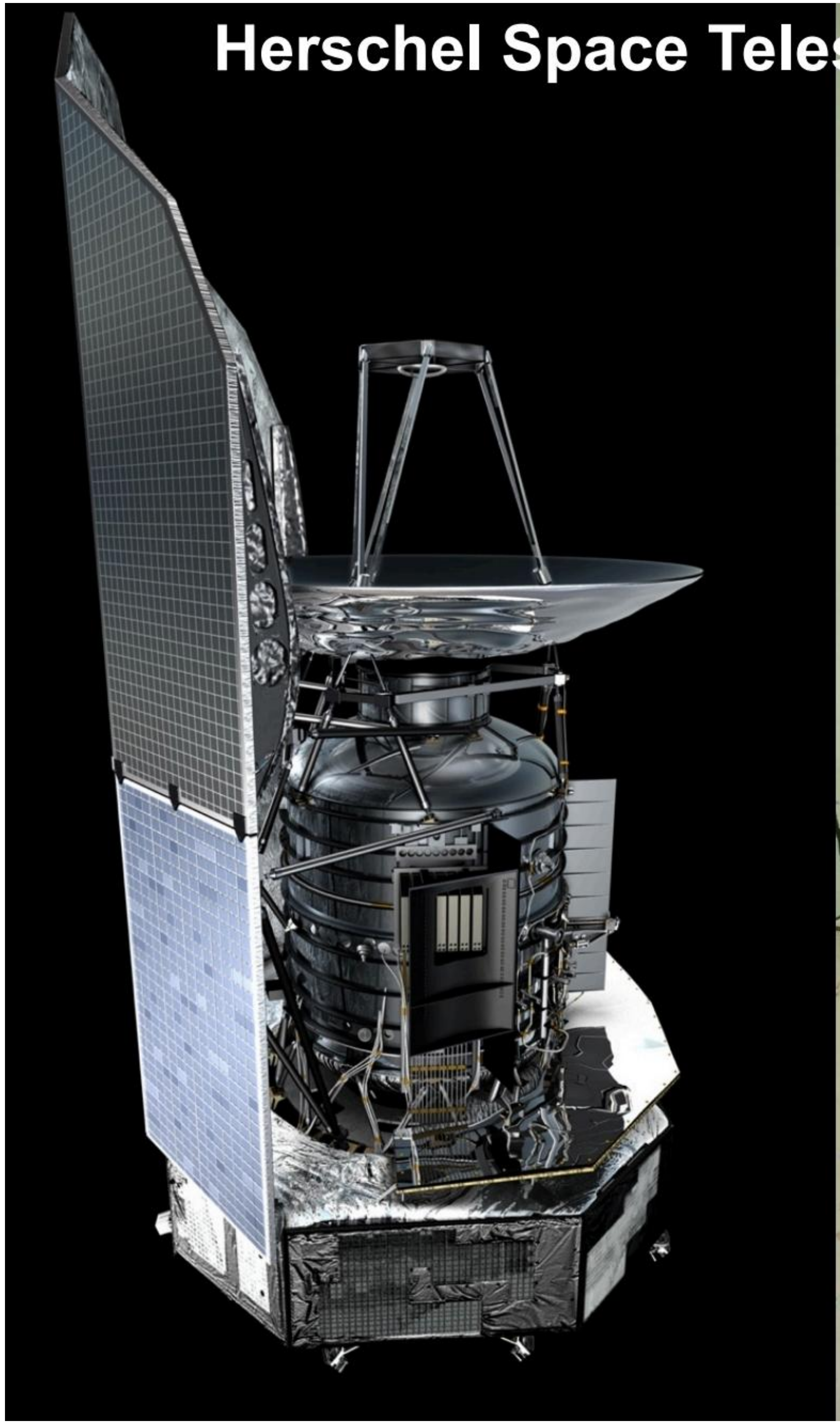


Geometry of a K elements Yagi-Uda

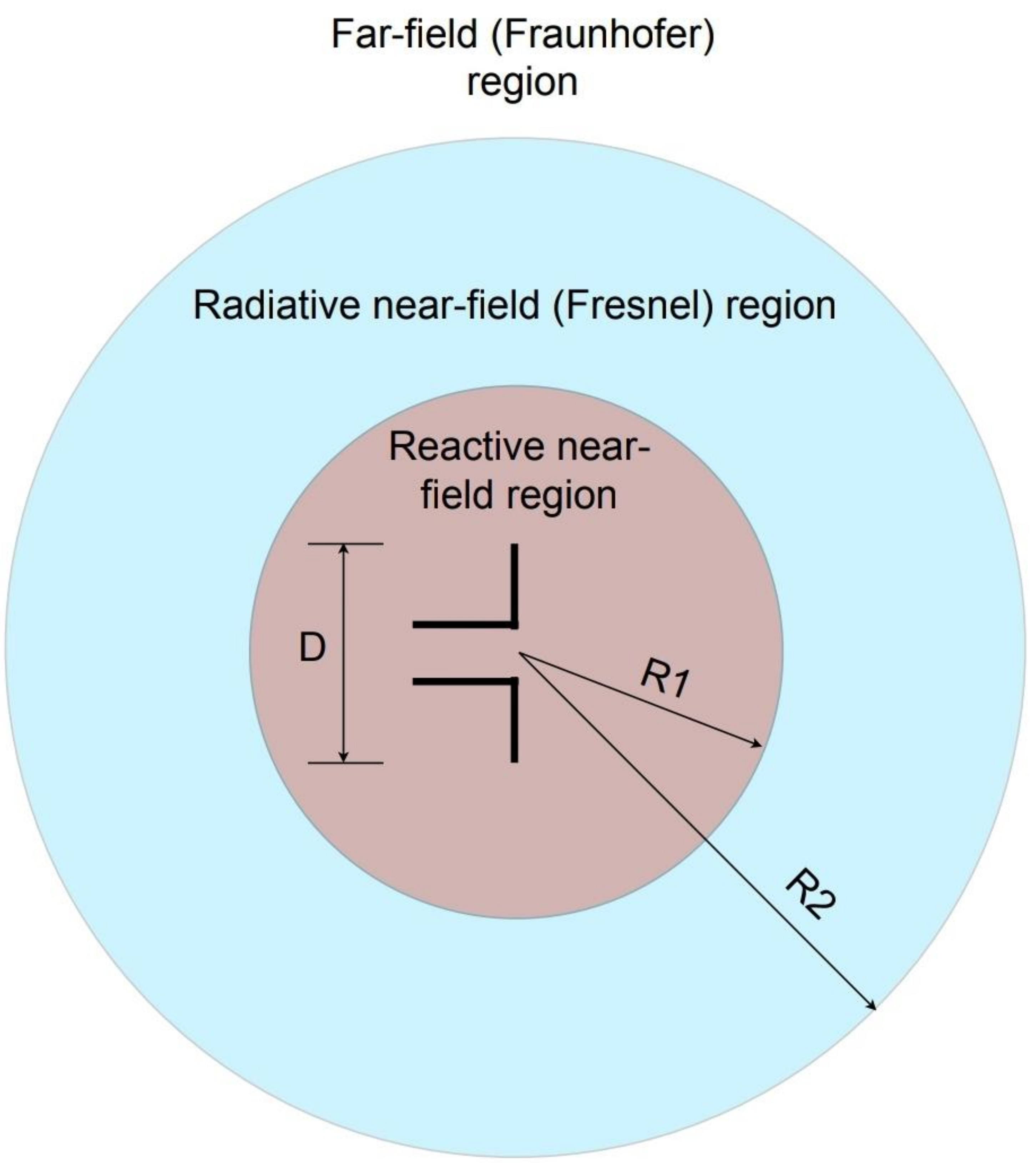
Reflector antennas



Herschel Space Telescope with a 3.5 m Mirror



Near field and Far field of antennas



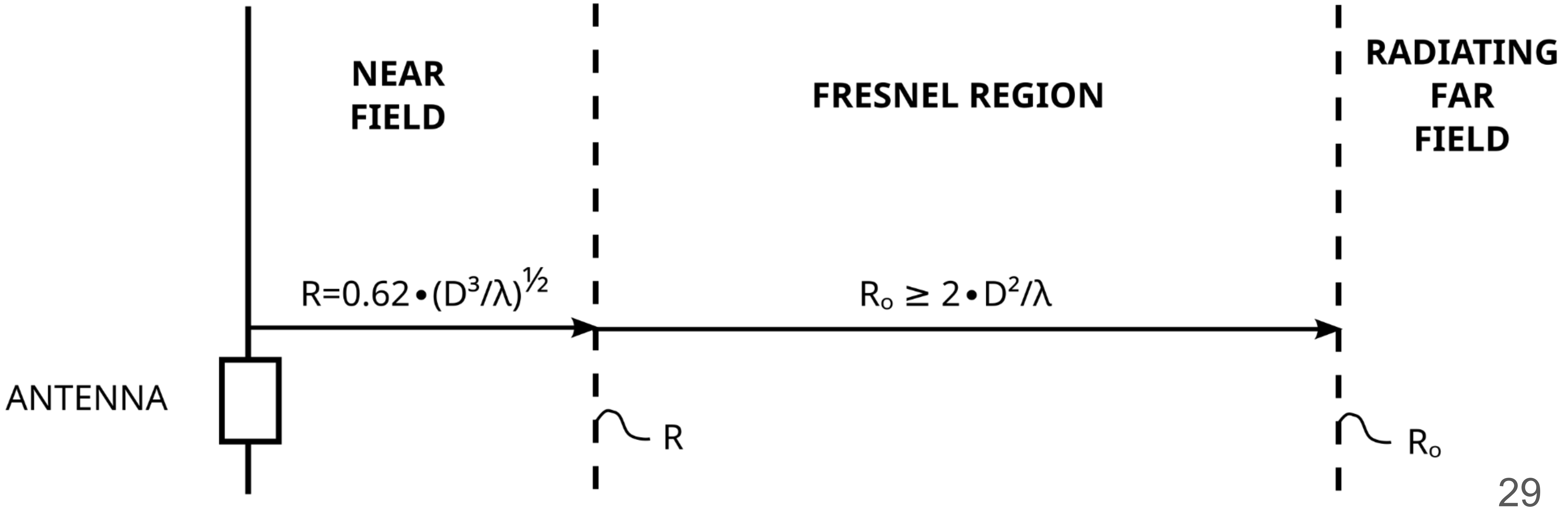
The electromagnetic field surrounding an antenna is divided into two main regions: the near field and the far field.

- The region close to the antenna where the electromagnetic field is dominated by reactive and non-radiative components.
- The far field, located further away, is characterized by well-defined radiated electromagnetic waves.

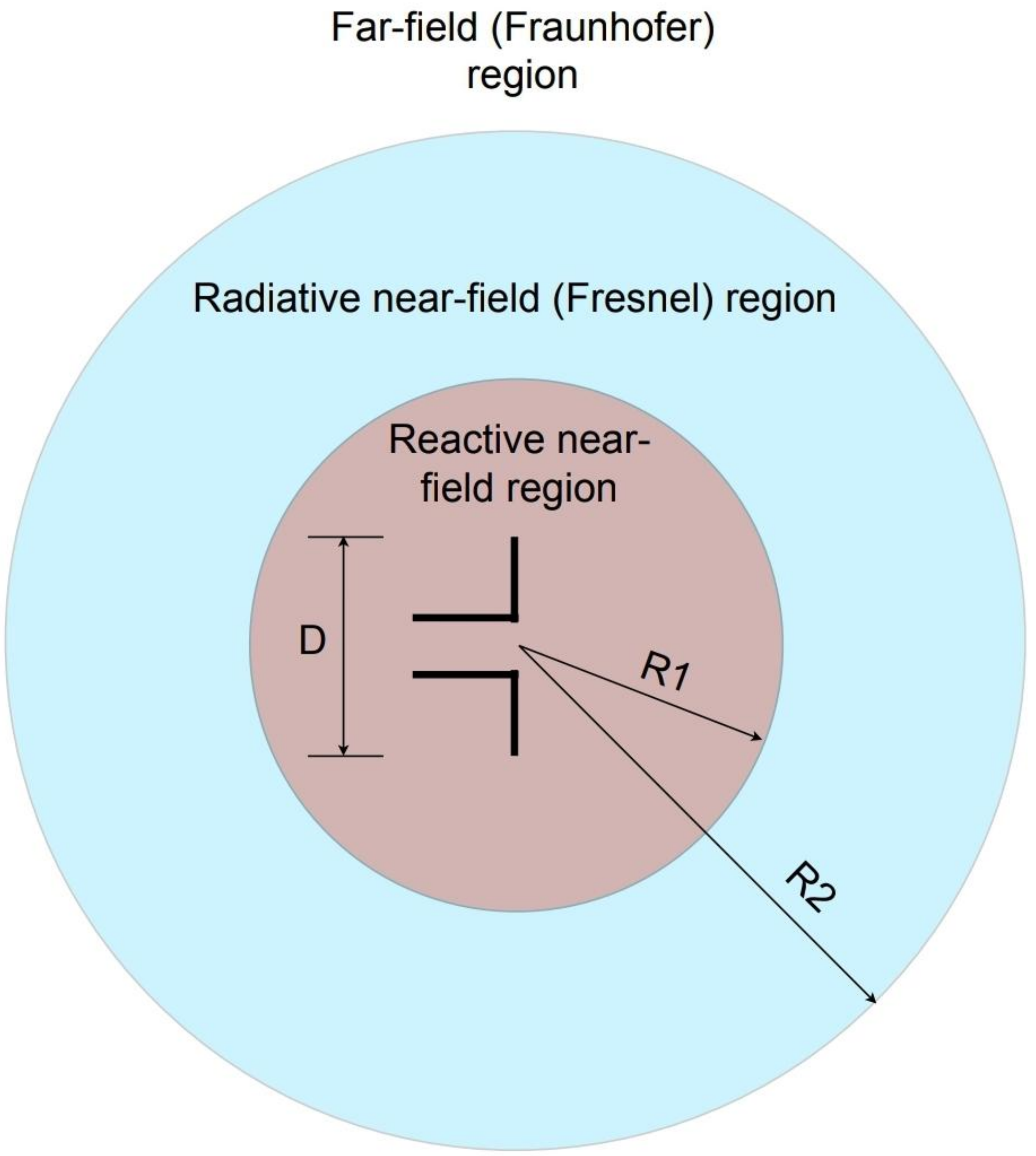
If the antenna has a maximum overall dimension D, the far-field region is commonly taken to exist at distance greater than $\boldsymbol{2D^2/\lambda}$ from the antenna, λ being the wavelength.

$$R_1 = 0.62 \times \sqrt{D^3 / \lambda}$$

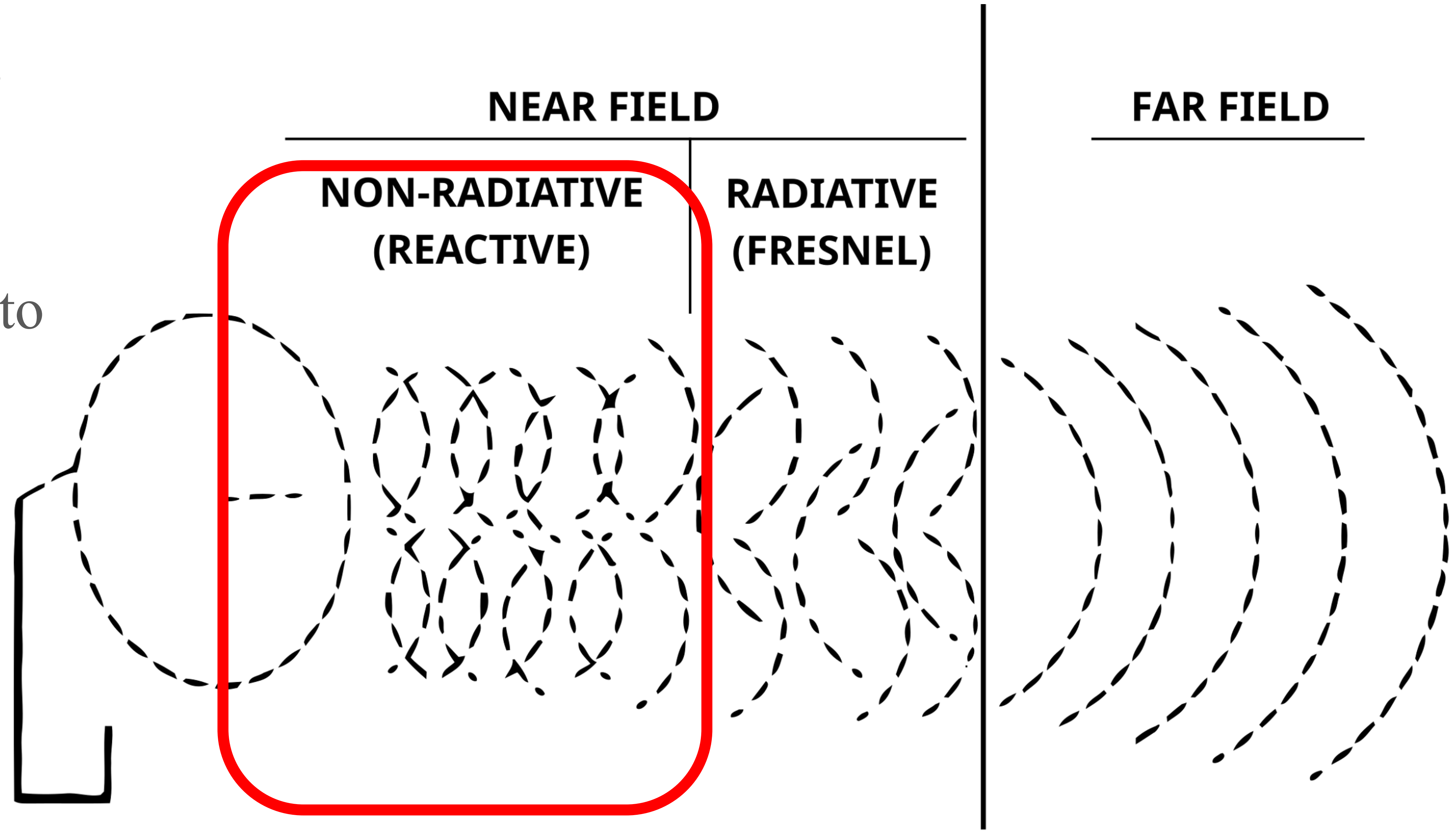
$$\boxed{R_2 = 2D^2 / \lambda}$$



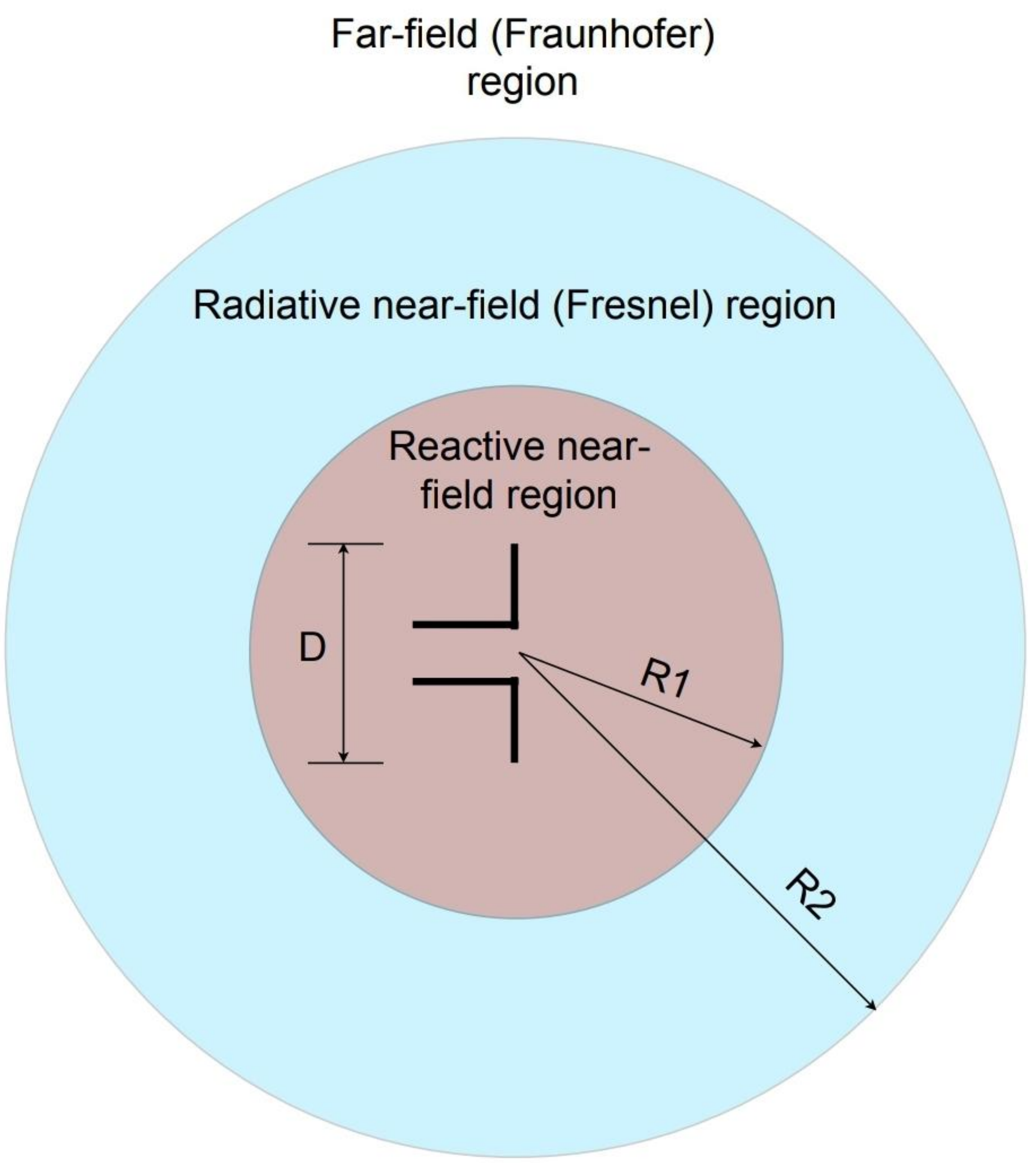
The Reactive Near-Field



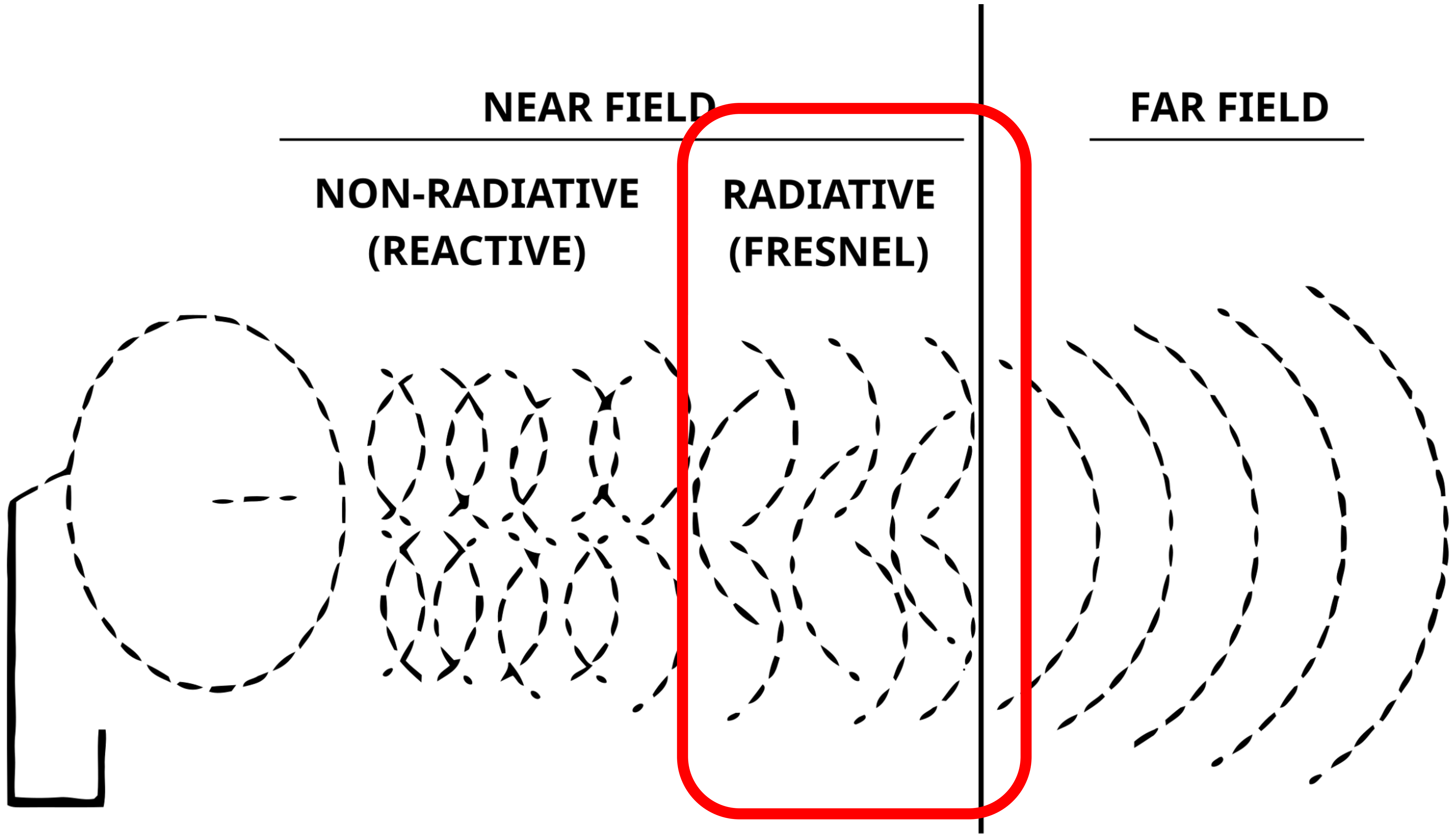
- **Dominant Physics:** In this region, the fields are primarily "reactive" or "stored." This means energy is being exchanged back and forth between the antenna's electric and magnetic fields, but it is not (yet) permanently escaping as radiation. It's like the energy stored in a capacitor or an inductor.
- **Field Structure:** The E and B fields are complex and not necessarily in phase or perpendicular to each other. The shape of the field is highly dependent on the exact size and shape of the antenna itself.
- **Practical Importance:** You have to be in this region for technologies like NFC (Near-Field Communication) or wireless charging to work. These technologies rely on this strong, non-radiating inductive or capacitive coupling. The energy is transferred directly, not radiated into space.
- **Boundary:** This region extends out to a distance of roughly $R < \lambda / (2\pi)$, where λ is the wavelength of the signal.



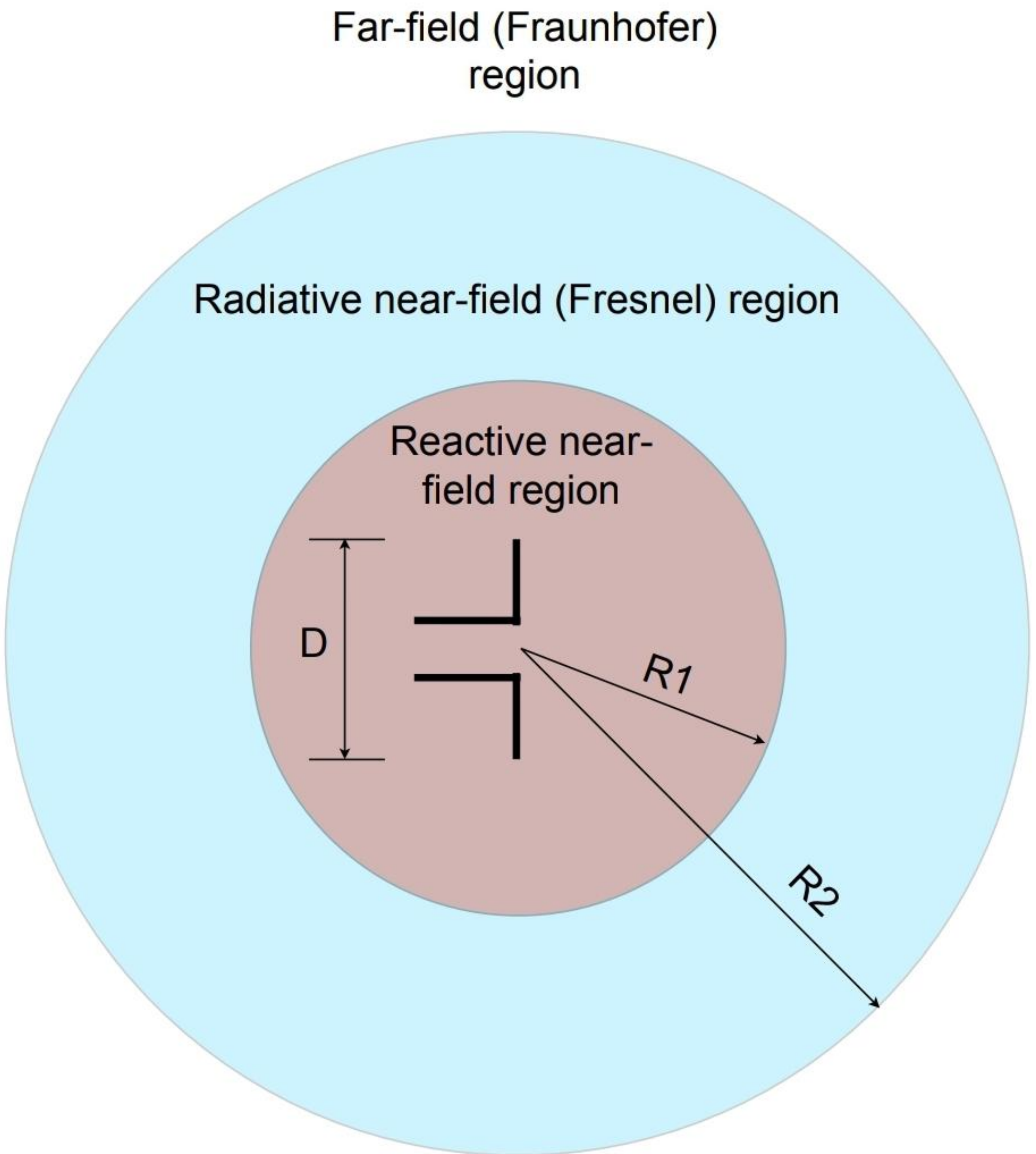
The Radiating Near-Field (or Fresnel Regi



- **Dominant Physics:** As you move further out, the radiating fields (the ones that will eventually escape) begin to form, but their shape is still changing with distance. The radiation pattern is not yet stable.
- **Practical Importance:** You generally want to avoid making antenna measurements in this region because your results will depend on your exact distance, making them unreliable and not representative of the antenna's true performance at a distance.
- **Boundary:** This region exists between the reactive near-field and the far-field.

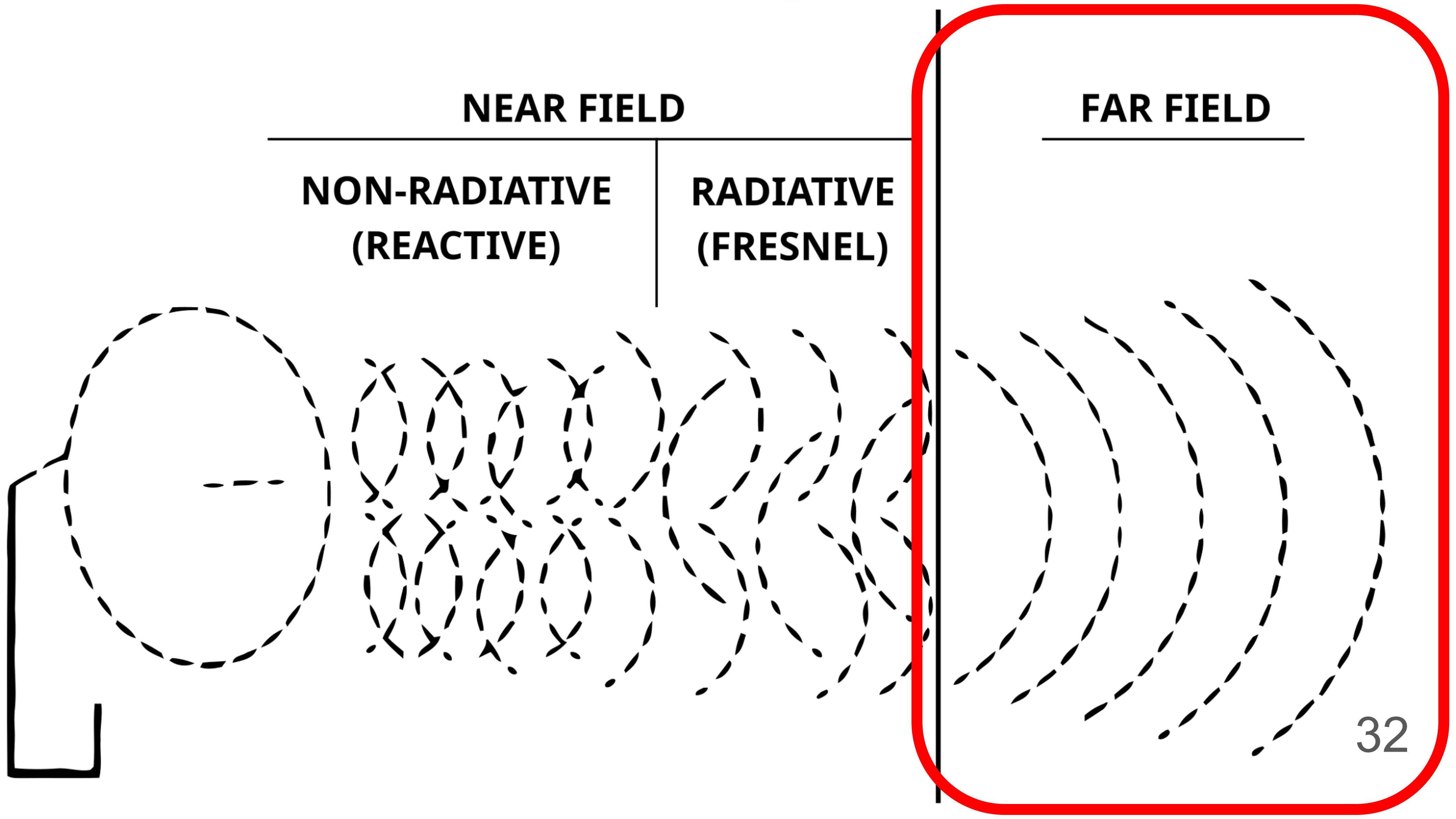


The Far-Field (The "Radiation" or Fraunhofer Region)



This is the region far away from the antenna where the magic of radio communication happens.

- **Dominant Physics:** By the time the wave gets here, it has become a true, self-propagating electromagnetic wave. The non-radiating fields from the near-field have died out completely.
- **Field Structure:**
  - **Stable Pattern:** The shape of the radiation pattern (the main lobe, side lobes, etc.) is now fixed and does not change as you move further away. The beam pattern is now only a function of angle, not distance.
  - **Transverse Wave:** The E and B fields are perpendicular to each other and to the direction of travel.
  - **Plane Wave:** From the perspective of a receiver, the wavefront looks like a flat plane (a "plane wave").
  - **Power Decay:** The power density of the wave decreases predictably with the inverse square of the distance ***(1/R²)***, just as you'd expect for radiation spreading out over a sphere.



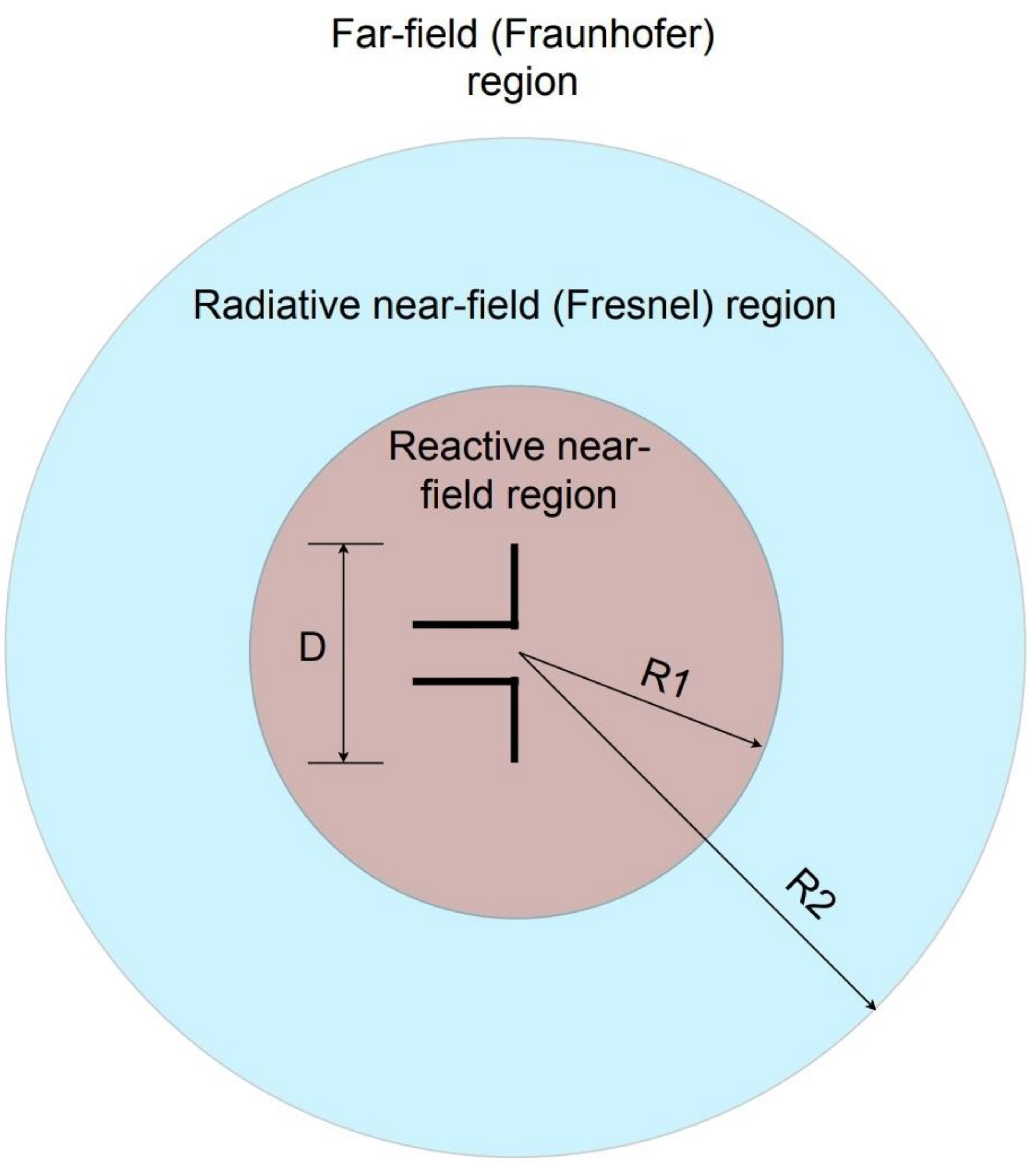
The Far-Field (The "Radiation" or Fraunhofer Region)

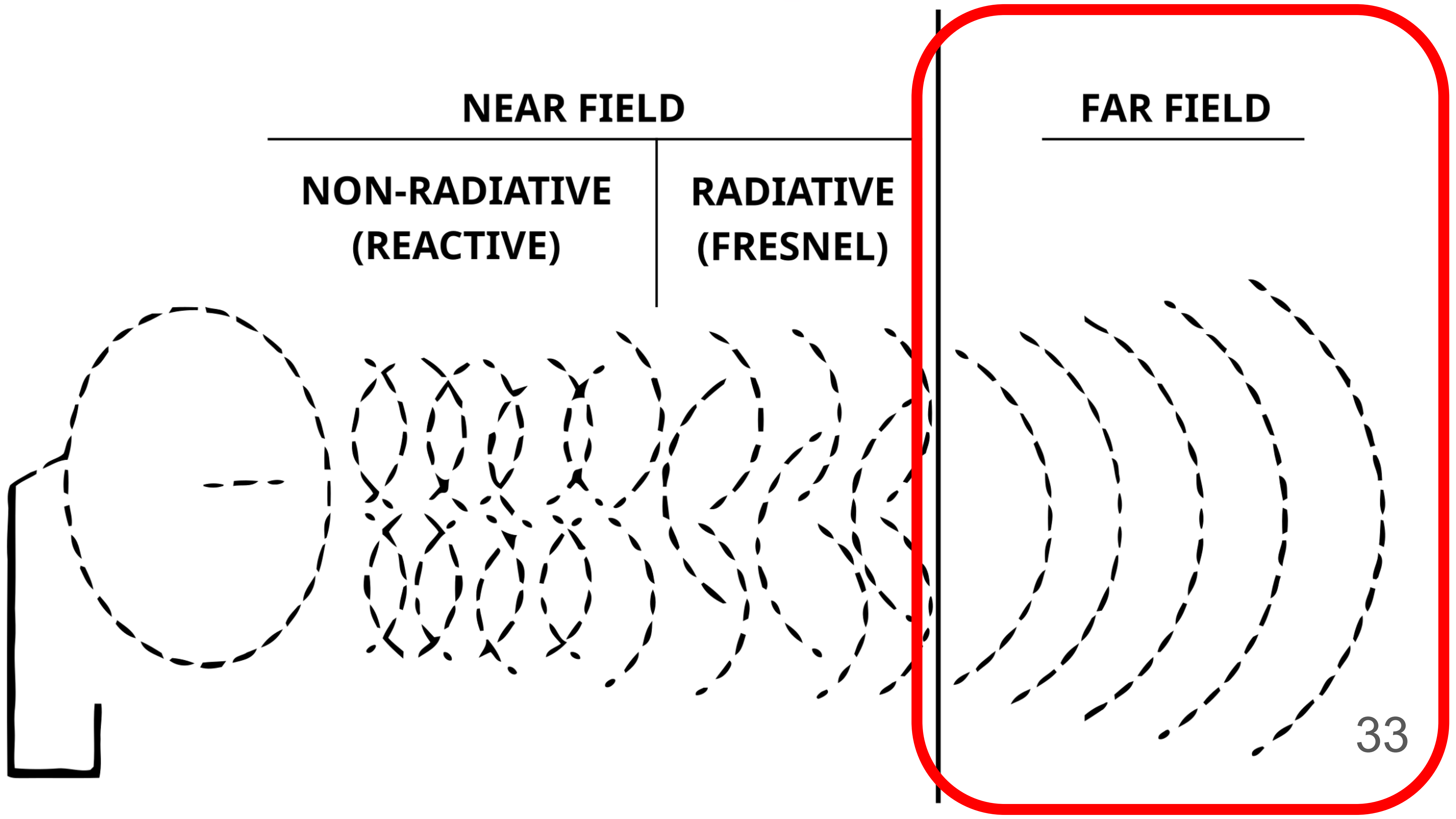
- **Practical Importance:** This is the region where almost all radio communication and radio astronomy takes place. When we talk about an antenna's "gain" or "beam pattern," we are always referring to its properties as measured in the far-field.
- **The Far-Field Boundary:** The rule of thumb for where the far-field begins is given by the formula:

$$R > 2D^2 / \lambda$$

Where:

- R is the distance from the antenna.
- D is the largest dimension of the antenna (e.g., the diameter of a satellite dish).
- λ is the wavelength of the signal.





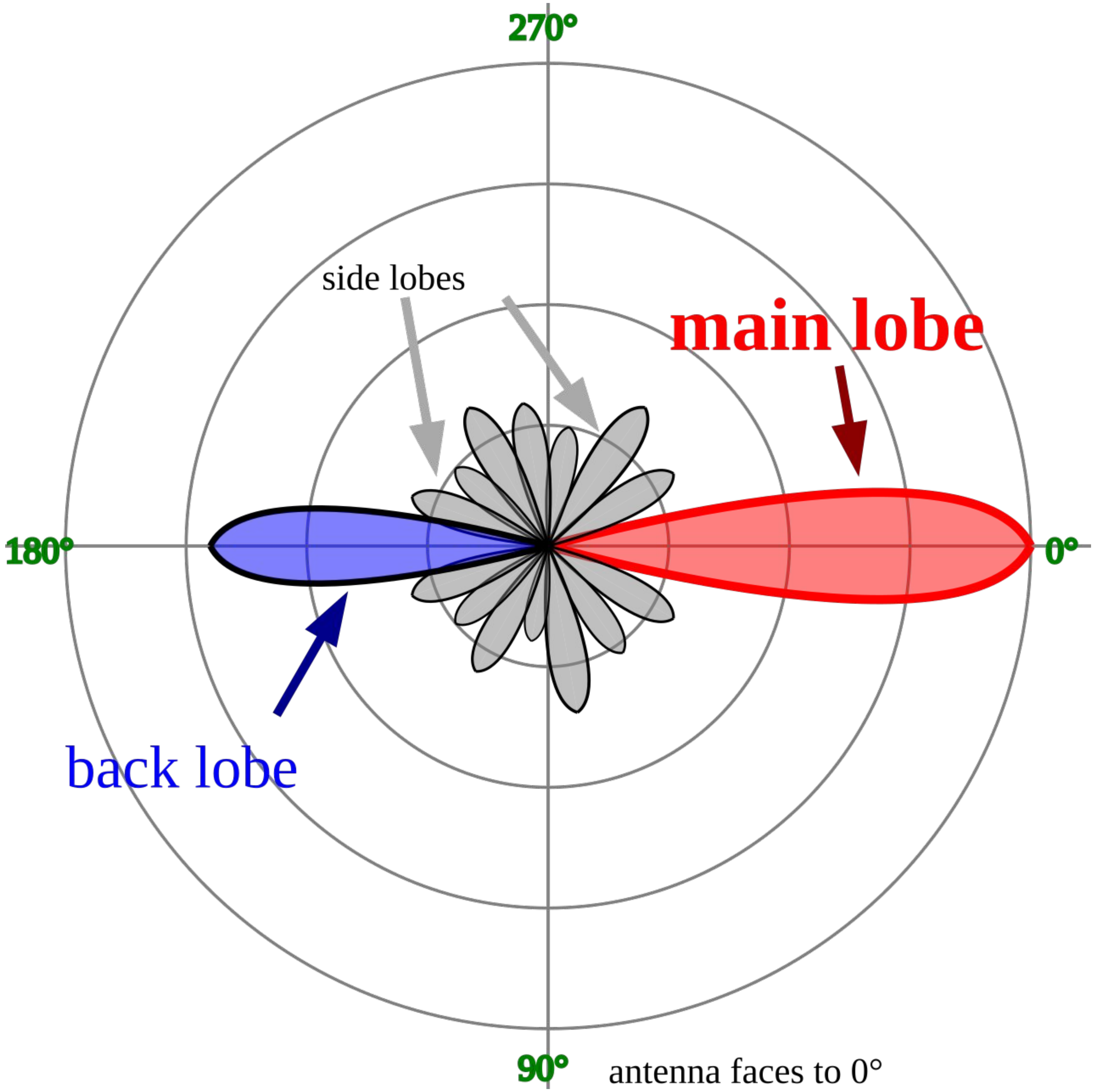
Near-Field vs. Far-Field

Feature	Near-Field	Far-Field
Distance	Close to the antenna ($R < 2D^2/\lambda$)	Far from the antenna ($R > 2D^2/\lambda$)
Primary Fields	Stored, reactive energy & forming radiation	True, self-propagating radiation
Field Structure	Complex, changing with distance, not transverse	Simple, stable pattern, transverse (E ⊥ B ⊥ dir)
Power Decay	Complex, faster than $1/R^2$	Follows the inverse-square law ($1/R^2$)
Antenna Pattern	Not yet formed, depends on distance	Fully formed, depends only on angle
Primary Application	NFC, wireless charging, RFID	Radio, Wi-Fi, radar, satellite comms, astronomy

The Radiation Pattern

An antenna does not radiate or receive equally in all directions. The "Radiation Pattern" or "Beam" is a map of its sensitivity.

- **Main Lobe:** The direction of maximum sensitivity. This is where you want to point your source.
- **Side Lobes:** Smaller lobes of sensitivity in other directions. These are undesirable "leaks."
- **Back Lobe:** A lobe pointing in the opposite direction of the main lobe.



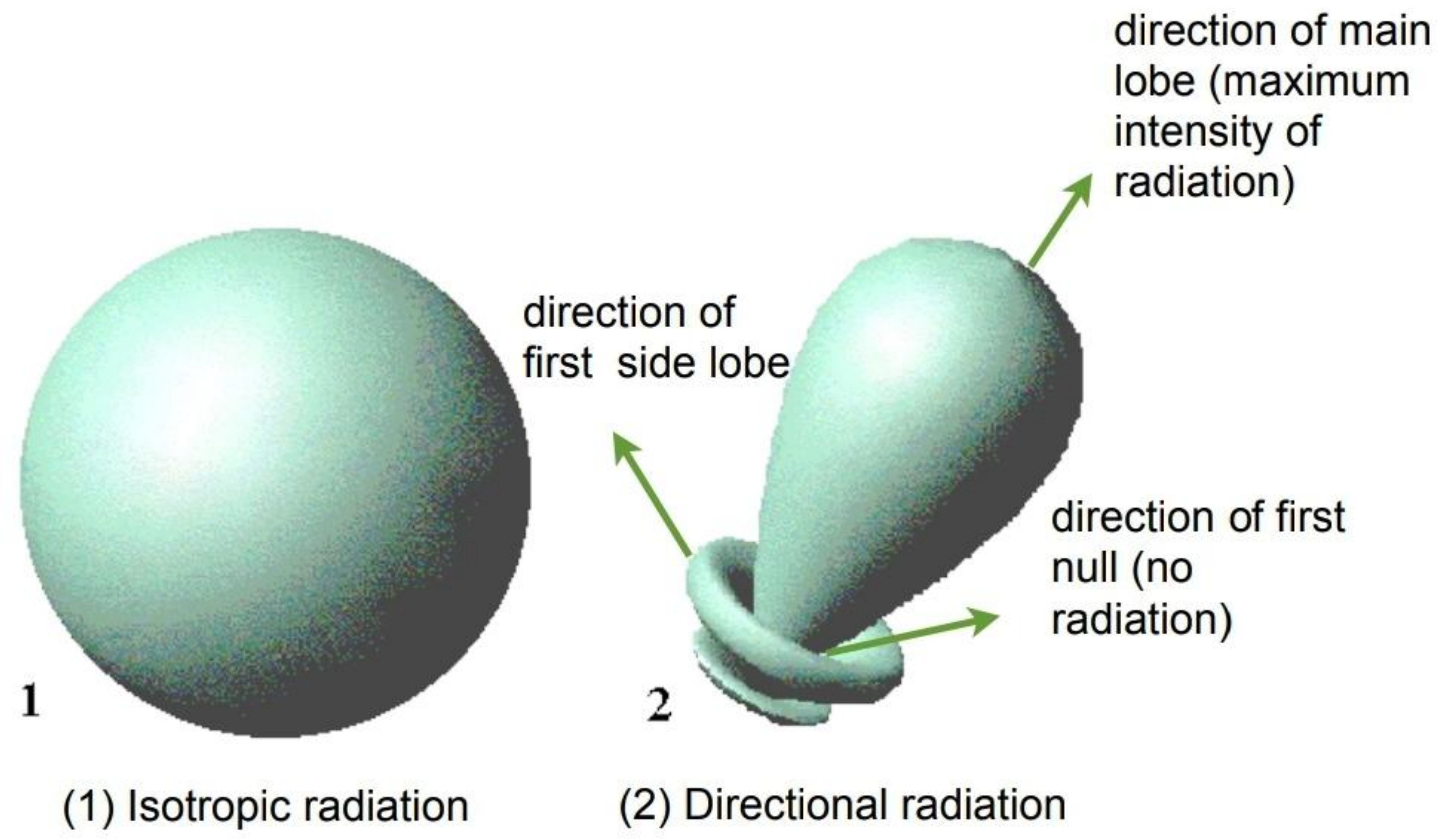
Isotopic antenna vs. Directional antenna

An isotropic antenna is a hypothetical, theoretical construct. It does not and cannot exist in reality.

Definition: An isotropic antenna is a point source that radiates energy equally in all directions. Its radiation pattern is a perfect sphere.

Key Properties:

- **Radiation Pattern:** A perfect sphere.
- **Directivity / Gain:** By definition, it has a gain of 1, or 0 dBi (decibels relative to isotropic). It has no ability to focus energy.
- **Purpose:** It serves as the ultimate reference baseline. When we say a "real" antenna has a gain of 13 dBi, we mean it concentrates power in its preferred direction 13 dB more than an isotropic antenna would with the same input power. It's the "zero point" on the antenna gain scale.

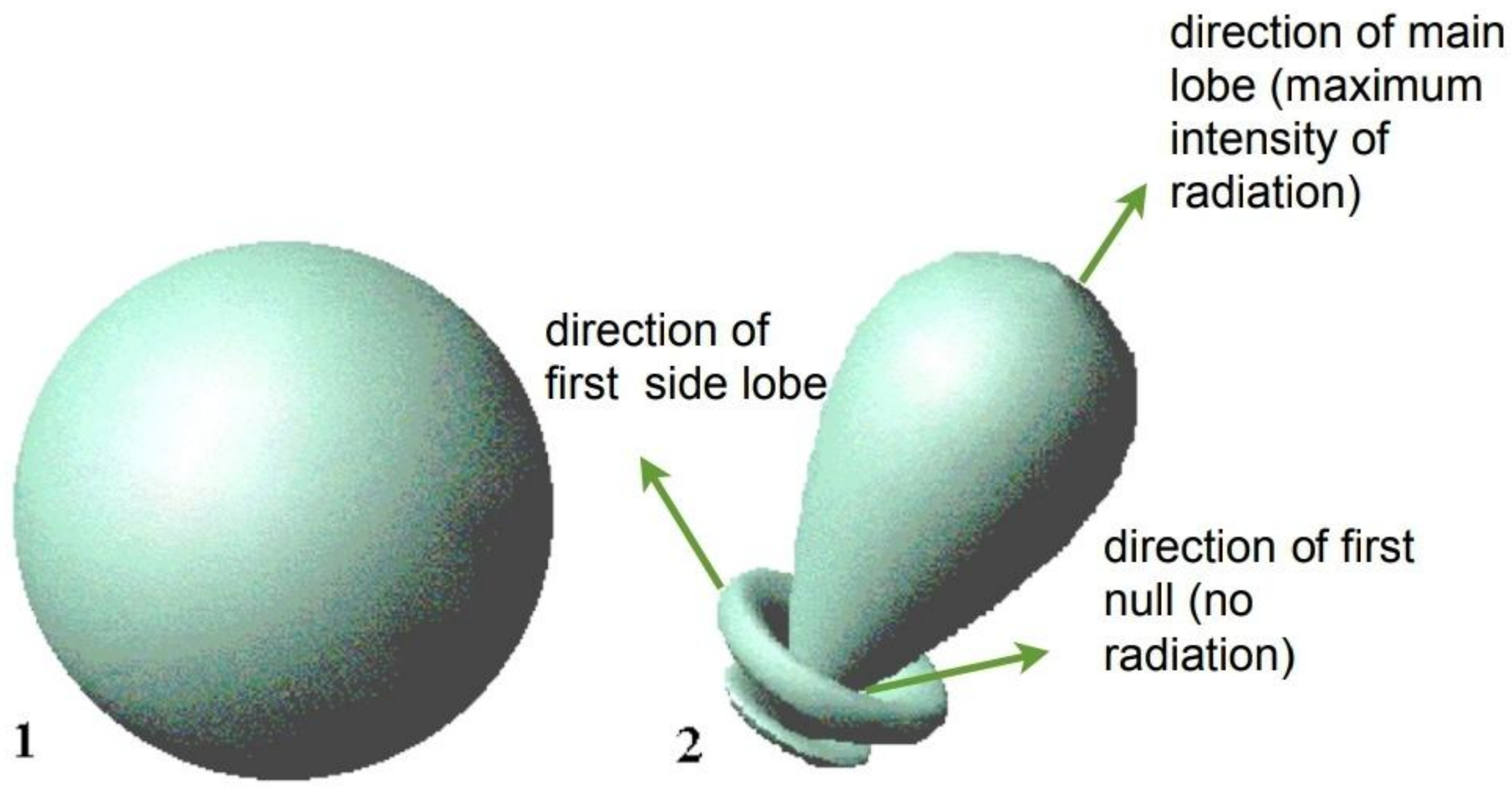


Isotopic antenna vs. Directional antenna

A directional antenna is any real-world antenna. All practical antennas are directional to some degree.

Definition: A directional antenna radiates (and receives) energy more effectively in some directions than in others.
Analogy: A flashlight, a laser pointer, a megaphone, or the reflector behind a car's headlight. All these devices take energy and focus it into a specific direction, making it more intense there at the expense of other directions.
Key Properties:

- **Radiation Pattern:** A complex shape with lobes and nulls.
- **Main Lobe:** The primary direction of maximum radiated power. This is where you point the antenna to communicate.
- **Side Lobes**: Smaller, unwanted lobes of radiation in other directions.
- **Back Lobe:** A lobe pointing away from the main direction.
- **Nulls:** Directions of minimum or zero radiation.
- **Directivity / Gain:** Always greater than 1 (or > 0 dBi). High-gain antennas (like satellite dishes) have a very narrow, powerful main lobe. Low-gain antennas (like a simple dipole on a Wi-Fi router) have a very broad, doughnut-shaped pattern.
- **Purpose:** To concentrate energy where it's needed, increasing the signal strength and range, and to reject interference from unwanted directions.



(1) Isotropic radiation (2) Directional radiation

Credit: PHAM Viet Dung