Lecture 30

Reciprocity Theorem
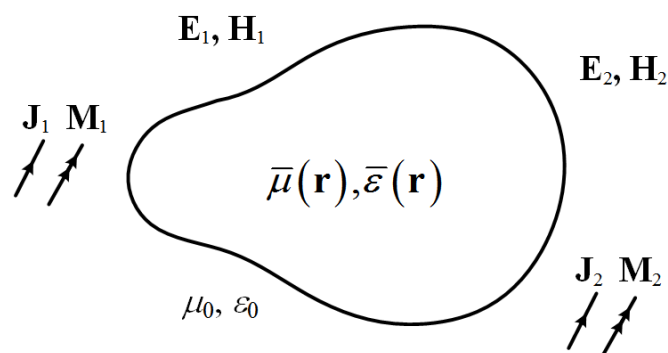
30.1   Reciprocity Theorem

Figure 30.1: The geometry for proving reciprocity theorem. We perform two experiments: With sources $\mathbf{J}_1$ and $\mathbf{M}_1$ turned on, generating fields $\mathbf{E}_1$ and $\mathbf{H}_1$, and $\mathbf{J}_2$ and $\mathbf{M}_2$ turned off, and vice versa.

Reciprocity theorem is one of the most important theorems in electromagnetics. With it we can develop physical intuition to ascertain if a certain design or experiment is wrong. It also tells us what is possible and what is impossible in design of many systems. Reciprocity theorem is like "tit-for-tat" relationship in humans: Good-will is reciprocated with good will while ill-will is reciprocated with ill-will. Not exactly: In in electromagnetics, this relationship can be expressed precisely and succinctly using mathematics. We shall see how this is done.

Consider a general anisotropic inhomogeneous medium where both $\overline{\boldsymbol{\mu}}(\mathbf{r})$ and $\overline{\boldsymbol{\varepsilon}}(\mathbf{r})$ are described by permeability tensor and permittivity tensor over a finite part of space as shown in Figure 30.1. This representation of the medium is quite general, and it can include conductive

media as well. It can represent complex terrain as well as complicated electronic circuit structures in circuit boards or microchips, and complicated antenna structures.

When only $\mathbf{J}_1$ and $\mathbf{M}_1$ are turned on, they generate fields $\mathbf{E}_1$ and $\mathbf{H}_1$ in this medium. On the other hand, when only $\mathbf{J}_2$ and $\mathbf{M}_2$ are turned on, they generate $\mathbf{E}_2$ and $\mathbf{H}_2$ in this medium. Therefore, the pertinent equations, for linear time-invariant systems, for these two cases are[1]

$$\nabla \times \mathbf{E}_1 = -j\omega\overline{\boldsymbol{\mu}} \cdot \mathbf{H}_1 - \mathbf{M}_1 \tag{30.1.1}$$

$$\nabla \times \mathbf{H}_1 = j\omega\overline{\boldsymbol{\varepsilon}} \cdot \mathbf{E}_1 + \mathbf{J}_1 \tag{30.1.2}$$

$$\nabla \times \mathbf{E}_2 = -j\omega\overline{\boldsymbol{\mu}} \cdot \mathbf{H}_2 - \mathbf{M}_2 \tag{30.1.3}$$

$$\nabla \times \mathbf{H}_2 = j\omega\overline{\boldsymbol{\varepsilon}} \cdot \mathbf{E}_2 + \mathbf{J}_2 \tag{30.1.4}$$

From the above, we can show that (after left dot-multiply (30.1.1) with $\mathbf{H}_2$ and (30.1.4) with $\mathbf{E}_1$),

$$\mathbf{H}_2 \cdot \nabla \times \mathbf{E}_1 = -j\omega\mathbf{H}_2 \cdot \overline{\boldsymbol{\mu}} \cdot \mathbf{H}_1 - \mathbf{H}_2 \cdot \mathbf{M}_1 \tag{30.1.5}$$

$$\mathbf{E}_1 \cdot \nabla \times \mathbf{H}_2 = j\omega\mathbf{E}_1 \cdot \overline{\boldsymbol{\varepsilon}} \cdot \mathbf{E}_2 + \mathbf{E}_1 \cdot \mathbf{J}_2 \tag{30.1.6}$$

Then, using the above, and the following identity, we get the second equality in the following expression:

$$\begin{aligned} \nabla \cdot (\mathbf{E}_1 \times \mathbf{H}_2) &= \mathbf{H}_2 \cdot \nabla \times \mathbf{E}_1 - \mathbf{E}_1 \cdot \nabla \cdot \mathbf{H}_2 \\ &= -j\omega\mathbf{H}_2 \cdot \overline{\boldsymbol{\mu}} \cdot \mathbf{H}_1 - j\omega\mathbf{E}_1 \cdot \overline{\boldsymbol{\varepsilon}} \cdot \mathbf{E}_2 - \mathbf{H}_2 \cdot \mathbf{M}_1 - \mathbf{E}_1 \cdot \mathbf{J}_2 \end{aligned} \tag{30.1.7}$$

By the same token,

$$\nabla \cdot (\mathbf{E}_2 \times \mathbf{H}_1) = -j\omega\mathbf{H}_1 \cdot \overline{\boldsymbol{\mu}} \cdot \mathbf{H}_2 - j\omega\mathbf{E}_2 \cdot \overline{\boldsymbol{\varepsilon}} \cdot \mathbf{E}_1 - \mathbf{H}_1 \cdot \mathbf{M}_2 - \mathbf{E}_2 \cdot \mathbf{J}_1 \tag{30.1.8}$$

If one assumes that

$$\overline{\boldsymbol{\mu}} = \overline{\boldsymbol{\mu}}^t, \qquad \overline{\boldsymbol{\varepsilon}} = \overline{\boldsymbol{\varepsilon}}^t \tag{30.1.9}$$

or when the tensors are symmetric, then $\mathbf{H}_1 \cdot \overline{\boldsymbol{\mu}} \cdot \mathbf{H}_2 = \mathbf{H}_2 \cdot \overline{\boldsymbol{\mu}} \cdot \mathbf{H}_1$ and $\mathbf{E}_1 \cdot \overline{\boldsymbol{\varepsilon}} \cdot \mathbf{E}_2 = \mathbf{E}_2 \cdot \overline{\boldsymbol{\varepsilon}} \cdot \mathbf{E}_1$.[2]

Upon subtracting (30.1.7) and (30.1.8), one gets

$$\nabla \cdot (\mathbf{E}_1 \times \mathbf{H}_2 - \mathbf{E}_2 \times \mathbf{H}_1) = -\mathbf{H}_2 \cdot \mathbf{M}_1 - \mathbf{E}_1 \cdot \mathbf{J}_2 + \mathbf{H}_1 \cdot \mathbf{M}_2 + \mathbf{E}_2 \cdot \mathbf{J}_1 \tag{30.1.10}$$

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[1]The current sources are impressed currents so that they are immutable, and not changed by the environment they are immersed in [47].

[2]It is to be noted that in matrix algebra, the dot product between two vectors are often written as $\mathbf{a}^t \cdot \mathbf{b}$, but in the physics literature, the transpose on $\mathbf{a}$ is implied. Therefore, the dot product between two vectors is just written as $\mathbf{a} \cdot \mathbf{b}$.
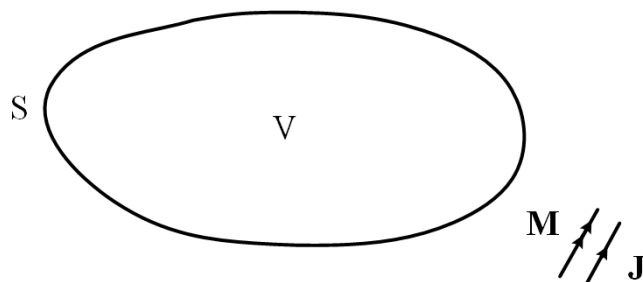
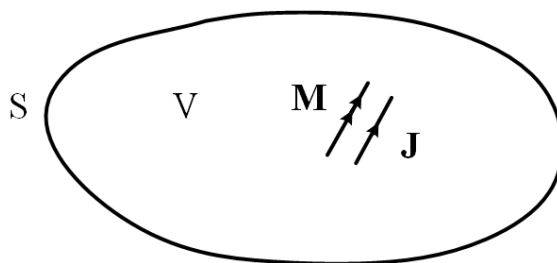Figure 30.2: The geometry for proving reciprocity theorem when the surface S does not enclose the sources.

Figure 30.3: The geometry for proving reciprocity theorem when the surface S encloses the sources.

Now, integrating (30.1.10) over a volume V bounded by a surface S, and invoking Gauss' divergence theorem, we have the reciprocity theorem that

$$\oiint_S d\mathbf{S} \cdot (\mathbf{E}_1 \times \mathbf{H}_2 - \mathbf{E}_2 \times \mathbf{H}_1)$$

$$= - \iiint_V dV [\mathbf{H}_2 \cdot \mathbf{M}_1 + \mathbf{E}_1 \cdot \mathbf{J}_2 - \mathbf{H}_1 \cdot \mathbf{M}_2 - \mathbf{E}_2 \cdot \mathbf{J}_1] \qquad (30.1.11)$$

When the volume V contains no sources (see Figure 30.2), the reciprocity theorem reduces to

$$\oiint_S d\mathbf{S} \cdot (\mathbf{E}_1 \times \mathbf{H}_2 - \mathbf{E}_2 \times \mathbf{H}_1) = 0 \qquad (30.1.12)$$

The above is also called Lorentz reciprocity theorem by some authors.[3]

Next, when the surface S contains all the sources (see Figure 30.3), then the right-hand side of (30.1.11) will not be zero. On the other hand, when the surface $S \to \infty$, $\mathbf{E}_1$ and

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[3]Harrington, Time-Harmonic Electric Field [47].

$\mathbf{H}_2$ becomes spherical waves which can be approximated by plane waves sharing the same $\boldsymbol{\beta}$ vector. Moreover, under the plane-wave approximation, $\omega\mu_0\mathbf{H}_2 = \boldsymbol{\beta} \times \mathbf{E}_2$, $\omega\mu_0\mathbf{H}_1 = \boldsymbol{\beta} \times \mathbf{E}_1$, then

$$\mathbf{E}_1 \times \mathbf{H}_2 \sim \mathbf{E}_1 \times (\boldsymbol{\beta} \times \mathbf{E}_2) = \mathbf{E}_1(\boldsymbol{\beta} \cdot \mathbf{E}_2) - \boldsymbol{\beta}(\mathbf{E}_1 \cdot \mathbf{E}_2) \tag{30.1.13}$$

$$\mathbf{E}_2 \times \mathbf{H}_1 \sim \mathbf{E}_2 \times (\boldsymbol{\beta} \times \mathbf{E}_1) = \mathbf{E}_2(\boldsymbol{\beta} \cdot \mathbf{E}_1) - \boldsymbol{\beta}(\mathbf{E}_2 \cdot \mathbf{E}_1) \tag{30.1.14}$$

But $\boldsymbol{\beta} \cdot \mathbf{E}_2 = \boldsymbol{\beta} \cdot \mathbf{E}_1 = 0$ in the far field and the $\boldsymbol{\beta}$ vectors are parallel to each other. Therefore, the two terms on the left-hand side of (30.1.11) cancel each other, and it vanishes when $S \to \infty$. (Furthermore, they cancel each other so that the remnant field vanishes faster than $1/r^2$. This is necessary as the surface area S is growing larger and proportional to r^2.)

As a result, (30.1.11) can be rewritten simply as

$$\int_V dV[\mathbf{E}_2 \cdot \mathbf{J}_1 - \mathbf{H}_2 \cdot \mathbf{M}_1] = \int_V dV[\mathbf{E}_1 \cdot \mathbf{J}_2 - \mathbf{H}_1 \cdot \mathbf{M}_2] \tag{30.1.15}$$

The inner product symbol is often used to rewrite the above as

$$\langle \mathbf{E}_2, \mathbf{J}_1 \rangle - \langle \mathbf{H}_2, \mathbf{M}_1 \rangle = \langle \mathbf{E}_1, \mathbf{J}_2 \rangle - \langle \mathbf{H}_1, \mathbf{M}_2 \rangle \tag{30.1.16}$$

where the inner product $\langle \mathbf{A}, \mathbf{B} \rangle = \int_V dV \mathbf{A}(\mathbf{r}) \cdot \mathbf{B}(\mathbf{r})$.

The above inner product is also called reaction, a concept introduced by Rumsey. Therefore, the above is rewritten more succinctly as

$$\langle 2, 1 \rangle = \langle 1, 2 \rangle \tag{30.1.17}$$

where

$$\langle 2, 1 \rangle = \langle \mathbf{E}_2, \mathbf{J}_1 \rangle - \langle \mathbf{H}_2, \mathbf{M}_1 \rangle \tag{30.1.18}$$

The concept of inner product or reaction can be thought of as a kind of "measurement". The reciprocity theorem can be stated as that the fields generated by sources 2 as "measured" by sources 1 is equal to fields generated by sources 1 as "measured" by sources 2. This measurement concept is more lucid if we think of these sources as Hertzian dipoles.

30.1.1 Conditions for Reciprocity

It is seen that the above proof hinges on (30.1.9). In other words, the anisotropic medium has to be described by symmetric tensors. They include conductive media, but not gyrotropic media. A ferrite biased by a magnetic field is often used in electronic circuits, and it corresponds to a gyrotropic, non-reciprocal medium.[4] Also, our starting equations (30.1.1) to (30.1.4) assume that the medium and the equations are linear time invariant so that Maxwell's equations can be written down in the frequency domain easily.

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[4]Non-reciprocal media are important for making isolators in microwave. Microwave signals can travel from Port 1 to Port 2, but not vice versa.
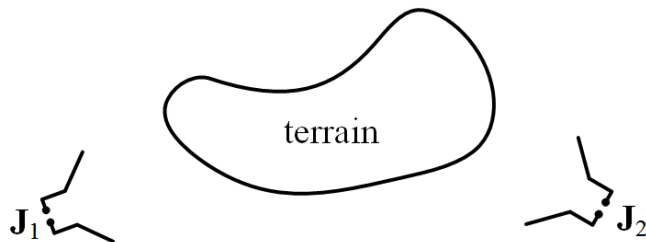
30.1.2 Application to a Two-Port Network

Figure 30.4: A geometry for proving the circuit relationship between two antennas using reciprocity theorem. Circuit relationship is possible when the ports of the antennas are small compared to wavelength.

The reciprocity theorem can be used to distill and condense the interaction between two antennas over a complex terrain as long as the terrain comprises reciprocal media. In Figure 30.4, we assume that antenna 1 is driven by current $\mathbf{J}_1$ while antenna 2 is driven by current $\mathbf{J}_2$. Since the system is linear time invariant, it can be written as the interaction between two ports as in circuit theory as shown in Figure 30.5. Assuming that these two ports are small compared to wavelengths, then we can apply circuit concepts like potential theory at the ports.
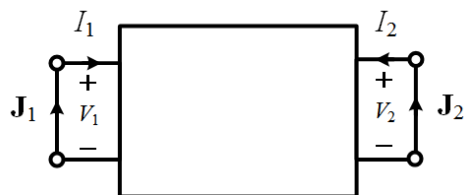

Figure 30.5: The interaction between two antennas in the far field of each other can be reduced to a circuit theory description since the input and output ports of the antennas are small compared to wavelength.

Focusing on a two-port network as shown in Figure 30.5, we have

$$\begin{bmatrix} V_1 \\ V_2 \end{bmatrix} = \begin{bmatrix} Z_{11} & Z_{12} \\ Z_{21} & Z_{22} \end{bmatrix} \begin{bmatrix} I_1 \\ I_2 \end{bmatrix} \tag{30.1.19}$$

Then assuming that the port 2 is turned on with $\mathbf{J}_2 \neq 0$, while port 1 is turned off with $\mathbf{J}_1 = 0$. In other words, port 1 is open circuit, and the source $\mathbf{J}_2$ will produce an electric field

$\mathbf{E}_2$ at port 1. Consequently,

$$\langle \mathbf{E}_2, \mathbf{J}_1 \rangle = \int_V dV (\mathbf{E}_2 \cdot \mathbf{J}_1) = I_1 \int_{\text{Port 1}} \mathbf{E}_2 \cdot d\mathbf{l} = -I_1 V_1^{oc} \tag{30.1.20}$$

Even though port 1 is assumed to be off, the $\mathbf{J}_1$ to be used above is the $\mathbf{J}_1$ when port 1 is turned on. Given that the port is in the circuit physics regime, then the current $\mathbf{J}_1$ is a constant current at the port when it is turned on. The current $\mathbf{J}_1 = \hat{l} I_1 / A$ where A is the cross-sectional area of the wire, and $\hat{l}$ is a unit vector aligned with the axis of the wire. The volume integral $dV = A dl$, and hence the second equality follows above, where $d\mathbf{l} = \hat{l} dl$. Since $\int_{\text{Port 1}} \mathbf{E}_2 \cdot d\mathbf{l} = -V_1^{oc}$, we have the last equality above.

We can repeat the derivation with port 2 to arrive at

$$\langle \mathbf{E}_1, \mathbf{J}_2 \rangle = I_2 \int_{\text{Port 2}} \mathbf{E}_1 \cdot d\mathbf{l} = -I_2 V_2^{oc} \tag{30.1.21}$$

But from (30.1.19), we can set the pertinent currents to zero to find these open circuit voltages. Therefore, $V_1^{oc} = Z_{12} I_2$, $V_2^{oc} = Z_{21} I_1$. Since $I_1 V_1^{oc} = I_2 V_2^{oc}$ by the reaction concept or by reciprocity, then $Z_{12} = Z_{21}$. The above analysis can be easily generalized to an N-port network.

The simplicity of the above belies its importance. The above shows that the reciprocity concept in circuit theory is a special case of reciprocity theorem for electromagnetic theory. The terrain can also be replaced by complex circuits as in a circuit board, as long as the materials are reciprocal, linear and time invariant. The complex terrain can also be replaced by complex antenna structures.

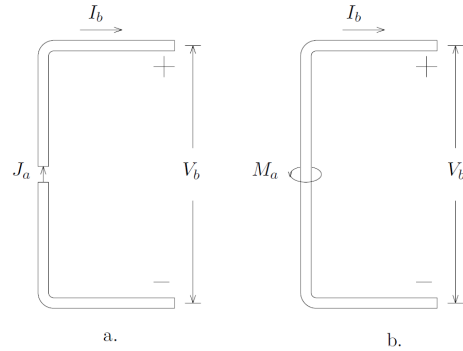### 30.1.3 Voltage Sources in Electromagnetics

Figure 30.6: Two ways to model voltage sources: (i) A current source $\mathbf{J}_a$ driving a very short antenna, and (ii) A magnetic frill source (loop source) $\mathbf{M}_a$ driving a very short antenna (courtesy of Kong, ELectromagnetic Wave Theory [31]).

In the above discussions, we have used current sources in reciprocity theorem to derive certain circuit concepts. Before we end this section, it is prudent to mention how voltage sources are modeled in electromagnetic theory. The use of the impressed currents so that circuit concepts can be applied is shown in Figure 30.6. The antenna in (a) is driven by a current source. But a magnetic current can be used as a voltage source in circuit theory as shown by Figure 30.6b. By using duality concept, an electric field has to curl around a magnetic current just in Ampere's law where magnetic field curls around an electric current. This electric field will cause a voltage drop between the metal above and below the magnetic current loop making it behave like a voltage source.[5]

30.1.4   Hind Sight

The proof of reciprocity theorem for Maxwell's equations is very deeply related to the symmetry of the operator involved. We can see this from linear algebra. Given a matrix equation driven by two different sources, they can be written succinctly as

$$\overline{\mathbf{A}} \cdot \mathbf{x}_1 = \mathbf{b}_1 \tag{30.1.22}$$

$$\overline{\mathbf{A}} \cdot \mathbf{x}_2 = \mathbf{b}_2 \tag{30.1.23}$$

We can left dot multiply the first equation with $\mathbf{x}_2$ and do the same with the second equation with $\mathbf{x}_1$ to arrive at

$$\mathbf{x}_2^t \cdot \overline{\mathbf{A}} \cdot \mathbf{x}_1 = \mathbf{x}_2^t \cdot \mathbf{b}_1 \tag{30.1.24}$$

$$\mathbf{x}_1^t \cdot \overline{\mathbf{A}} \cdot \mathbf{x}_2 = \mathbf{x}_1^t \cdot \mathbf{b}_2 \tag{30.1.25}$$

If $\overline{\mathbf{A}}$ is symmetric, the left-hand side of both equations are equal to each other. Subtracting the two equations, we arrive at

$$\mathbf{x}_2^t \cdot \mathbf{b}_1 = \mathbf{x}_1^t \cdot \mathbf{b}_2 \tag{30.1.26}$$

The above is analogous to the statement of the reciprocity theorem. The above inner product is that of dot product in matrix theory, but the inner product for reciprocity is that for infinite dimensional space. So if the operators in Maxwell's equations are symmetrical, then reciprocity theorem applies.

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[5]More can be found in Jordain and Balmain, Electromagnetic Waves and Radiation Systems [48].

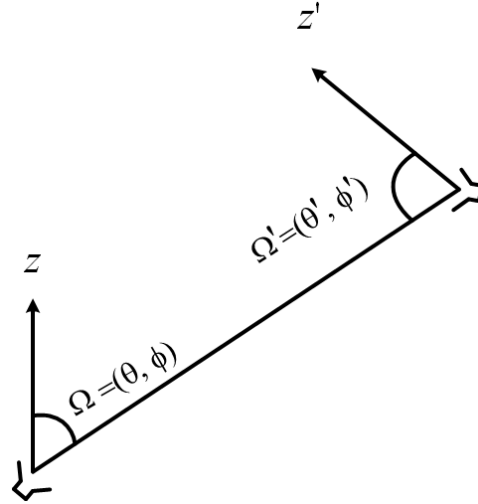### 30.1.5   Transmit and Receive Patterns of an Antennna

Figure 30.7: The schematic diagram for studying the transmit and receive properties of antennas.

Reciprocity also implies that the transmit and receive properties of an antenna is similar to each other. Consider an antenna in the transmit mode. Then the radiation power density that it will yield around the antenna is[6]

$$S_{\text{rad}} = \frac{P_t}{4\pi r^2} G(\theta, \phi) \tag{30.1.27}$$

where P_t is the total power radiated by the transmit antenna, and $G(\theta, \phi)$ is its directive gain function. It is to be noted that in the above $\int_{4\pi} d\Omega G(\theta, \phi) = 4\pi$.

Effective Gain versus Directive Gain

At this juncture, it is important to introduce the concept of effective gain versus directive gain. The effective gain, also called the power gain, is

$$G_e(\theta, \phi) = f_e G(\theta, \phi) \tag{30.1.28}$$

where f_e is the efficiency of the antenna, a factor less than 1. It accounts for the fact that not all power pumped into the antenna is delivered as radiated power. For instance, power can be lost in the circuits and mismatch of the antenna. Therefore, the correct formula the

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[6]The author is indebted to inspiration from E. Kudeki of UIUC for this part of the lecture notes [126].

radiated power density is

$$S_{\text{rad}} = \frac{P_t}{4\pi r^2} G_e(\theta, \phi) \tag{30.1.29}$$

If this power density is intercepted by a receive antenna, then the receive antenna will see an incident power density as

$$S_{\text{inc}} = S_{\text{rad}} = \frac{P_t}{4\pi r^2} G_e(\theta, \phi) \tag{30.1.30}$$

The effective area or aperture of a receive antenna is used to characterize its receive property. The power received by such an antenna is then

$$P_r = S_{\text{inc}} A_e(\theta', \phi') \tag{30.1.31}$$

where (θ', ϕ') are the angles at which the plane wave is incident upon the receiving antenna (see Figure 30.7). Combining the above formulas, we have

$$P_r = \frac{P_t}{4\pi r^2} G_e(\theta, \phi) A_e(\theta', \phi') \tag{30.1.32}$$

Now assuming that the transmit and receive antennas are identical. We swap their roles of transmit and receive, and also the circuitries involved in driving the transmit and receive antennas. Then,

$$P_r = \frac{P_t}{4\pi r^2} G_e(\theta', \phi') A_e(\theta, \phi) \tag{30.1.33}$$

We also assume that the receive antenna, that now acts as the transmit antenna is transmitting in the (θ', ϕ') direction. Moreover, the transmit antenna, that now acts as the receive antenna is receiving in the (θ, ϕ) direction (see Figure 30.7).

By reciprocity, these two powers are the same, because $Z_{12} = Z_{21}$. Furthermore, since these two antennas are identical, $Z_{11} = Z_{22}$. So by swapping the transmit and receive electronics, the power transmitted and received will not change.

Consequently, we conclude that

$$G_e(\theta, \phi) A_e(\theta', \phi') = G_e(\theta', \phi') A_e(\theta, \phi) \tag{30.1.34}$$

The above implies that

$$\frac{A_e(\theta, \phi)}{G_e(\theta, \phi)} = \frac{A_e(\theta', \phi')}{G_e(\theta', \phi')} = \text{constant} \tag{30.1.35}$$

The above Gedanken experiment is carried out for arbitrary angles. Therefore, the constant is independent of angles. Moreover, this constant is independent of the size, shape, and efficiency of the antenna, as we have not used their shape, size, and efficiency in the above discussion. One can repeat the above for a Hertzian dipole, wherein the mathematics of calculating P_r

and P_t is a lot simpler. This constant is found to be $\lambda^2/(4\pi)$.[7] Therefore, an interesting relationship between the effective aperture (or area) and the directive gain function is that

$$A_e(\theta, \phi) = \frac{\lambda^2}{4\pi} G_e(\theta, \phi) \tag{30.1.36}$$

One amusing point about the above formula is that the effective aperture, say of a Hertzian dipole, becomes very large when the frequency is low, or the wavelength is very long. Of course, this cannot be physically true, and I will let you meditate on this paradox and muse over this point.

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[7]See Kong [31][p. 700]. The derivation is for 100% efficient antenna. A thermal equilibrium argument is used in [126] and Wikipedia [127] as well.

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26 décembre 1820, 10 juin 1822, 22 décembre 1823, 12 septembre et 21 novembre 1825. Bachelier, 1825.

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