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CABLING AND COUPLING

EIE521

EIE521 MODULE 2

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Learning outcomes

- At the end of the course, students will be able to:
- Explain the coupling mechanisms that occur between fields and cables, cables and cables (crosstalk), shielded, and unshielded cables.
- solve simple problems involving coupling mechanisms.

Introduction

- Cables are important because they are usually the longest parts of a system and therefore act as efficient antennas that pick up and/or radiate noise.

Assumptions

1. Shields are made of nonmagnetic materials and have a thickness much less than a skin depth at the frequency of interest.

2. The receptor is not coupled so tightly to the source that it loads down the source.

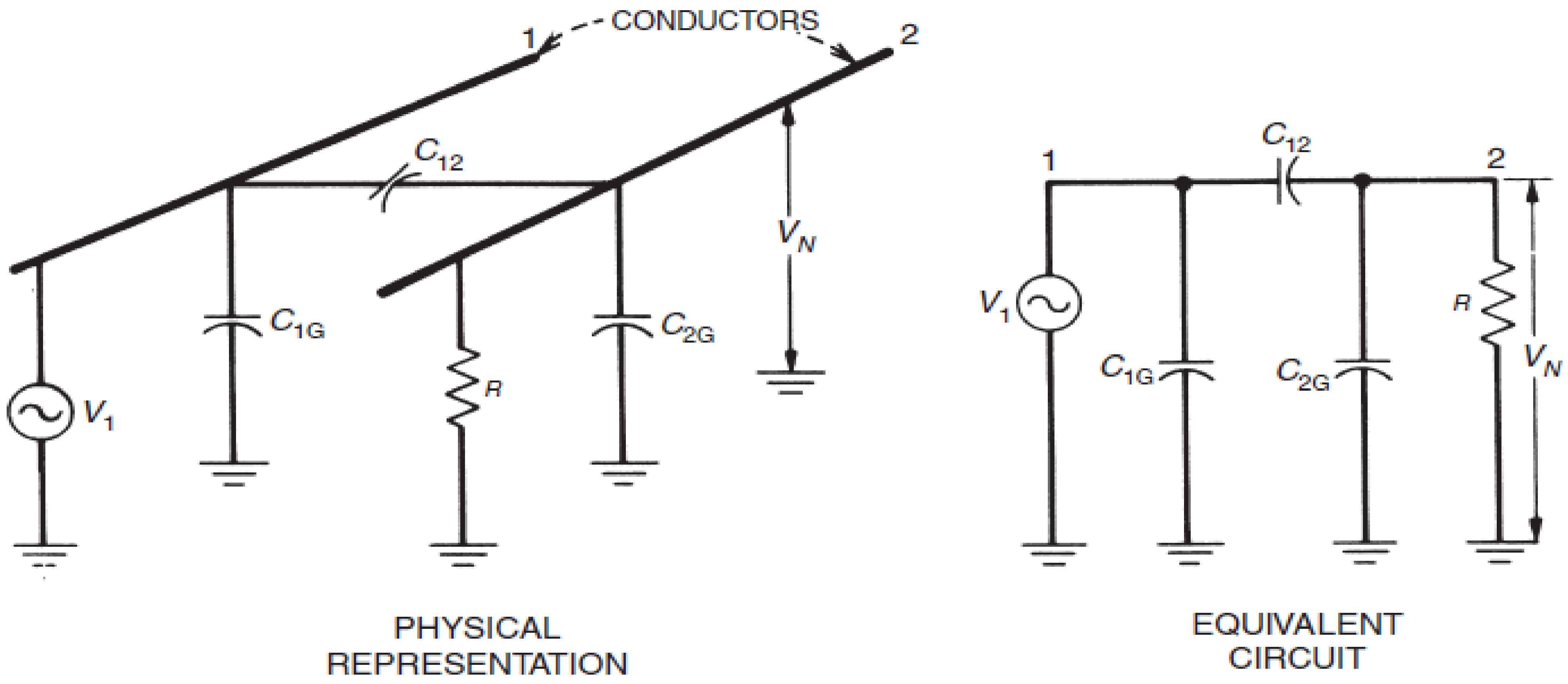
3. Induced currents in the receptor circuit are small enough not to distort the original field.

4. Cables are short compared with a wavelength.

Types of Couplings

1. Capacitive (electrical) Coupling
2. Inductive (magnetic) Coupling
3. Electromagnetic (radiation) Coupling

Capacitive Coupling



Capacitive coupling between two conductors.

C_{12} — stray capacitance between conductors 1 and 2

C_{1G} - capacitance between conductor 1 and ground

C_{2G} - capacitance between conductor 2 and ground

R – resistance between conductor 2 and ground

V_1- source of interference

V_N - noise voltage between conductor 2 and ground

- A simple representation of capacitive coupling between two conductors is shown in the previous slide. The equivalent circuit of the coupling is also shown on the previous slide.
- Consider the voltage V_1 on conductor 1 as the source of interference and conductor 2 as the affected circuit or receptor.
- Any capacitance connected directly across the source, such as C_{1G} can be neglected because it has no effect on the noise coupling.
- The noise voltage V_N produced between conductor 2 and ground can be expressed as follows:

$$V_N = \frac{j\omega[C_{12}/(C_{12} + C_{2G})]}{j\omega + 1/R(C_{12} + C_{2G})} V_1 \qquad Eqn\ (1)$$

In practice,

$$R \ll \frac{1}{jw(C_{12} + C_{2G})}$$

Therefore eqn 1 becomes reduced to:

$$V_N = j\omega R C_{12} V_1 \qquad Eqn\ (2)$$

Eqn 2 describes the noise coupling between two conductors.

- The noise voltage is directly proportional to the frequency, ω of the noise source, the resistance R of the affected circuit to ground, the mutual capacitance C_{12} between the conductors 1 and 2, and the magnitude of the voltage V_1.
- If ω and V_1 cannot be changed, the noise voltage V_N can be suppressed by:

a. Physically separating the conductors, shielding, or proper orientation to reduce C_{12}.

b. Designing a receiver circuit with a lower resistance level.

But when,

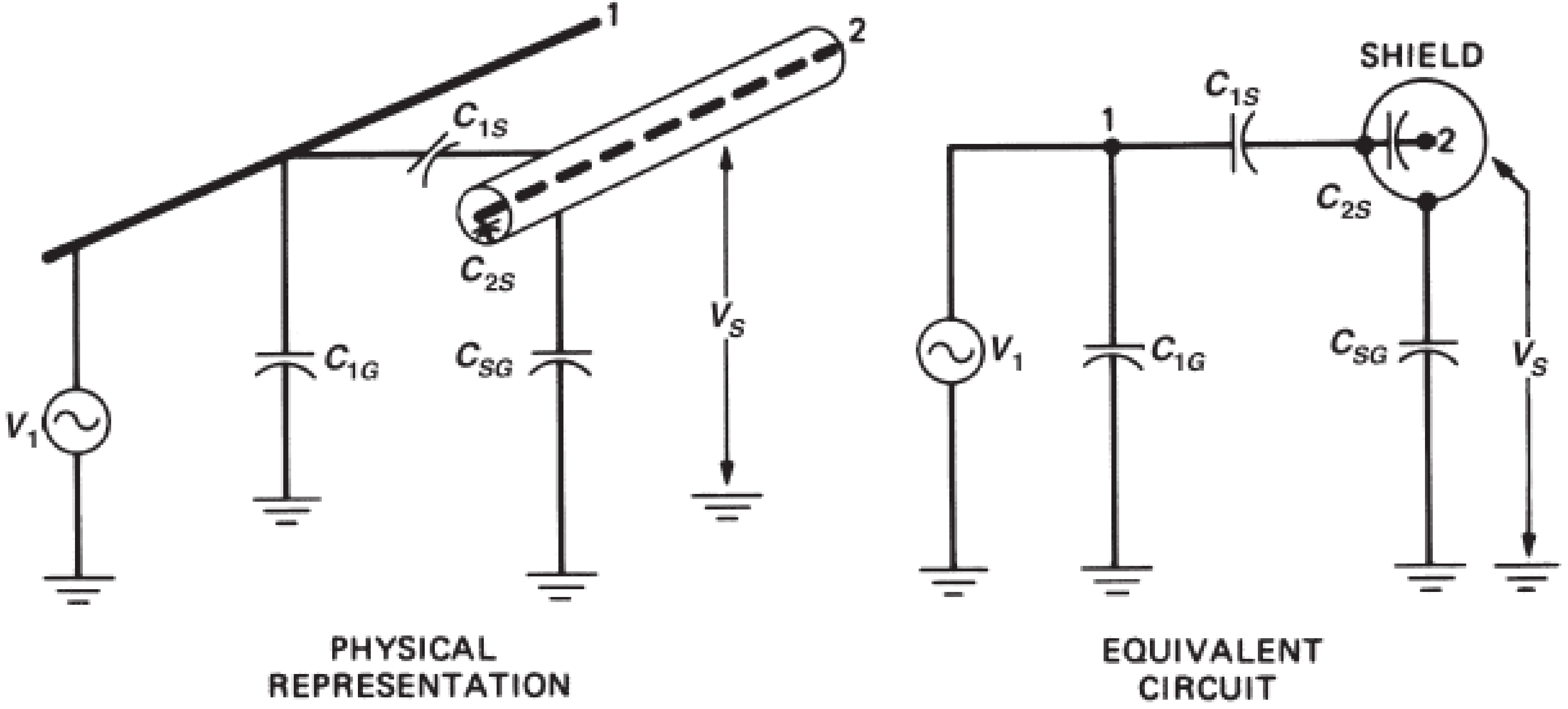
$$R \gg \frac{1}{jw(C_{12} + C_{2G})}$$

Eqn 1 becomes reduced to:

$$V_N = \left(\frac{C_{12}}{C_{12} + C_{2G}}\right) V_1 \qquad Eqn\ (3)$$

Eqn 3 describes the **maximum** noise coupling between two conductors. The noise voltage is also independent of frequency ω.

Effect of Shield on Capacitive Coupling



Capacitive coupling with shield placed around receptor conductor.

- The shielding is assumed to be ideal due to the following assumptions:

a. The shield completely encloses conductor 2—none of conductor 2 extends beyond the shield.
b. The shield is solid—there are no holes in the shield such as would be the case of a braided shield.
c. The shield is not terminated, and there is no terminating impedance on conductor 2.
d. There is no resistive circuit connected to conductor 2.

- The shield has a high impedance and is fully exposed to conductor 1, therefore the noise voltage picked by the shield V_S can be expressed in a similar way as eqn 3 as:

$$V_S = \left(\frac{C_{1S}}{C_{1S} + C_{SG}}\right) V_1 \qquad Eqn\ 4$$

- Since the conductor 2 has only the impedance between itself and the shield C_{2S} connected to it, there cannot be any voltage drop across C_{2S} and thus the noise voltage V_N picked up by conductor 2 becomes:

$$V_N = V_S \qquad Eqn\,5$$

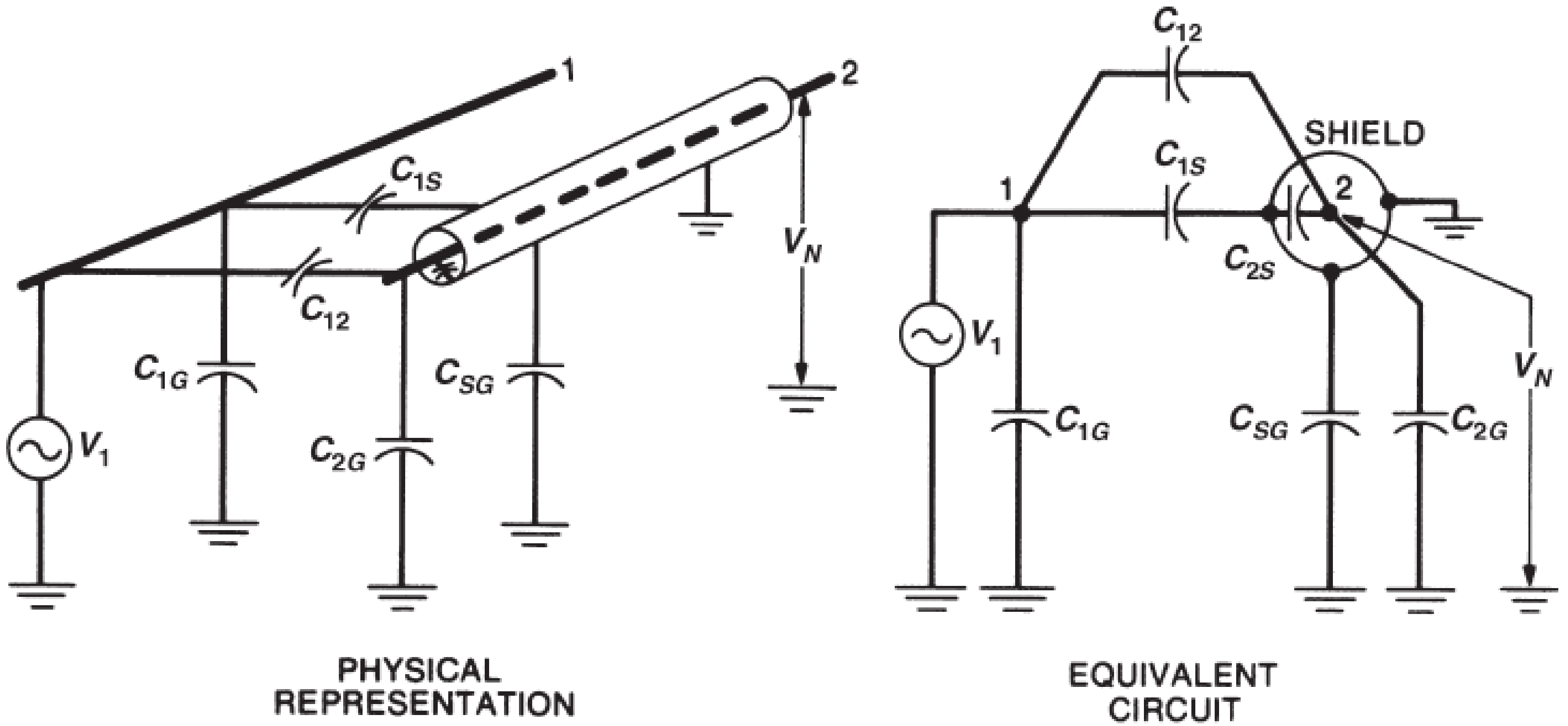
- From eqn 5 the shield did not reduce the noise voltage picked up by conductor 2.

- But when the shield is grounded, $V_S = 0$, thus eqn 5 becomes:

$$V_N = 0$$

- The shield is not effective if it is **not properly grounded or terminated.**

• **When conductor extends more than the shield:**



Capacitive coupling when center conductor extends beyond shield; shield grounded at one point.

- When conductor 2 extends beyond the shield as it is obtainable in most practical cases the noise voltage is given as:

$$V_N = \frac{C_{12}}{C_{12} + C_{2G} + C_{2s}} V_1 \qquad Eqn\ 6$$

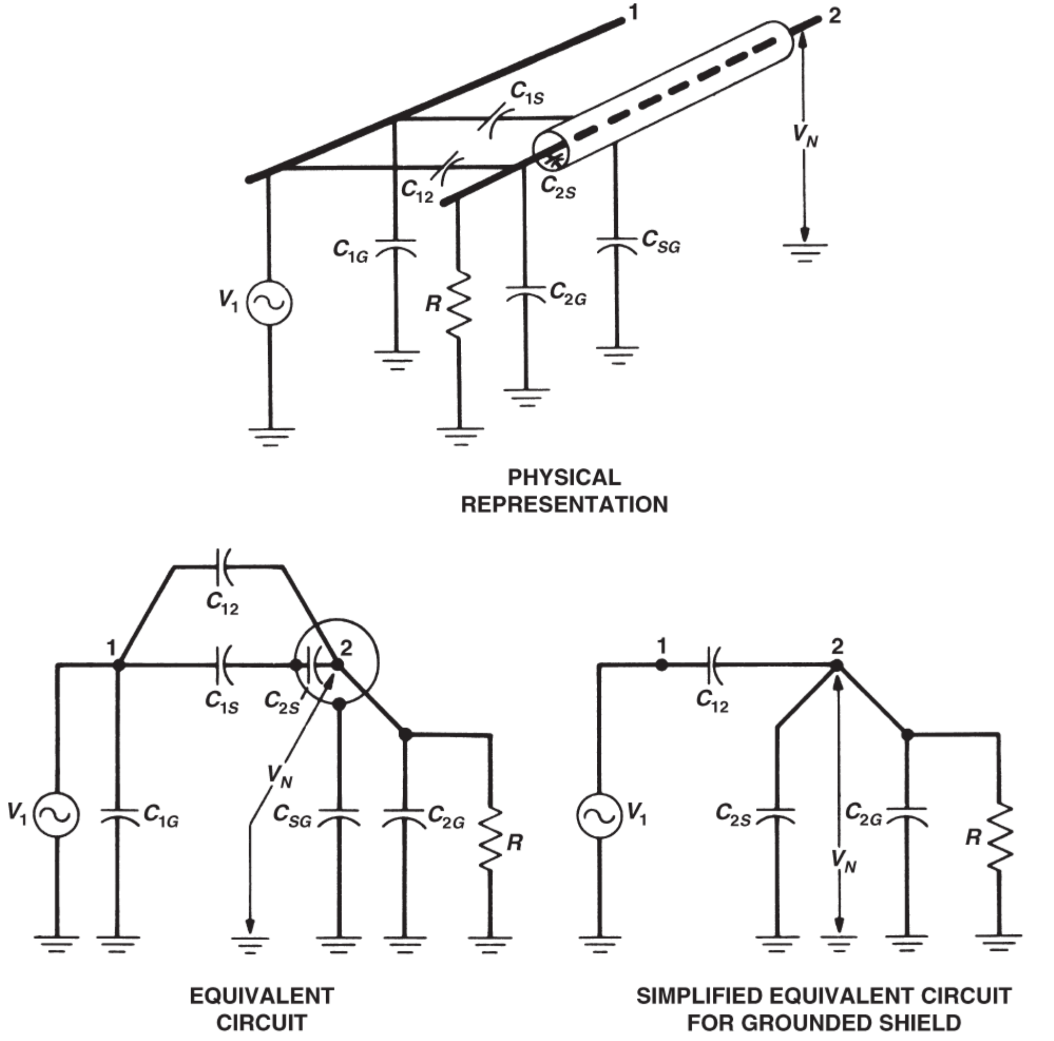
- For good electric field shielding, it is therefore necessary:

a. to minimize the length of the center conductor that extends beyond the shield.

b. to provide a good ground on the shield.

Note: A single ground connection makes a good shield ground, provided the cable is not longer than one twentieth of a wavelength. On longer cables, multiple grounds may be necessary.

- **When there is a finite resistive circuit connected to conductor 2 as shown:**



Capacitive coupling when receptor conductor has resistance to ground.

- With the shield grounded, V_N can be determined by:

$$V_N = \frac{j\omega[C_{12}/(C_{12} + C_{2G} + C_{2S})]}{j\omega + 1/R(C_{12} + C_{2G} + C_{2S})} V_1 \qquad Eqn\ 7$$

If $R \ll \frac{1}{jw(C_{12}+C_{2G}+C_{2S})}$

Therefore eqn 7 becomes reduced to:

$$V_N = j\omega R C_{12} V_1 \qquad Eqn\ 8$$

But when,

$$R \gg \frac{1}{jw(C_{12} + C_{2G} + C_{2S})}$$

$$V_N = \frac{C_{12}}{C_{12} + C_{2G} + C_{2s}} V_1 \qquad Eqn\ 9$$

- This is the same as Eqn 2, which is for an unshielded cable, except that C_{12} is greatly reduced by the presence of the shield.
- Capacitance C_{12} now consists primarily of the capacitance between conductor 1 and the unshielded portions of conductor 2.
- If the shield is braided, any capacitance that exists from conductor 1 to 2 through the holes in the braid must also be included in C_{12}.

Inductive Coupling

- When a current I flows through a conductor, it produces a magnetic flux Φ, which is proportional to the current. The constant of proportionality is the inductance L; hence, we can write:

$$\Phi_T = LI \qquad Eqn\,1$$

Φ_T is the total magnetic flux.

- Therefore self-inductance of a conductor becomes:

$$L = \frac{\Phi_T}{I} \qquad Eqn\ 2$$

- The inductance depends on the geometry of the circuit and the magnetic properties of the media containing the field.

- When current flow in one circuit produces a flux in a second circuit, there is a mutual inductance M_{12} between circuits 1 and 2 defined as:

$$M_{12} = \frac{\Phi_{12}}{I_1} \qquad Eqn\ 3$$

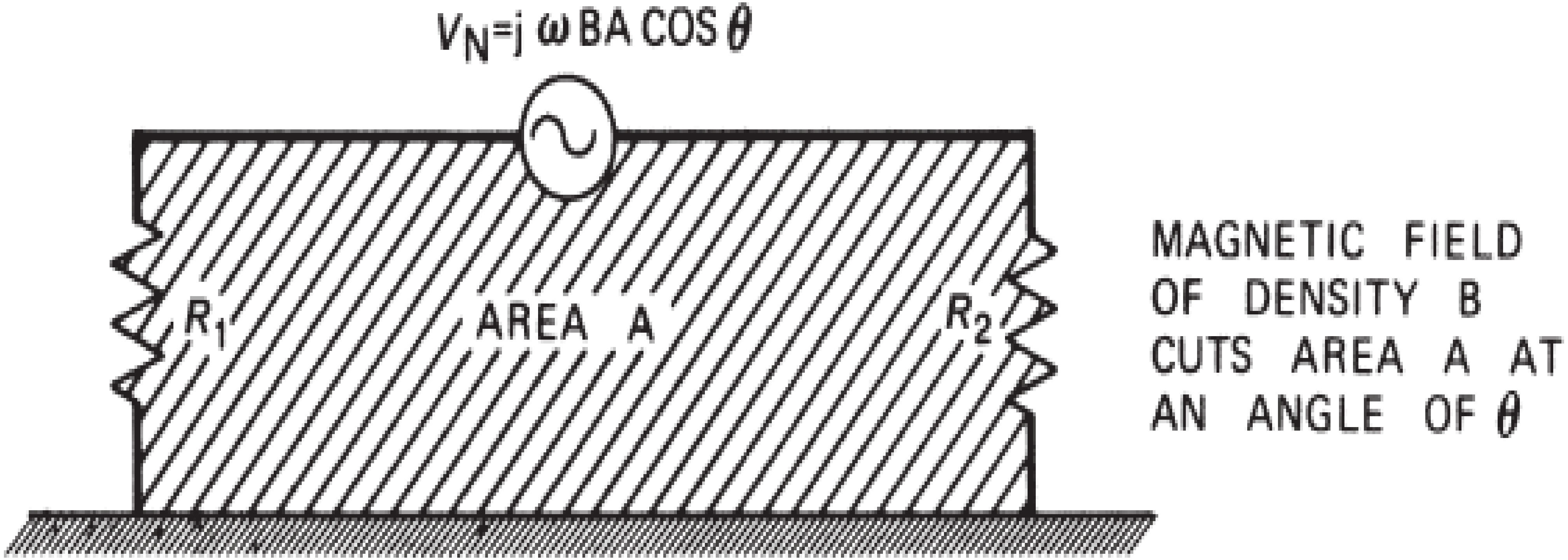
Φ_{12} represents the flux in circuit 2 due to the current I_1 in circuit 1.

- The voltage V_N induced in a closed loop of area A resulting from a magnetic field of flux density B can be derived from Faraday's law (Hayt, 1974, p. 331) and is:

$$V_N = -\frac{d}{dt}\int_A \bar{B}.\overline{dA} \qquad Eqn\ 4$$

- If the closed loop is stationary and the flux density is sinusoidally varying with time but constant over the area of the loop, Eqn 4 reduces to:

$$V_N = j\omega BAcos\theta \qquad Eqn\ 5$$



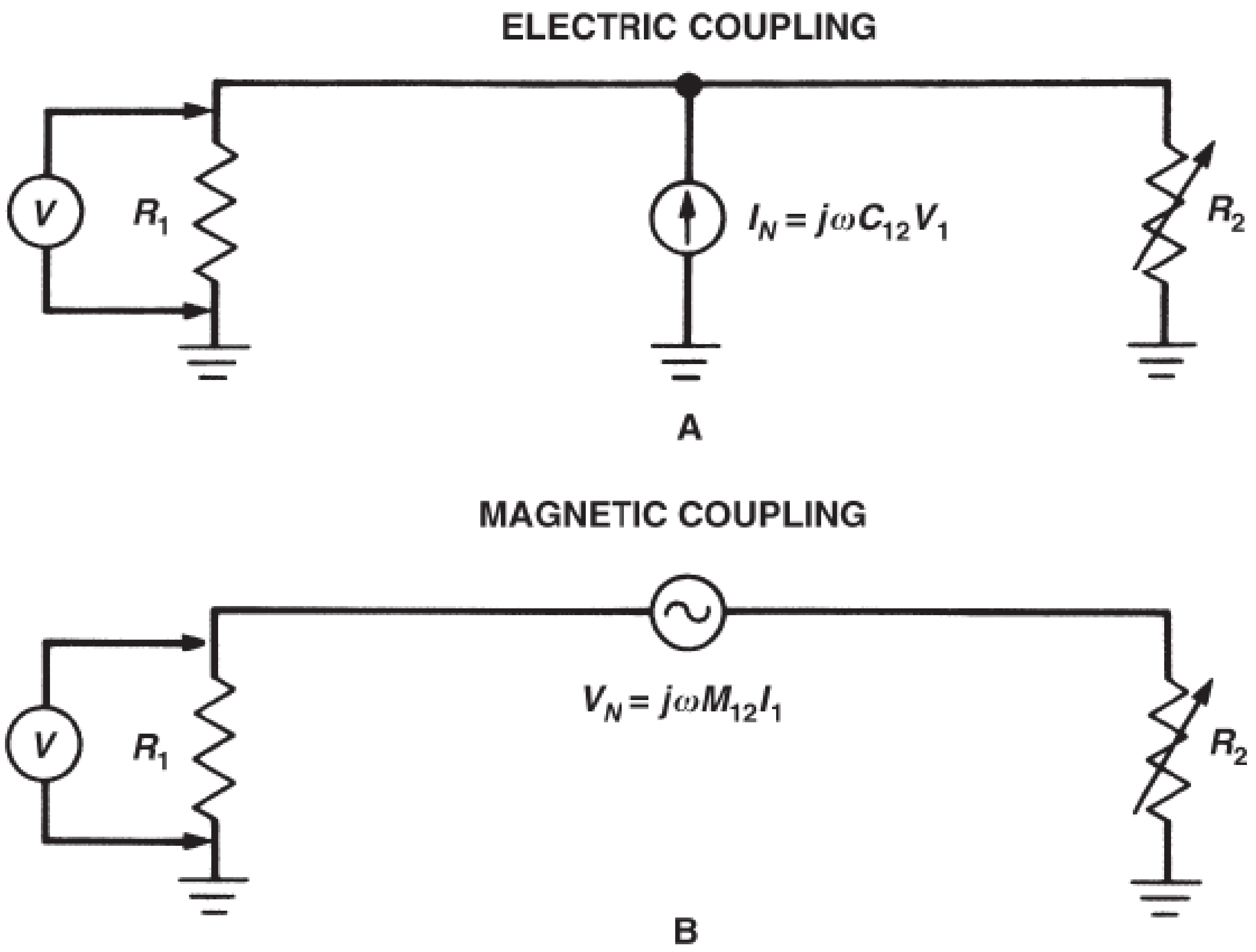
Induced noise depends on the area enclosed by the disturbed circuit.

- The noise voltage V_N may be expressed in terms of mutual inductance as:

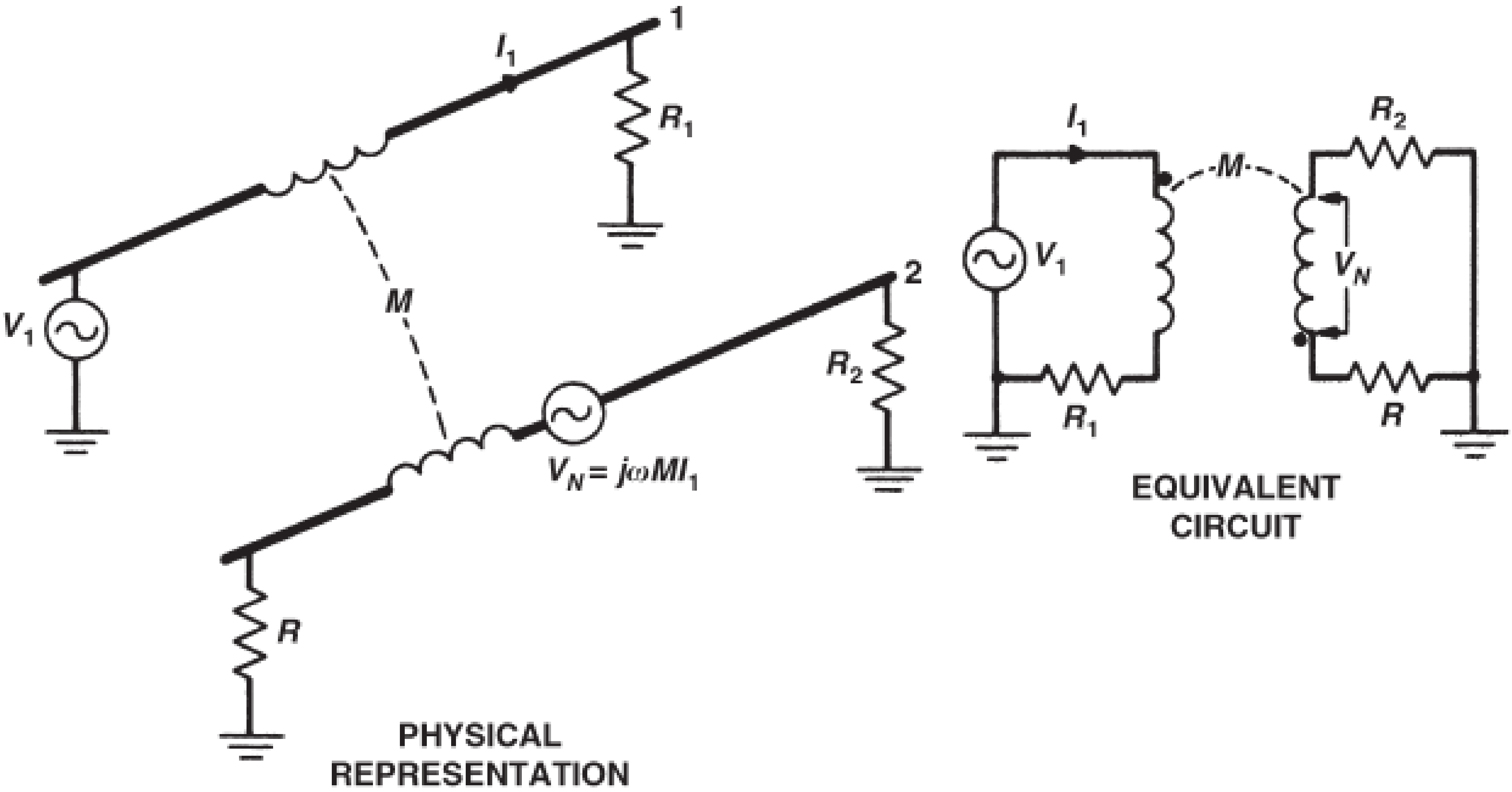
$$V_N = j\omega M_{12} I_1 \qquad Eqn\ 6$$

- **Eqn 6 is the basic equation describing inductive coupling.**
- From Eqn 5, to reduce inductive coupling, the terms $B, A\ and\ \cos\theta$ must be reduced.
- The B term can be reduced by physical separation of the circuits or by twisting the source wires, provided the current flows in the twisted pair and not through the ground plane. Under these conditions, twisting causes the B fields from each of the wires to cancel.

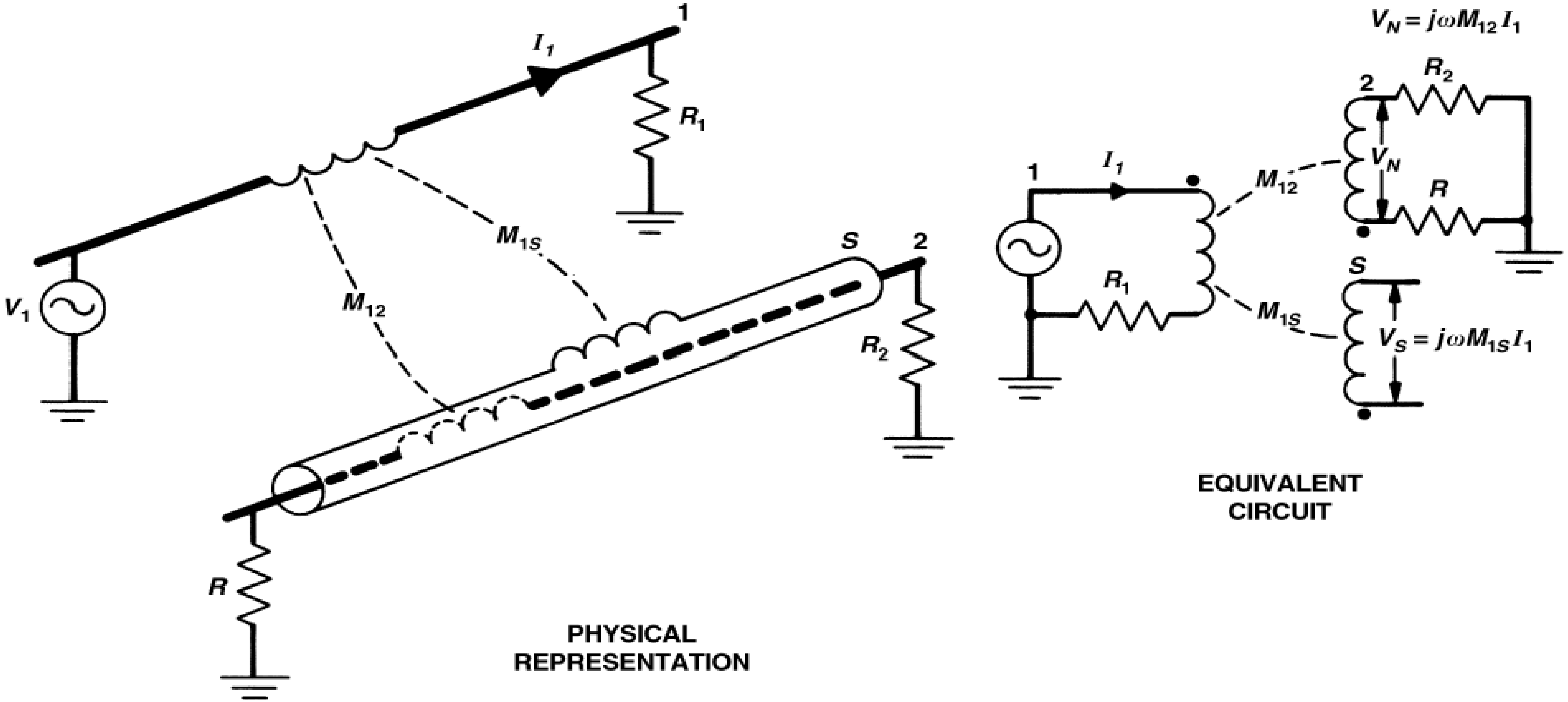
- The area A of the receiver circuit can be reduced by placing the conductor closer to the ground plane (if the return current is through the ground plane) or by using two conductors twisted together (if the return current is on one of the pair instead of the ground plane).
- The $\cos\theta$ term can be reduced by proper orientation of the source and receiver circuits.



(A) Equivalent circuit for electric field coupling; (B) equivalent circuit for magnetic field coupling.



Magnetic coupling between two circuits.



Magnetic coupling when a shield is placed around the receptor conductor.

EFFECT OF SHIELD ON MAGNETIC COUPLING

- If an ungrounded and nonmagnetic shield is now placed around conductor 2 as shown in the previous slide, The shield pick up a voltage because of the current in conductor 1:

$$V_s = j\omega M_{1S} I_1 \qquad \text{Eqn 7}$$

- A ground connection on one end of the shield does not change the situation.

- It follows, therefore, that a nonmagnetic shield placed around a conductor and grounded at one end has no effect on the magnetically induced voltage in that conductor.
- If the shield is grounded at both ends, a closed loop is formed. The magnetic flux due to the current i_1 in circuit 1 can couple to the closed loop, causing a current to flow.

- If the shield is properly oriented, the induced current flowing on the shield will give rise to a magnetic flux, Φ_S that is directed opposite to the flux Φ_{12} over the area "A“ enclosed by circuit 2.
- This will have the effect of reducing the induced noise voltage V_N.
- In order to determine the amount of this reduction, the interaction between the shield and conductor 2 must be determined.

Magnetic Coupling Between Shield and Inner Conductor

- Consider the magnetic field produced by a tubular conductor carrying a uniform axial current.
- Now, let a conductor be placed inside the tube to form a coaxial cable. All of the flux Φ from the current in the shield tube encircles the inner conductor. The inductance of the shield is equal to:

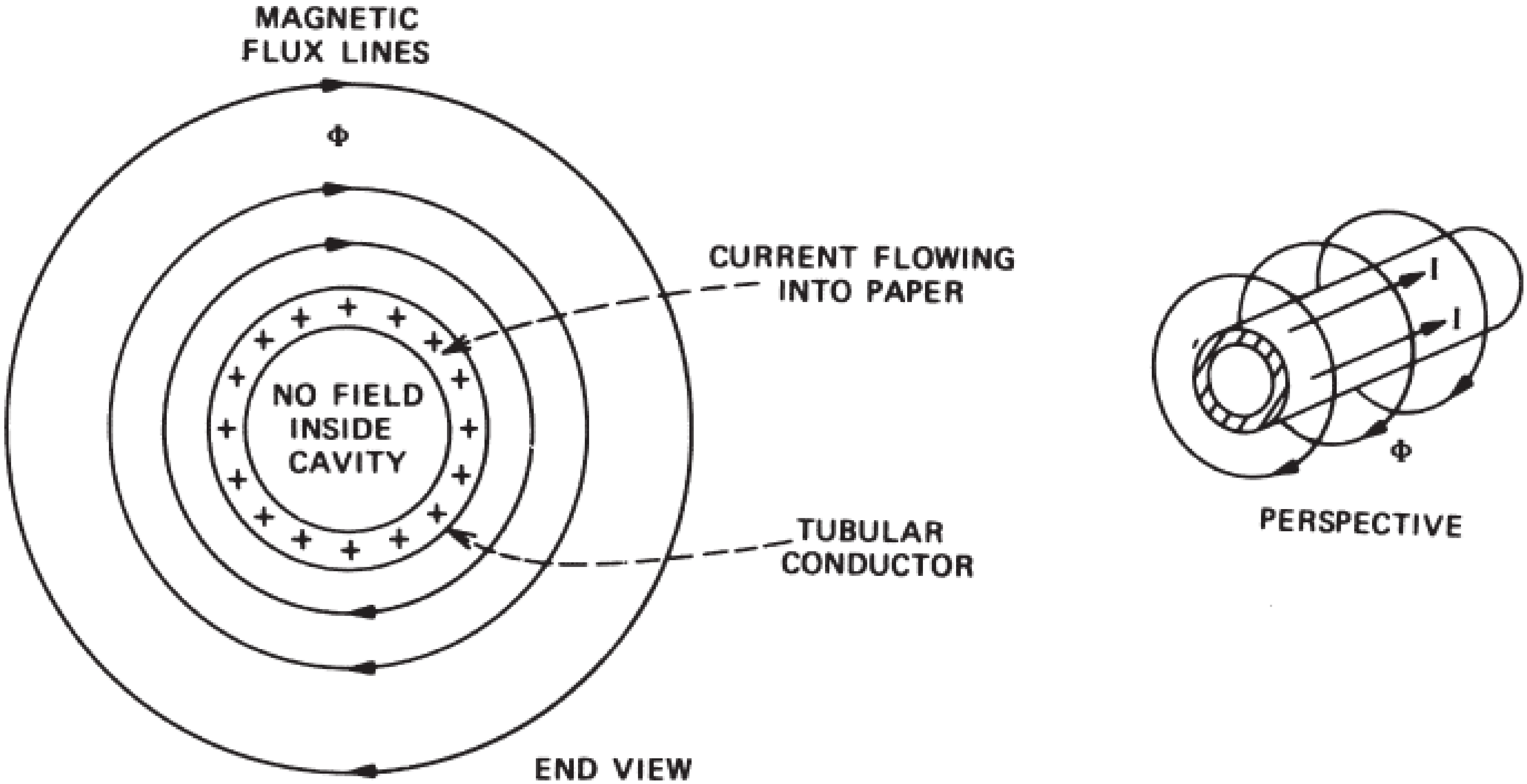
$$L_S = \frac{\Phi}{I_S} \qquad Eqn\ 8$$

- The mutual inductance between the shield and the inner conductor is equal to:

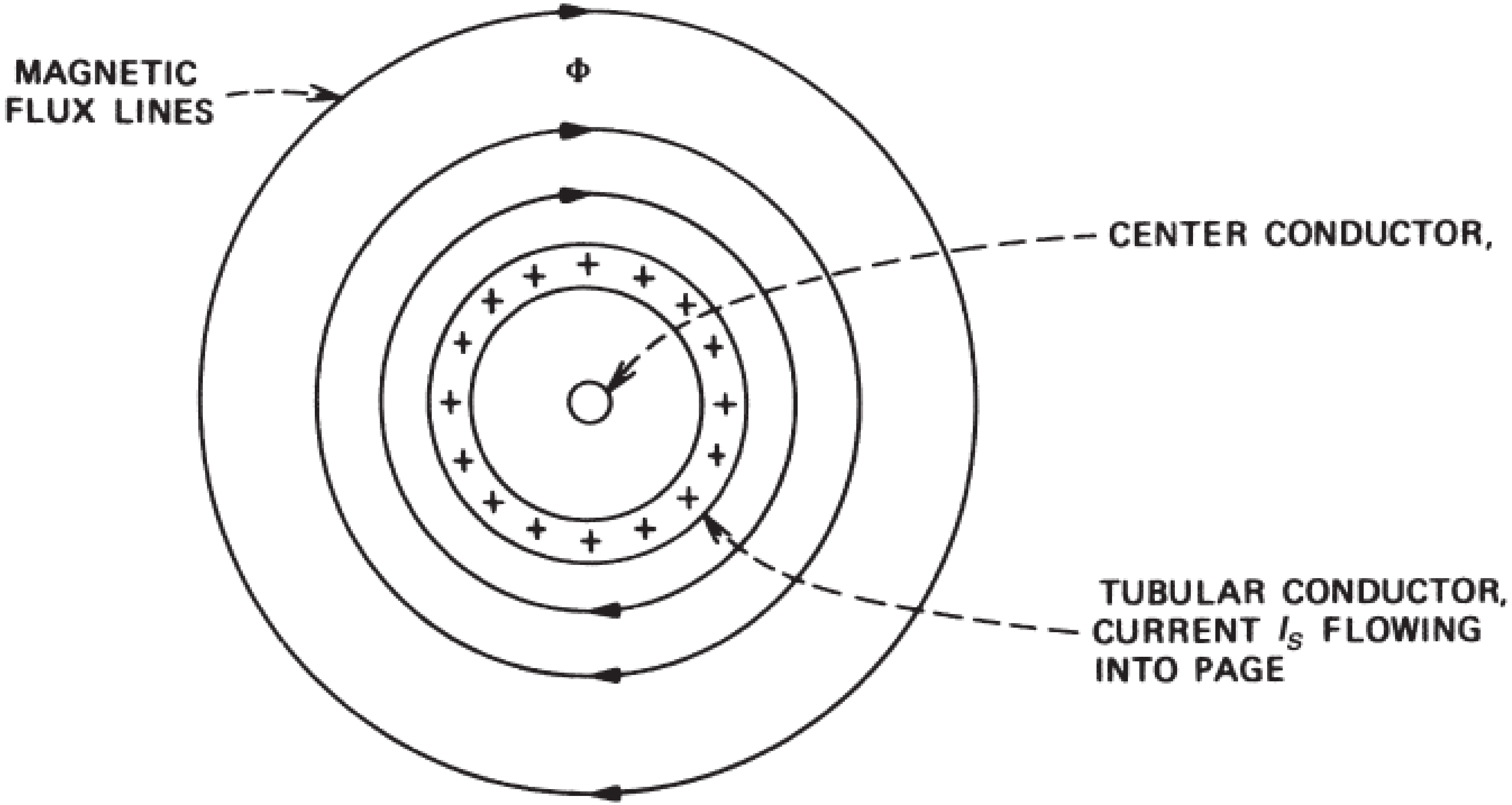
$$M = \frac{\Phi}{I_S} \qquad Eqn\ 9$$

- All the flux produced by the shield current encircles the center conductor, the flux Φ is therefore unchanged.
- The mutual inductance between the shield and center conductor is equal to the self-inductance of the shield.

$$M = L_S \qquad Eqn\ 10$$

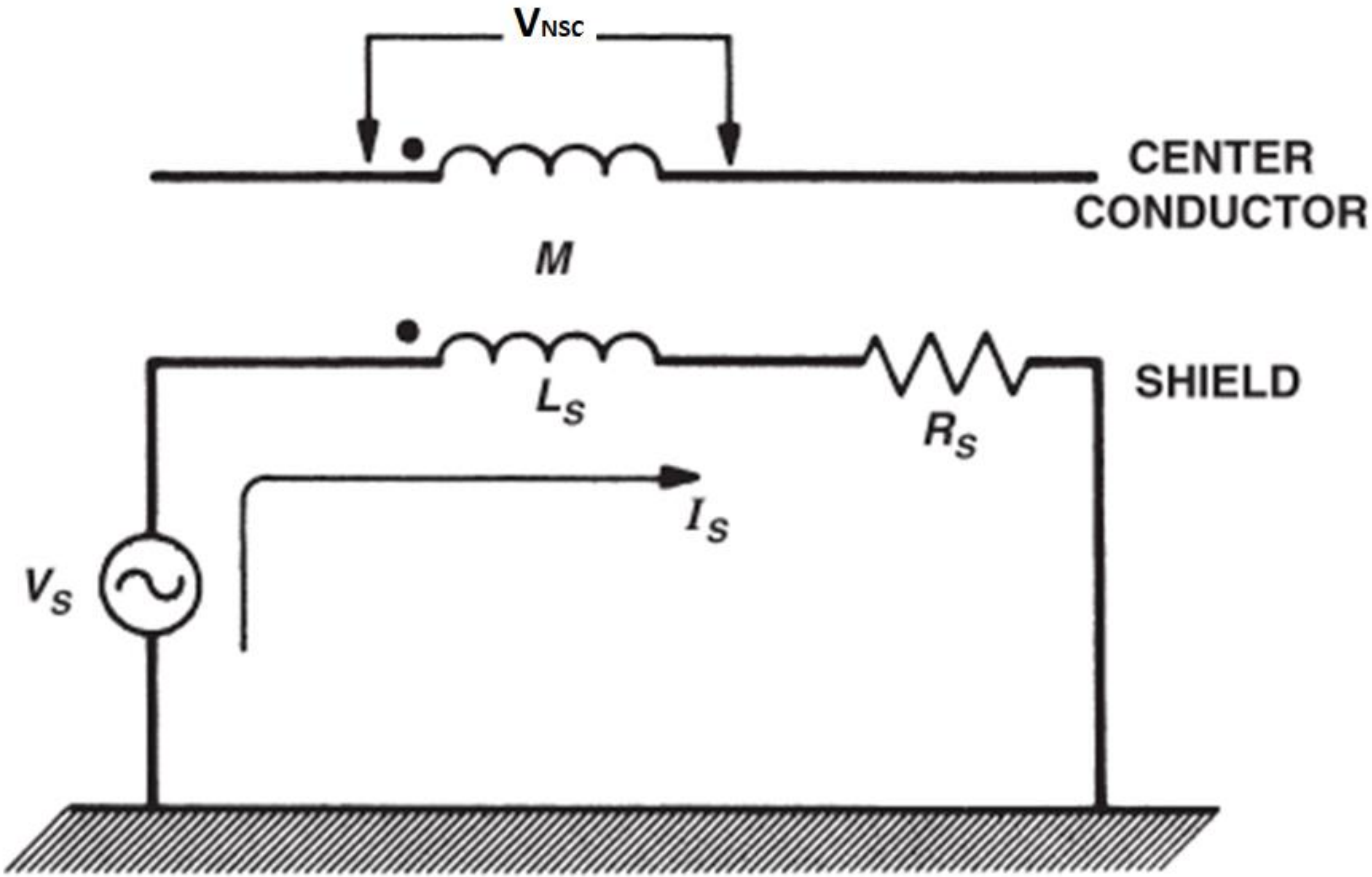


Magnetic field produced by current in a tubular conductor.



Coaxial cable with shield current flowing uniformally around the circumference of the shield.

- Eqn 10 shows that the mutual inductance between the shield and the center conductor is equal to the shield inductance.
- **The voltage** V_{NSC} **induced into the center conductor due to a current** I_S in the shield can now be calculated.
- Assume that the shield current is produced by a voltage V_S induced into the shield from some other circuit.
- As can be seen from the figure on the next slide, L_S and R_S are the inductance and resistance of the shield.



Equivalent circuis of shielded conductor.

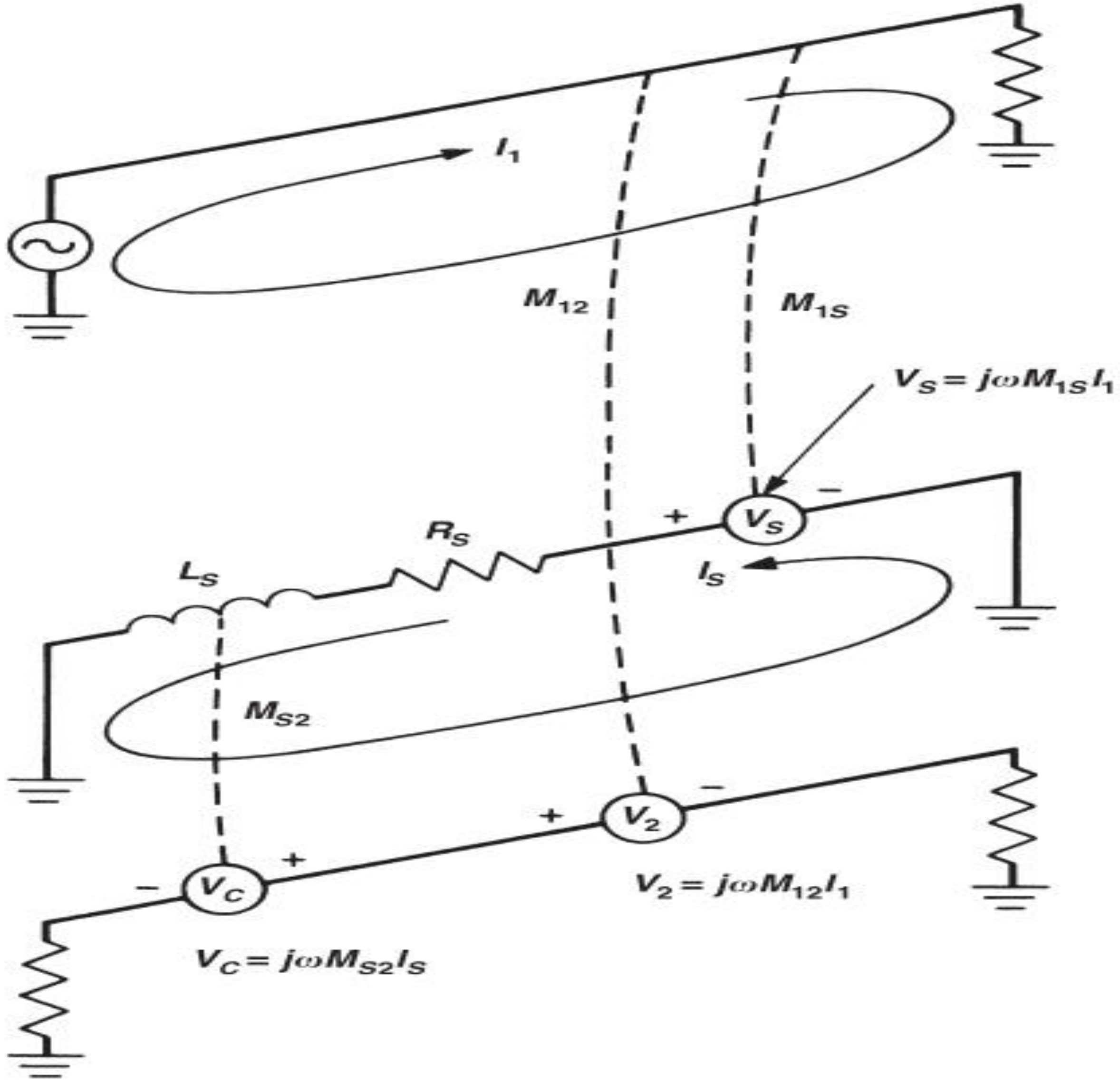
- The voltage V_{NSC} is equal to:

$$V_{NSC} = \left(\frac{j\omega}{j\omega + R_S/L_S}\right) V_S \qquad Eqn\ 11$$

Magnetic Coupling from Open Wire to Shielded Conductor

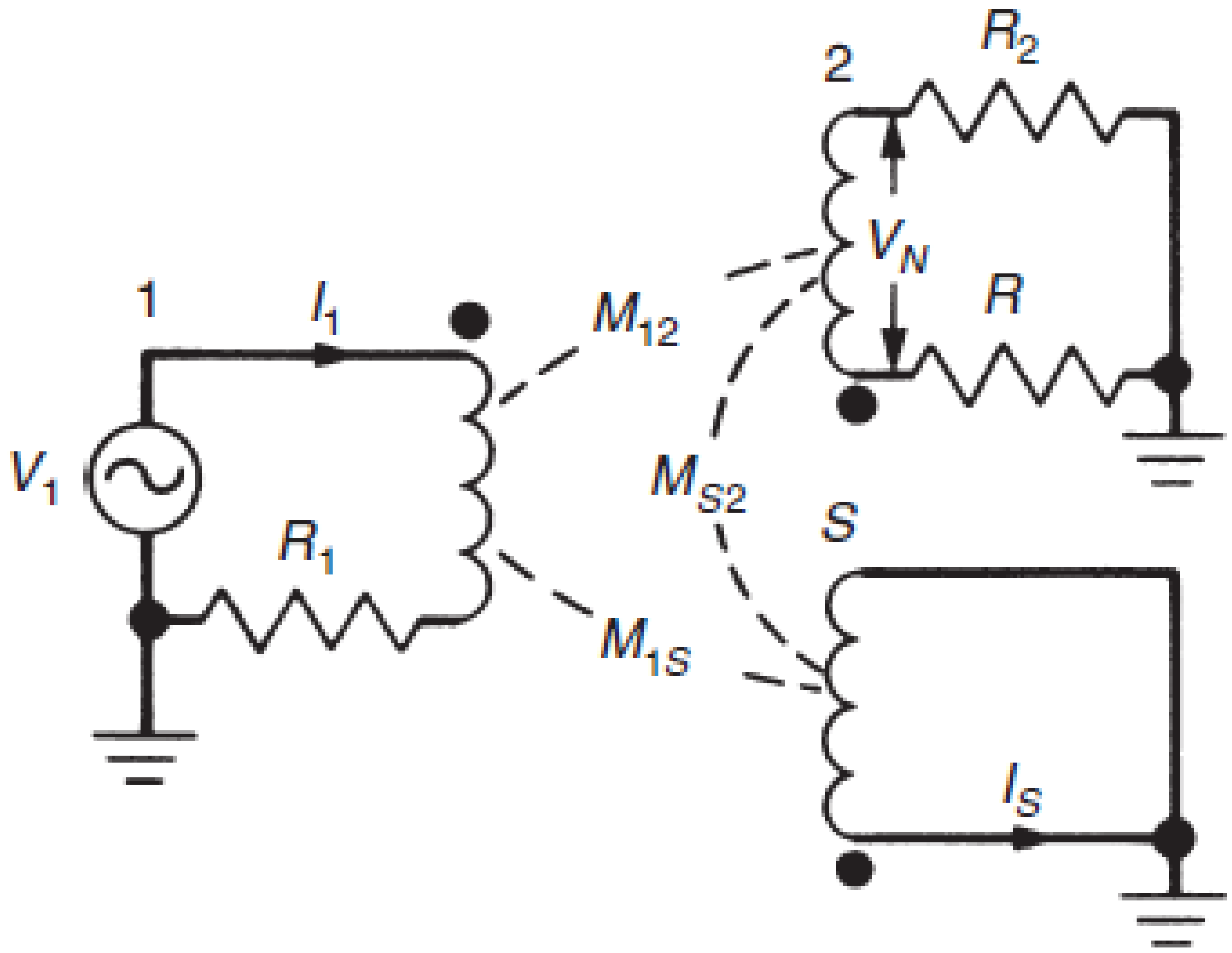
- The figure on the next slide shows the magnetic couplings that exist when a nonmagnetic shield is placed around conductor 2 and the shield is grounded at both ends.
- There are two components to the voltage induced into conductor 2. The voltage V_2 got through induction from conductor 1, and the voltage V_{NSC} got through the induced shield current, I_S.
- These two voltages are of opposite polarity.
- The total noise voltage induced into conductor 2 is therefore:

$$V_N = V_2 - V_{NSC} \qquad Eqn\ 12$$



Magnetic coupling to a shielded cable with the shield grounded at both ends.

$$V_N = j\omega M_{12} I_1 - j\omega M_{12} I_1$$



The Equivalent circuit of previous slide with shielding

- The adjusted noise voltage V_N becomes:

$$V_N = j\omega M_{12} i_1 \left[\frac{R_S/L_S}{j\omega + R_S/L_s}\right] \qquad Eqn\ 12$$

When ω is small, then $\frac{R_S/L_S}{j\omega+R_S/L_s} \cong 1$ and

$$V_N = j\omega M_{12} i_1$$

Which is the same as for an unshielded receptor circuit.

- If ω is large, $V_N \cong M_{12} i_1 [R_S/L_S]$.