# EMC

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## References

Basic:

Ott H. W., *Electromagnetic Compatibility Engineering*, Wiley, Hoboken, NJ, 2009

Additional:

Williams T., *EMC for Product Designers*, Elsevier-Newnes, 4-th ed., Oxford, 2007

All the illustrative materials have been taken from:

Ott H. W., *Electromagnetic Compatibility Engineering*, Wiley, Hoboken, NJ, 2009

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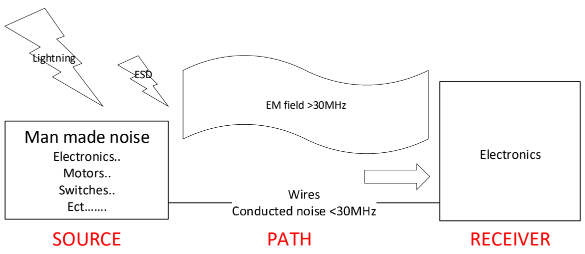


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## „Transmitters" and „Receivers"

- Transmitters (sources of disturbance)
  - car ignition systems
  - fluorescent lamps
  - universal motors
  - power supply units
  - switching contacts
  - atmospherical discharges
  - integrated circuit microprocessors
  - etc.
- Receiver
  - broadcasting and TV receivers
  - automation systems
  - microelectronics (e.g. cars, toys)
  - measuring instruments, controlling devices and instruments
  - data processing equipment (Computers)
  - heart pacemakers
  - bio-organisms
  - etc



## Overvoltage suppretion

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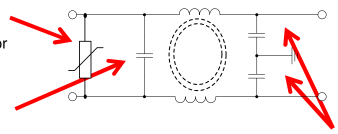
## X and Y capacitors in EMI filter

varistor



X capacitor failure could not lead to electric shock (hot to neutral)

2 Y capacitors failure could lead to electric shock if the ground connection were lost

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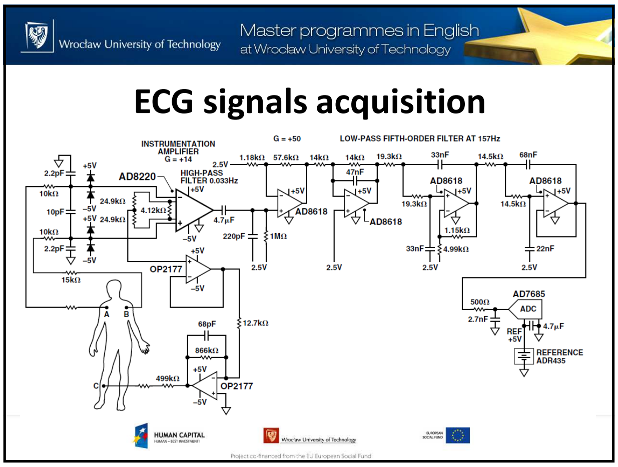
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ECG signals acquisition
INSTRUMENTATION AMPLIFIER G = +14
G = +50
LOW-PASS FIFTH-ORDER FILTER AT 157Hz
HIGH-PASS FILTER 0.033Hz
AD8220
AD8618
OP2177
AD7685
ADC
REFERENCE ADR435
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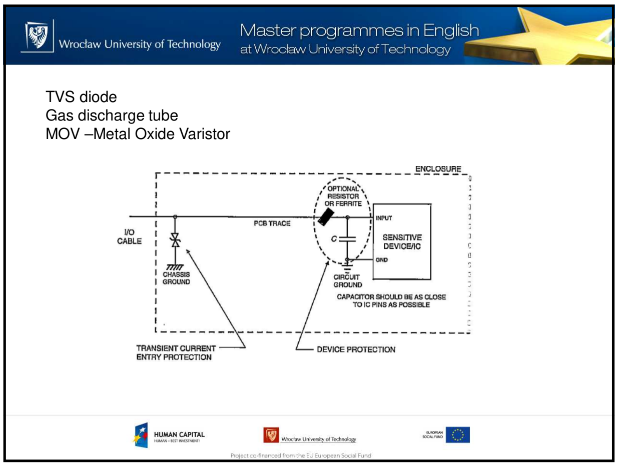
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TVS diode
Gas discharge tube
MOV –Metal Oxide Varistor
ENCLOSURE
OPTIONAL RESISTOR OR FERRITE
I/O CABLE
PCB TRACE
INPUT
SENSITIVE DEVICE/IC
GND
CHASSIS GROUND
CIRCUIT GROUND
CAPACITOR SHOULD BE AS CLOSE TO IC PINS AS POSSIBLE
TRANSIENT CURRENT ENTRY PROTECTION
DEVICE PROTECTION
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RADIATION
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## Digital Circuit Radiation

**Differential-mode radiation** is the result of the normal operation of the circuit and results from current flowing around loops formed by the conductors of the circuit, as shown in the following slide.



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## Circuit Radiation

**Common-mode radiation** is the result of parasitics in the circuit and results from undesired voltage drops in the conductors.

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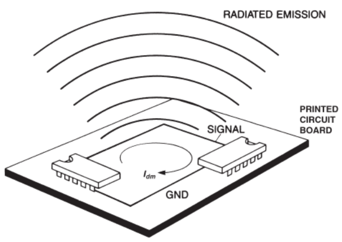
## Differential-mode radiation

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# DIFFERENTIAL-MODE RADIATION

Differential-mode radiation can be modeled as a small loop antenna. For a small loop of area A, carrying a current $I_{dm}$, the magnitude of the electric field E measured in free space at a distance r, in the far field, is equal to

$$E = 131.6 \times 10^{-16}\left(f^2 A I_{dm}\right)\left(\frac{1}{r}\right)\sin\theta$$

*All small loops having equal area radiate the same regardless of their shape.*

Differential-mode (loop) radiation can be controlled by

1. Reducing the magnitude of the current
2. Reducing the frequency or harmonic content of the current
3. Reducing the loop area

For a current waveform other than a sine wave, the Fourier series of the current waveshape must be determined before substitution into the discussed equation.

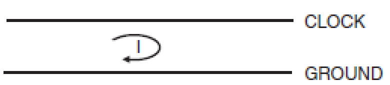




# CONTROLLING DIFFERENTIAL-MODE RADIATION

## Canceling Loops

Consider the case of a clock trace and its ground return path as shown in the figure. The emission from this loop will be a function of the area of the loop and the current in the loop.



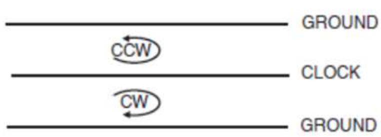





## CONTROLLING DIFFERENTIAL-MODE RADIATION

### Canceling Loops

Consider the layout shown in the figure below. We have a clock trace with two ground return traces, one on each side. Hence we have two loops, each of which has the same area as the loop shown in the previous slide.



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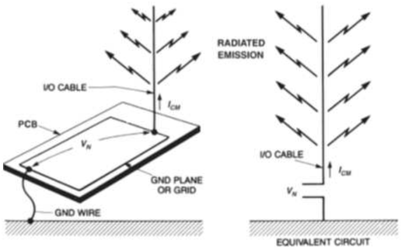
## Common-mode radiation



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## COMMON-MODE RADIATION

Differential-mode radiation can be controlled in the design and layout of the PCB.
Common-mode radiation is harder to control and often determines the overall emission performance of a product.

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## COMMON-MODE RADIATION

Common-mode emission can be modeled as a dipole, or monopole, antenna (the cable) driven by a noise voltage (the ground voltage). For a short dipole antenna (ideal uniform current antenna) of length l, the magnitude of the electric field strength measured, in the far field, at a distance r from the source is

$$E = \frac{4\pi \times 10^{-7}(flI_{cm})\sin\theta}{r}$$

where E is in volts/meter, f is in hertz, I is the common-mode current on the cable (antenna) in amperes, l and r are in meters, and Θ is the angle from the axis of the antenna that the observation is made. The maximum field strength will occur perpendicular to the axis of the antenna where Θ = 90º.

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## COMMON-MODE RADIATION

Common-mode (dipole) radiation can be controlled by:

1. Reducing the magnitude of the common-mode current
2. Reducing the frequency or harmonic content of the current
3. Reducing the antenna (cable) length

For a current waveform other than a sine wave, the Fourier series of the current must be determined before substitution into the equation.





## COMMON-MODE RADIATION

Common-mode emission is more likely to be a problem at low frequencies, and differential-mode emission is more likely to be a problem at high frequencies.

For a long cable (**l > λ/4**) we use the **λ/4** prediction at all frequencies above where the cable is a quarter-wavelength long.





## CONTROLLING COMMON-MODE RADIATION

As is the case for differential-mode radiation, it is desirable to limit both the rise time and frequency of the signal to decrease the common-mode emission.

*No common-mode current is required for normal system operation.*

## CONTROLLING COMMON-MODE RADIATION

The net common-mode current on a cable can be controlled by:

1. Minimizing the common-mode source voltage, normally the ground potential
2. Providing a large common-mode impedance (choke) in series with the cable
3. Shunting the current off the cable
4. Shielding the cable
5. Isolating the cable from the PCB ground, for example, with a transformer or optical coupler



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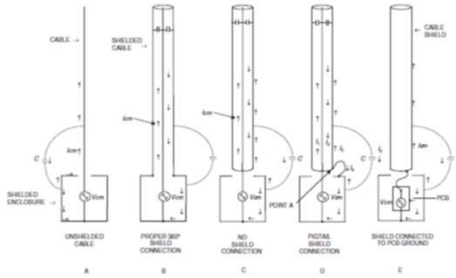
## CONTROLLING COMMON-MODE RADIATION

### Cable Filtering and Shielding

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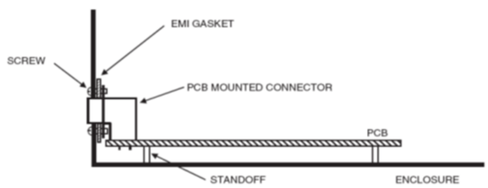
## CONTROLLING COMMON-MODE RADIATION

### Cable Filtering and Shielding

Cable shields should be terminated to the enclosure not to the PCB ground, but there are economic advantages to mounting the I/O connectors on the PCB, not on the enclosure.

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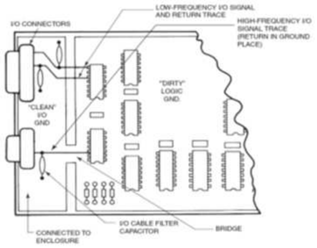
## CONTROLLING COMMON-MODE RADIATION
### Separate I/O Grounds

Digital PCB with a separate "clean" I/O ground plane that contains only I/O cable filter capacitors and connectors








## CONTROLLING COMMON-MODE RADIATION
### Separate I/O Grounds

Generally, the key is to have a low inductance connection between the I/O ground and the enclosure.

The PCB's power plane should not be allowed to extend into the I/O ground area.

The clean I/O ground should be located at the point where the cables leave/enter the system.





## Test quastions example (Radiation):

1. Differential-Mode radiation and Common-Mode radiation
2. Methods of controlling the differential-mode (loop) radiation
3. Methods of controlling the common-mode (dipole) radiation

# SYSTEM NOISE LEVEL SUPRESSION

To implement system level suppression, the following general techniques are generally required:

- Decoupling
- Cabling
- Grounding
- Shielding
- Isolation and separation

And more other technics can be involved:

- Signal symetrization
- Gasketing
- Filtering
- Proper track routing
- Circuit impedance control
- I/O interconnect design
- PCB suppression techniques designed internal to a component package



# DECOUPLING

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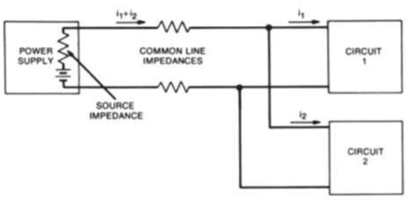
# METHODS OF NOISE COUPLING

## Common Impedance Coupling

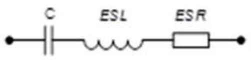
Example 2




Any change in the supply current required by circuit 2 will affect the voltage at the terminals of circuit 1 because of the common impedances of the power supply lines and the internal source impedance of the power supply.

## CAPACITORS

An actual capacitor is not a pure capacitance; it also has both resistance and inductance,




L is the equivalent series inductance (ESL) and is from the leads as well as from the capacitor structure.
R1 is the equivalent series resistance (ESR) of the capacitor and a function of the dissipation factor of the capacitor.



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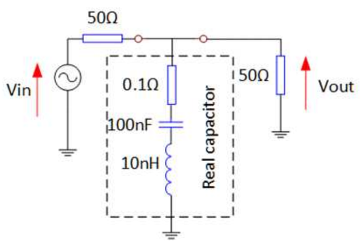


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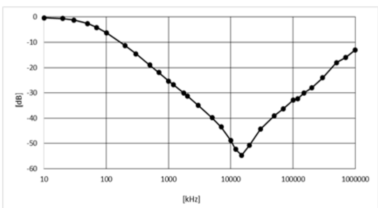
## CAPACITORS




Measured voltage gain for a SMD ceramic capacitor 10nF

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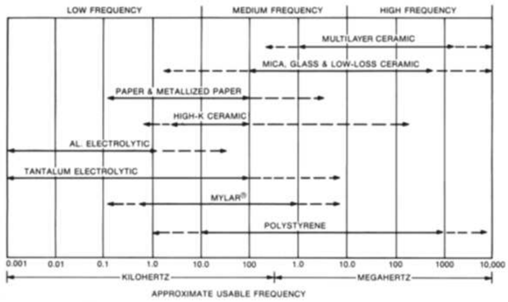
## CAPACITORS



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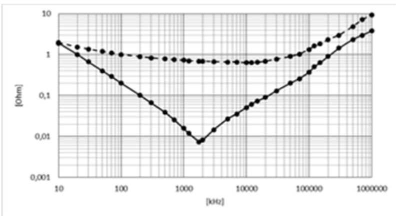
## SMD Electrolytic Capacitors




Impedance for a SMD tantalum capacitor 10µF and a SMD aluminum capacitor 10µF

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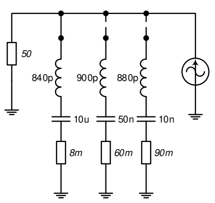
## Decoupling

### Paralleling Capacitors




Three capacitors connected in parallel: 10µF, 50nF and 10nF

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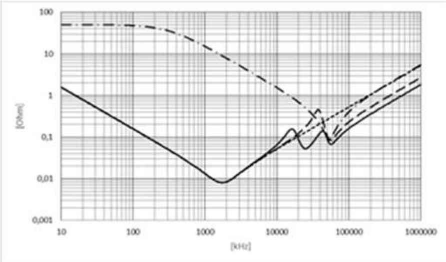


Impedance of the two capacitors connected in parallel (10μF and 10nF - dash) and of the three capacitors (10μF, and 10nF 50nF – cont.). Also impedance for the single 10μF (dash) and 10nF (dash-dot) capacitors.



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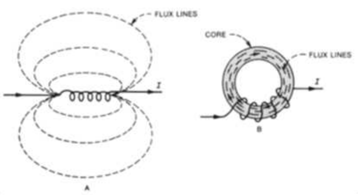
## INDUCTORS

Another important characteristic of inductors is their susceptibility to, and generation of, stray magnetic fields.

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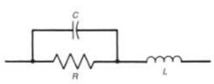
## RESISTORS

Fixed resistors can be grouped into the following three basic classes:
(1) wirewound,
(2) film type, and
(3) composition.




The shunt capacitance can be important when high-value resistors are used.

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# FERRITES

Ferrite is a term for a class of nonconductive ceramics that consists of oxides of iron, cobalt, nickel, zinc, magnesium, and some rare earth metals.



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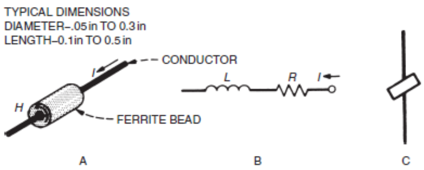
## FERRITES

Ferrites provide an inexpensive way of coupling high-frequency resistance into a circuit without introducing power loss at dc or affecting any low-frequency signals present.

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# Test quastions example (decoupling, passive elements):

1. Basic method for power decoupling
2. A capacitor, its equivalent circuit and impedance vs. frequency.
3. Definition of the target impedance

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# CABLING

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## Cabling

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:
- Shields are made of nonmagnetic materials
- Cables are short compared with a wavelength

Considered types of couplings are:
- Capacitive or electric coupling.
- Inductive, or magnetic coupling.

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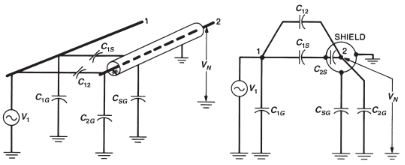
## EFFECT OF SHIELD ON CAPACITIVE COUPLING

In many practical cases, the center conductor does extend beyond the shield, and the situation becomes that of the figure below




PHYSICAL REPRESENTATION

EQUIVALENT CIRCUIT

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## EFFECT OF SHIELD ON CAPACITIVE COUPLING

For good electric field shielding, it is necessary
(1) to minimize the length of the center conductor that extends beyond the shield and
(2) to provide a good ground on the shield.

**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.



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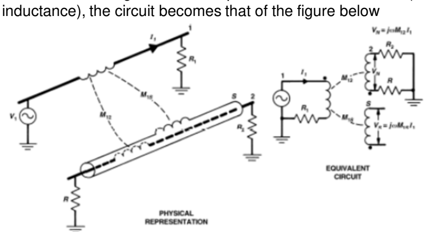
## EFFECT OF SHIELD ON MAGNETIC COUPLING

If an ungrounded and nonmagnetic shield is placed around conductor 2(***M1s*** is the mutual inductance), the circuit becomes that of the figure below

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## EFFECT OF SHIELD ON MAGNETIC COUPLING

The shield pick up a voltage because of the current in conductor 1:

$$V_S = j\omega M_{1S} I_1$$

*Note that mutual inductance* $\boldsymbol{M_{1S}}$ *from conductor 1 to the shield is equal to the mutual inductance* $\boldsymbol{M_{12}}$ *from conductor 1 to conductor 2*

A nonmagnetic shield placed around a conductor and **ungrounded or grounded at one end** has no effect on the magnetically induced voltage in that conductor.

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## EFFECT OF SHIELD ON MAGNETIC COUPLING
### Magnetic Coupling - Open Wire to Shielded Conductor

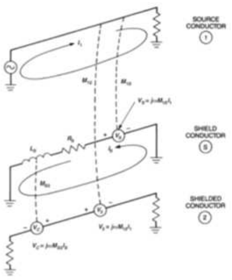
If the shield is **grounded at both ends**, the shield current flows and induces a voltage into conductor 2.

The total noise voltage induced into conductor 2 is

$$V_N = V_2 - V_c$$

*Note that **these two voltages are of opposite polarity.***

$$V_N = j\omega M_{12} I_1 \left[ \frac{R_S/L_S}{j\omega + R_S/L_S} \right]$$



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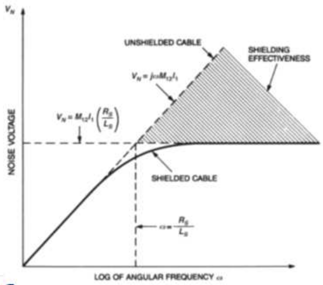
### Magnetic Coupling - Open Wire to Shielded Conductor

The equation for $V_N$ is plotted in the figure

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## EFFECT OF SHIELD ON MAGNETIC COUPLING

At low frequencies, the noise pickup in the shielded cable is the same as for an unshielded cable; however, at frequencies above the shield cutoff frequency, the pickup voltage stops increasing and remains constant.

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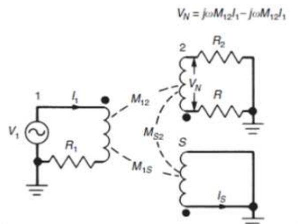
## Magnetic Coupling - Open Wire to Shielded Conductor

Figure below shows a transformer analogy equivalent circuit for the magnetic coupling to a shielded cable when shield is grounded at both ends. (Remember that the mutual inductances $\mathbf{M_{12}}$ and $\mathbf{M_{1S}}$ are equal.)



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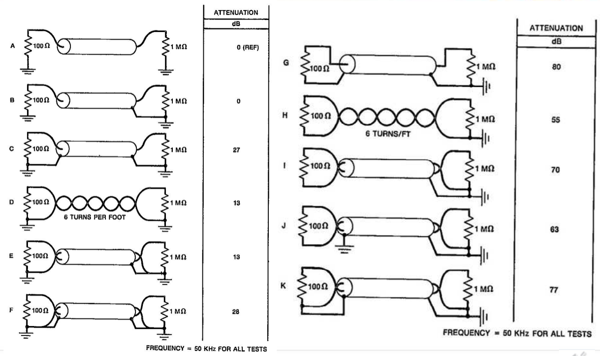


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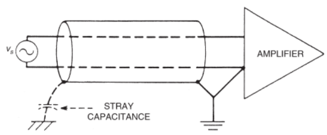
## Grounding of Cable Shields

*High-Frequency Cable Shield Grounding*

At frequencies above about 100 kHz, or where cable length exceeds one twentieth of a wavelength, it becomes necessary to ground the shield at both ends.

Another problem develops at high frequency; stray capacitance tends to complete the ground loop, as shown in the figure below, which makes it difficult or impossible to maintain ground isolation at the unterminated end of the shield.

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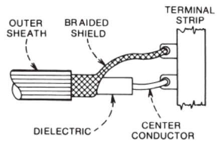
## SHIELD TERMINATIONS

### Pigtails

For maximum protection, the shield should be terminated uniformly around its circumference. This can be accomplished by using coaxial connectors such as BNC or Type N. A pigtail connection causes the shield current to be concentrated on one side of the shield and strongly degrades the shield performance.








## Test quastions example (cabling):

1. Capacitive coupling. Effect of shield on capacitive coupling.
2. Magnetic coupling. Effect of nonmagnetic shield on magnetic coupling.
3. How to avoid magnetic coupling at low frequencies ?



## GROUNDING

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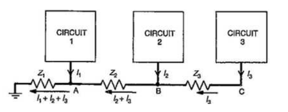


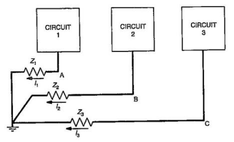




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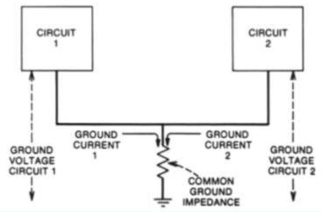
# METHODS OF NOISE COUPLING

## Common Impedance Coupling

Common impedance coupling occurs when currents from two different circuits flow through a common impedance.

Example 1

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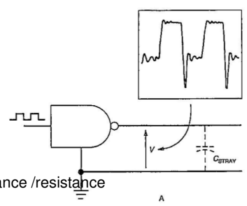


Inductance /resistance

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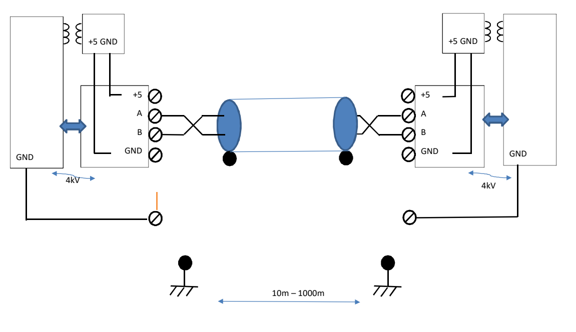




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## Test quastions example (grounding):

1. What it is common impedance coupling ?
2. How to avoid ground impedance coupling ?

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## SHILDING

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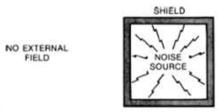
# Shielding

A shield is a metallic partition placed between two regions of space. It is used to control the propagation of electromagnetic fields from one region to the other.



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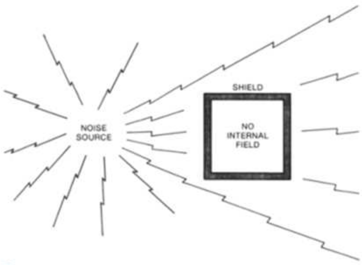
# Shielding

A shield may also be used to keep electromagnetic radiation out of a region. This technique provides protection only for the specific equipment contained within the shield.

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# Shielding and Filtering

It is of little value to make a shield, no matter how well designed, and then to allow electromagnetic energy to enter (or exit) the enclosure by an alternative path such as cable penetrations. Cables will pick up noise on one side of the shield and conduct it to the other side, where it will be reradiated.

To maintain the integrity of the shielded enclosure, noise voltages should be filtered from all cables that penetrate the shield.

This applies to power cables as well as signal cables.

Cable shields that penetrate a shielded enclosure must be **bonded** to that enclosure to prevent noise coupling across the boundary.

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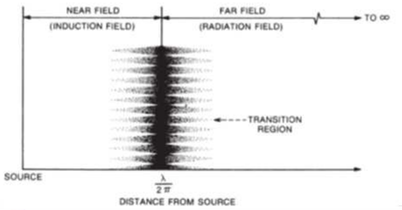
## NEAR FIELDS AND FAR FIELDS

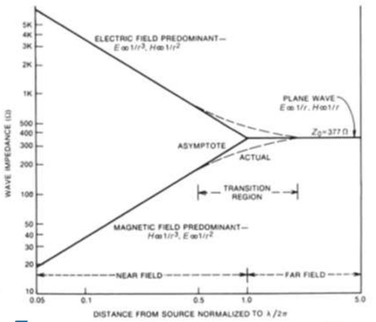
The characteristics of a field are determined by the source (the antenna), the media surrounding the source, and the distance between the source and the point of observation.








## NEAR FIELDS AND FAR FIELDS








## CHARACTERISTIC IMPEDANCES

The wave impedance:

$$Z_w = \frac{E}{H}$$

The characteristic impedance of a medium is defined by the following expression:

$$Z_0 = \sqrt{\frac{j\omega\mu}{\sigma + j\omega\varepsilon}}$$

## CHARACTERISTIC IMPEDANCES

For **insulators** (σ << ω ε) the characteristic impedance is independent of frequency and becomes

$$Z_0 = \sqrt{\frac{\mu}{\varepsilon}}$$

For free space, $Z_0$ equals 377 Ω.

In the case of **conductors** (σ >> ω ε), the characteristic impedance is called the shield impedance $Z_s$ and it becomes

$$Z_s = \sqrt{\frac{j\omega\mu}{\sigma}} = \sqrt{\frac{\omega\mu}{2\sigma}}(1+j) \qquad |Z_s| = \sqrt{\frac{\omega\mu}{2\sigma}}$$

For any conductor, in general,

$$|Z_s| = 3.68 \times 10^{-7}\sqrt{\frac{\mu_r}{\sigma_r}}\sqrt{f}$$



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## CHARACTERISTIC IMPEDANCES

| Material | Relative conductivity $\sigma_r$ | Relative permeability $\mu_r$ |
|---|---|---|
| Silver | 1.05 | 1 |
| Copper—annealed | 1.00 | 1 |
| Gold | 0.7 | 1 |
| Chromium | 0.664 | 1 |
| Aluminum (soft) | 0.61 | 1 |
| Aluminum (tempered) | 0.4 | 1 |
| Zinc | 0.32 | 1 |
| Beryllium | 0.28 | 1 |
| Brass | 0.26 | 1 |
| Cadmium | 0.23 | 1 |
| Nickel | 0.20 | 100 |
| Bronze | 0.18 | 1 |
| Platinum | 0.18 | 1 |
| Magnesium alloy | 0.17 | 1 |
| Tin | 0.15 | 1 |
| Steel (SAE 1045) | 0.10 | 1000 |
| Lead | 0.08 | 1 |
| Monel | 0.04 | 1 |
| Conetic (1 kHz) | 0.03 | 25,000 |
| Mumetal (1 (kHz) | 0.03 | 25,000 |
| Stainless steel (Type 304) | 0.02 | 500 |

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## SHIELDING EFFECTIVENESS

Schelkunoff's approach is to treat shielding as a transmission line problem with both loss and reflection components.

**Shielding effectiveness** (S) is defined for electric fields as

$$S = 20\log\frac{E_0}{E_1}\ \text{dB}$$

and for magnetic fields as

$$S = 20\log\frac{H_0}{H_1}\ \text{dB}$$

$E_0(H_0)$ is the incident field strength, and $E_1(H_1)$ is the field strength of the transmitted wave as it emerges from the shield.

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## SHIELDING EFFECTIVENESS

In the design of a shielded enclosure, there are two prime considerations:

(1) the shielding effectiveness of the shield material itself and

(2) the shielding effectiveness resulting from discontinuities and apertures in the shield.



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## SHIELDING EFFECTIVENESS

The total shielding effectiveness of a solid material with no apertures is equal to the sum of the absorption loss (A) plus the reflection loss (R) plus a correction factor (B) to account for multiple reflections in thin shields.
Total shielding effectiveness can be written as

$$S = A + R + B \text{ dB}$$

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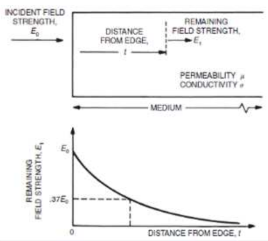
## ABSORPTION LOSS

When an electromagnetic wave passes through a medium, its amplitude decreases exponentially

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## ABSORPTION LOSS

This decay occurs because currents induced in the shield produce ohmic losses and heating of the material. Therefore, we can write

$$E_1 = E_0 e^{-t/\delta}$$

$$H_1 = H_0 e^{-t/\delta}$$

where $E_1(H_1)$ is the wave intensity at a distance t within the shield.





## ABSORPTION LOSS

The distance required for the wave to be attenuated to 1/e or 37% of its original value is defined as the skin depth, which is equal to

$$\delta = \sqrt{\frac{2}{\omega\mu\sigma}}$$





## ABSORPTION LOSS

The absorption loss through a shield can now be written as

$$A = 20 \log \frac{E_0}{E_1} = 20 \log e^{t/\delta}$$

$$A = 20 \left(\frac{t}{\delta}\right) log(e) \text{ dB},$$

$$A = 8.69 \left(\frac{t}{\delta}\right) \text{ dB}.$$

## ABSORPTION LOSS

General expression for absorption loss:

$$A = 0.132t\sqrt{f\mu_r\sigma_r} \quad \text{[dB]}$$

In this equation, t is equal to the thickness of the shield in mm.



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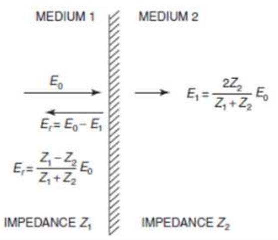
## REFLECTION LOSS

The reflection loss at the interface between two media is related to the difference in characteristic impedances between the media.

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## REFLECTION LOSS

The intensity of the transmitted wave from a medium with impedance $Z_1$ to a medium with impedance $Z_2$ is

$$E_1 = \frac{2Z_2}{Z_1 + Z_2}E_0$$

and

$$H_1 = \frac{2Z_1}{Z_1 + Z_2}H_0$$

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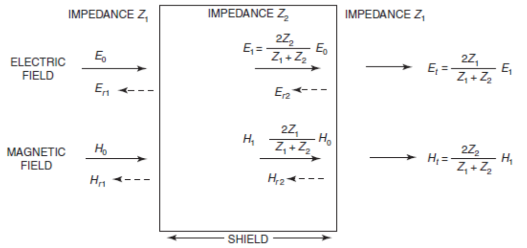
## REFLECTION LOSS

When a wave passes through a shield, it encounters two boundaries








## REFLECTION LOSS

The secondary boundary is between a medium with impedance $Z_2$ and a medium with impedance $Z_1$. The transmitted wave $E_t$ ($H_t$) through this boundary is given by

$$E_1 = \frac{2Z_1}{Z_1 + Z_2} E_1$$

and

$$H_t = \frac{2Z_2}{Z_1 + Z_2} H_1$$





## REFLECTION LOSS

| Material | Relative conductivity $\sigma_r$ | Relative permeability $\mu_r$ |
|---|---|---|
| Silver | 1.05 | 1 |
| Copper—annealed | 1.00 | 1 |
| Gold | 0.7 | 1 |
| Chromium | 0.664 | 1 |
| Aluminum (soft) | 0.61 | 1 |
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| Zinc | 0.32 | 1 |
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| Brass | 0.26 | 1 |
| Cadmium | 0.23 | 1 |
| Nickel | 0.20 | 100 |
| Bronze | 0.18 | 1 |
| Platinum | 0.18 | 1 |
| Magnesium alloy | 0.17 | 1 |
| Tin | 0.15 | 1 |
| Steel (SAE 1045) | 0.10 | 1000 |
| Lead | 0.08 | 1 |
| Monel | 0.04 | 1 |
| Conetic (1 kHz) | 0.03 | 25,000 |
| Mumetal (1 (kHz) | 0.03 | 25,000 |
| Stainless steel (Type 304) | 0.02 | 500 |

## Generalized Equation for Reflection Loss

Neglecting multiple reflections a generalized equation for reflection loss can be written as

$$R = C + 10\log\left(\frac{\sigma_r}{\mu_r}\right)\left(\frac{1}{f^n r^m}\right)$$

where the constants C, n and m are listed below for plane waves, electric fields, and magnetic fields, respectively.

| Type of Field | $C$ | $n$ | $m$ |
|---|---|---|---|
| Electric field | 322 | 3 | 2 |
| Plane wave | 168 | 1 | 0 |
| Magnetic field | 14.6 | –1 | –2 |



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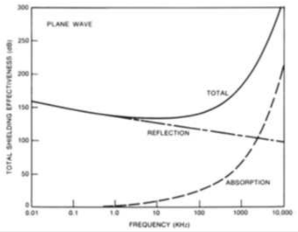
## COMPOSITE LOSS

FAR FIELD For example, the overall attenuation (or shielding effectiveness) of a 0.020-in thick solid copper shield is shown below.

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## COMPOSITE LOSS

ELECTRIC FIELD At low-frequency, reflection loss is the primary shielding mechanism for electric fields. At high-frequency, absorption loss is the primary shielding mechanism.

MAGNETIC FIELD The reflection loss to a low-frequency magnetic field is small. Because of multiple reflections, this effect is even more pronounced in a thin shield. The primary loss for magnetic fields is absorption loss. Because both the absorption and reflection loss are small at low frequencies, the total shielding effectiveness is low. It is therefore difficult to shield low-frequency magnetic fields.

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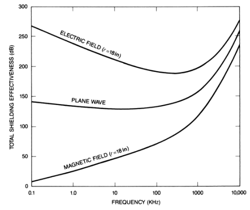
# SUMMARY OF SHIELDING EQUATIONS

Figure below shows the composite shielding effectiveness of a 0.5mm thick solid aluminum shield for an electric field, plane wave, and a magnetic field. As can be observed in the figure, considerable shielding exists in all cases exept for low frequency magnetic fields.








## SUMMARY OF SHIELDING EQUATIONS

At high frequencies (above 1MHz), absorption loss predominates in all cases, and any solid shield thick enough to be practical provides more than adequate shielding for most applications.





## SHIELDING WITH MAGNETIC MATERIALS

In summary,
**a magnetic material such as steel or mumetal makes a better magnetic field shield at low frequencies than does a good conductor such as aluminum or copper.**

**At high frequencies the good conductors provide the better magnetic shielding. The magnetic shielding effectiveness of solid nonmagnetic shields increases with frequency.**

## APERTURES

In the design of a shielded enclosure, there are two prime considerations:

(1) the shielding effectiveness of the shield material itself and

(2) the shielding effectiveness resulting from discontinuities and apertures in the shield.



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## APERTURES

In practice most shields are not solid. There must be access covers, doors, holes for cables, ventilation, switches, displays, and joints and seams.

The amount of leakage from an aperture depends mainly on the following three items:
1. The maximum linear dimension, not area, of the aperture.
2. The wave impedance of the electromagnetic field.
3. The frequency of the field.

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## GROUNDING OF SHIELDS

A solid shield that completely surrounds a product (a Faraday cage) can be at any potential and still provide effective shielding.
Thus, **the shield does not need to be grounded.**

In most cases, however, the shield should be connected to the circuit common, to prevent any potential difference between the shield and the circuits inside the shielded enclosure.

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## Test quastions example (shilding):

1. Wave impedance as a function of the distance from the source (far field and near field)
2. Characteristic impedance of a medium
3. Definition of the shielding effectiveness
4. The total shielding effectiveness of a solid material with no apertures
5. Absorption loss (A). Skin depth
6. Reflection loss (R).
7. Shielding effectiveness of a solid nonmagnetic shield