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[measurements, standards, technology]

**NATIONAL
NANOTECHNOLOGY
INITIATIVE**

[nanotechnology leadership]



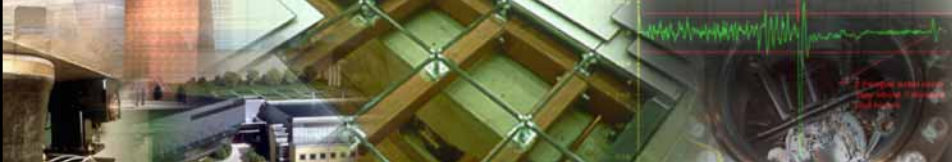
[research & development]

HDR

[architecture / engineering]

**COLIN
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[vibration / acoustics]



Interactions between Nanomeasurements and Nanobuilding Design

Bob Erdman
Erdman Measurement Consulting, Inc.
330-656-2275

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Interactions between Nanomeasurements and Nanobuilding Design

Overview



**How to design buildings so that
nanomeasurements CAN be made**

In spite of interactions between:

- The building
- The experiment or process
- The measuring instrumentation

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- **Nanomeasurements =
Measurements on nanostructures**
- **May be physical:**
Thickness, Spacing, Movement/vibration
- **May be chemical:**
Composition, processing
- **May be electrical or magnetic:**
Current, voltage, resistance, capacitance, field strength, and/or quantities derived from these

FOCUS OF
THIS TALK



THE PROBLEM:

- The building and the environment transmit unwanted signals
- The experiment and the measuring instrument[s] receive these signals
- This can cause the measurements to be in error
- **Those involved in design of the building are blamed: User/Scientist says:**
“We spent x years and zz M\$ on this lab and now I can’t do my experiment!!!!”

Interactions between Nanomeasurements and Nanobuilding Design

Overview



SOLUTION TO THE PROBLEM:

- Effective communication between the building designers and representative users, so that:
 - Both understand the demands of the experiments and processes that will be done in the nanobuilding
 - Both understand what to expect of the nanobuilding
- Analyze pros and cons of shielding in the building or at the experiment
 - If shielding CAN be done either place, at the experiment is usually more cost effective, up to practical limits of shielding
 - If the measurement cannot be made the building is not effective
- Agreement on acceptable levels of electromagnetic noise
 - Acceptable magnitude of interference at important frequencies
 - At the locations of experiments and processes

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Interactions between Nanomeasurements and Nanobuilding Design

Overview



THIS TALK WILL DISCUSS HOW TO QUANTIFY:

- Demands of the experiments and processes
- Shielding demands and performance
- Acceptable magnitudes of interference

ELECTROSTATIC SHIELDING :

Calculations and rules of thumb for estimating
Examples

MAGNETIC SHIELDING:

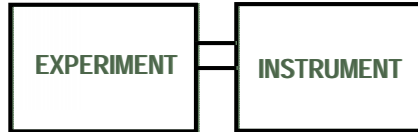
Calculations and examples

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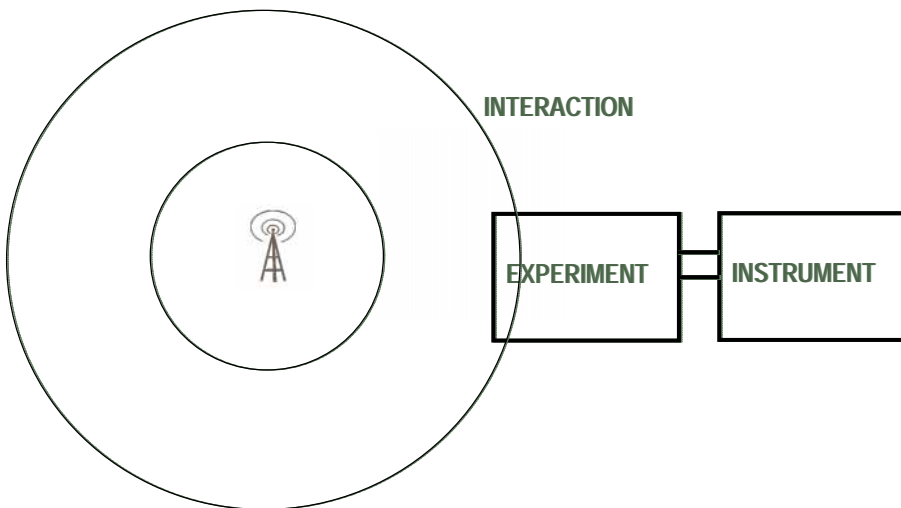
Interactions between Nanomeasurements and Nanobuilding Design

Interactions



Interactions between Nanomeasurements and Nanobuilding Design

Interactions

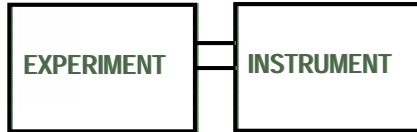
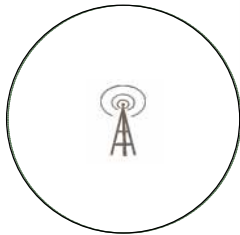


Interactions between Nanomeasurements and Nanobuilding Design



Interactions

BUILDING SHIELD



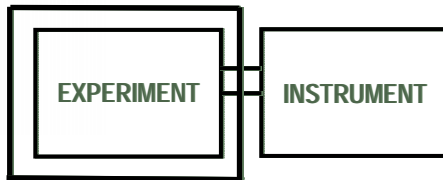
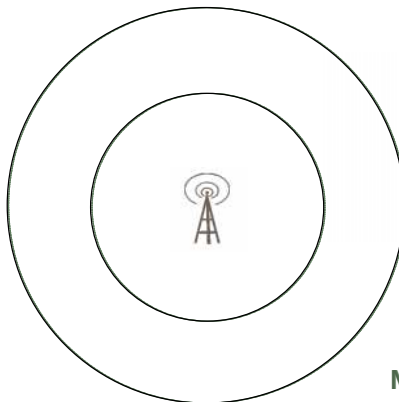
NO INTERACTION

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Interactions

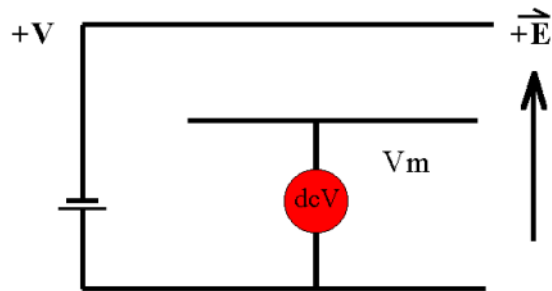
EXPERIMENT SHIELD



NO INTERACTION

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dc Electrostatic Coupling

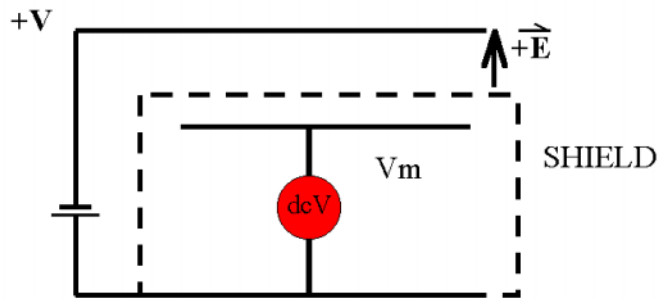


V generates field E , creating measured V_m

INTERACTION

Interactions between Nanomeasurements and Nanobuilding Design

dc Electrostatic Coupling

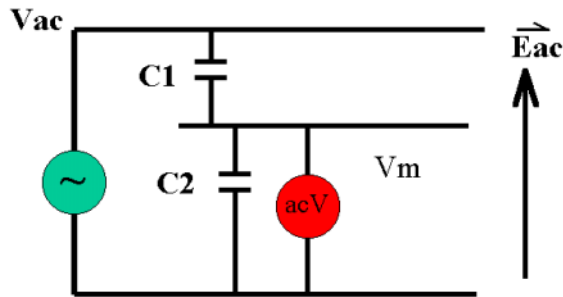


SHIELD eliminates \vec{E} at the experiment, $V_m=0$

NO INTERACTION

Interactions between Nanomeasurements and Nanobuilding Design

ac Electrostatic Coupling

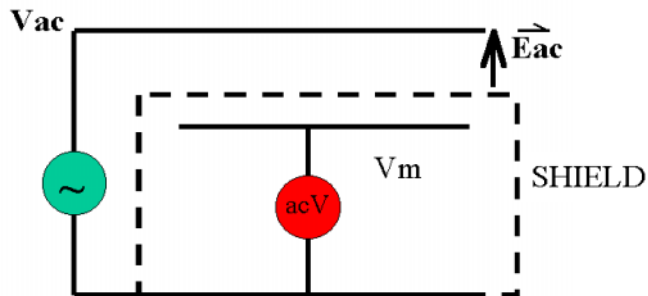


$$V_m = V_{ac} \cdot Z_2 / [Z_1 + Z_2] = V_{ac} \cdot C_1 / [C_1 + C_2]$$

INTERACTION

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ac Electrostatic Coupling



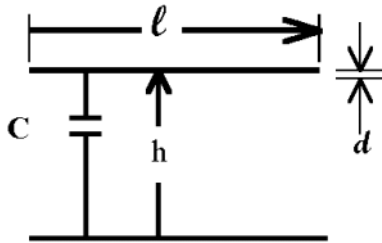
SHIELD eliminates E_{ac} at the experiment, thus $V_m = 0$

NO INTERACTION

Interactions between Nanomeasurements and Nanobuilding Design



Rough Calculations:
ac Electrostatics



For $\ell = 10\text{cm}$ of
a $\frac{1}{2}\text{ mm}$ diameter wire,
far enough from wall
that $h \gg d$, $C \sim 1\text{pF}$.

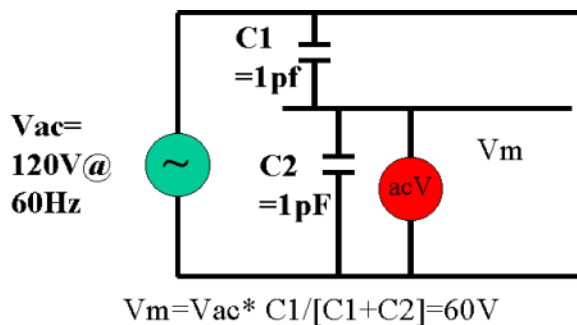
If $\ell < 4 * h$, C is primarily
dependent on ℓ/d , not h.

C increases to:
2pF at $h=5d$. 8pF at $h=d/2$.

Interactions between Nanomeasurements and Nanobuilding Design



Rough Calculations:
ac Electrostatics



$$V_m = V_{ac} * C_1 / [C_1 + C_2] = 60V$$

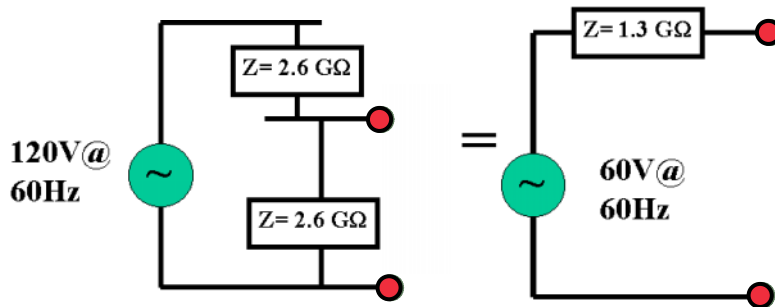
$$Z = 1 / (2 * \pi * f * C)$$

For 1pF, 60Hz,
 $Z = 1000 / 377 \text{ G}\Omega$
 $= 2.65 \text{ G}\Omega$
 $= 2650 \text{ M}\Omega$

INTERACTION

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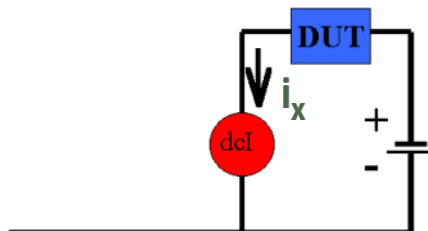
Rough Calculations:
ac Electrostatics



Equivalent circuits

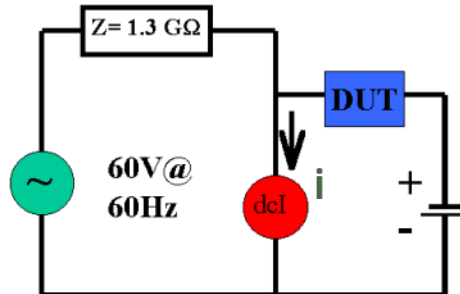
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User Circuit



User circuit or experiment

i_x = Desired experimental current to be read



User circuit with interaction
[no shield]

$$i = i_x + i_{ac}$$

How much AC is a problem?

What is the dc signal level?

- Determined only by experiment

What is the signal bandwidth in the experiment?

- Determined only by experiment

What constitutes a significant error?

- Determined by user

How much ac can the instrument tolerate?

- Determined by acceptable error and NMRR of instrument

Is shielding required?

- Yes if ac coupled from environment exceeds NMRR limit

NMRR = Normal Mode Rejection Ratio

Ratio of two quantities:

- ac signal at the input of a dc instrument
- Indicated dc signal error due to the presence of the ac

Given as a ratio, in dB

- $\text{dB} = 20\text{LOG}_{10} [\text{ac input}/\text{dc error}]$
- 20dB per decade of ratio
- For example: 60dB=1000:1

NMRR EXAMPLE:

1uA signal measured on 1uA range

NMRR=60dB=1000:1

Desired error due to ac is <1%

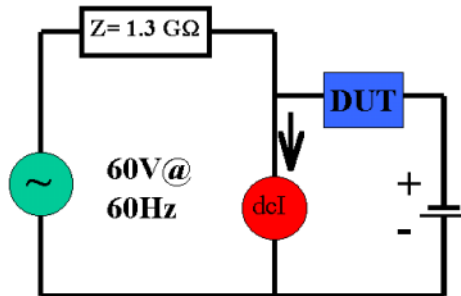
- 1% of 1uA = 10nA

ac must be kept below 10uA

- $1000 * 10\text{nA} = 10\text{uA}$

Interactions between Nanomeasurements and Nanobuilding Design

Interaction: ac current calculation



$$i_{ac} = 60V / 1.3 \text{ G}\Omega \\ = 50nA$$

Note that at higher frequencies, impedance is proportionally lower and current is proportionally higher

User circuit with interaction

Interactions between Nanomeasurements and Nanobuilding Design

Interaction: ELF Examples



INTERACTION EXAMPLE 1: How much AC is a problem?

What is the dc signal level? 1uA

What is the signal bandwidth in the experiment? 1Hz

What constitutes a significant error? 1%

How much ac can the instrument tolerate? 60dBNMRR
Corresponds to 10uA for <1% error in 1uA signal

Is shielding required? $50nA \ll 10uA$ NO
200 times safety margin

INTERACTION, NO PROBLEM

INTERACTION EXAMPLE 2:

How much AC is a problem?

- What is the dc signal level? 1nA
- What is the signal bandwidth in the experiment? 1Hz
- What constitutes a significant error? 1%
- How much ac can the instrument tolerate? 60dBNMRR
▪ Corresponds to 10nA for <1% error in 1nA signal
- Is shielding required? 50nA > 10nA **YES**
To 0.2pF or lower capacitance [5 times lower current]
This requires 80% effective shield, such as aluminum foil

INTERACTION EXAMPLE 3:

How much AC is a problem?

- What is the dc signal level? [0.001pA] 1fA
- What is the signal bandwidth in the experiment? 1Hz
- What constitutes a significant error? 20%
- How much ac can the instrument tolerate? 60dBNMRR
▪ Corresponds to 0.2pA for <20% error in 1fA signal
- Is shielding required? 50nA >> 0.2pA **YES FOR SURE**
To 0.004fF or lower capacitance [250K times lower current] CAN THIS BE DONE??? **YES!**

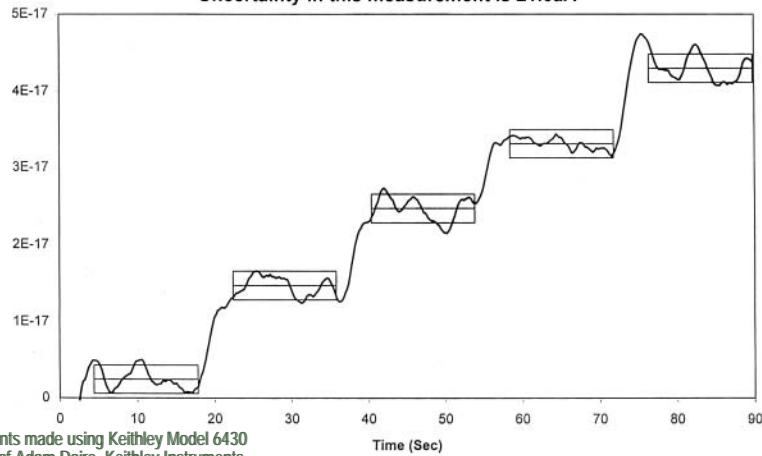
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Interactions: Electrostatic Summary



If Proper attention is paid to electrostatic shielding, it is possible to make very low current measurements in a normal laboratory atmosphere: $1\text{aA} = 10^{-18}\text{ A}$
Zero to 40aA staircase

Uncertainty in this measurement is $\pm 1.6\text{aA}$



Measurements made using Keithley Model 6430
Courtesy of Adam Daire, Keithley Instruments

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Interactions between Nanomeasurements and Nanobuilding Design

Overview



Attoamp Experimental Apparatus in the Lab
[Normal building does not limit shielded electrostatic measurement]



Picture by
Robert Erdman,
Assisted by
Adam Daire of
Keithley
Instruments

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Electrostatic Interactions:

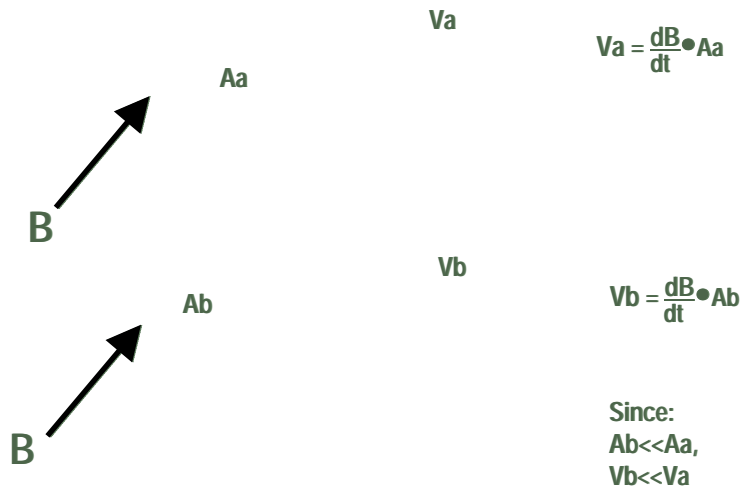
- Estimate coupling between the building and the experiment:
This is “order of magnitude” estimate only
With no shielding, and experiment located far from mains:
 $1\text{pF}/10\text{cm}=0.1\text{pF}/\text{cm}$; $I_{60\text{Hz}}=50\text{nA}/10\text{cm}=5\text{nA}/\text{cm}$
- If estimate indicates a possible problem, measure the actual current generated in similar setting, using the analog output of a wideband Picoammeter connected to Oscilloscope or DMM.
- Determine shielding effectivity at experiment:
Test reasonable shielding:
Move hands around circuit
Put power cords near circuit
Make shielding “light-tight” as needed to minimize stray capacitance around the shield
Retest until induced current is within acceptable levels

Magnetic Interactions are different:

- The only “perfect” shield is a superconductor
Used in cryogenic work only; has max field [H_{C1}]
- Most metals do not reduce magnetic fields
High-permeability materials are used for shielding
Large plates can be used for lossy [eddy-current] shielding
Different materials for different frequencies and field strengths
- Loops is bad
Any current-carry loop is a transmitter of magnetic fields
Any loop in an experiment is a receiver of magnetic fields
Alignment of loops matters

Interactions between Nanomeasurements and Nanobuilding Design

Overview: Magnetic interaction



Interactions between Nanomeasurements and Nanobuilding Design

Magnetic Interaction



$$V = [dB/dt] \bullet A$$

For a 60Hz, $B = B_0 \sin(2 \cdot \pi \cdot 60 \cdot t) = B_0 \sin(377t)$

$$[dB/dt] = 377 B_0 \cos(377t)$$

$V = 377 A B_0 \cos(377t)$, where:

V is the peak voltage developed

B_0 is the peak 60Hz magnetic field, and

A is the area, whose vector is perpendicular

- Indicates that if the vectors are not parallel, the effective area is the measured area multiplied by the cosine of angle between B and A vectors

Interactions between Nanomeasurements and Nanobuilding Design



Magnetic Interaction

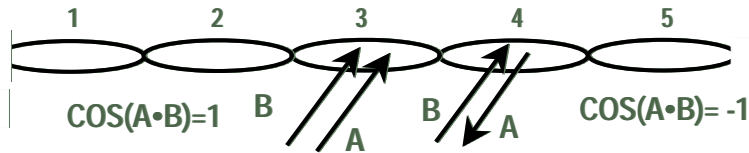
$$V = 377AB_0 \cos(377t), \text{ at } 60\text{Hz}$$

TWISTED PAIR AREA CALCULATION:

$$\text{If } A_b = 0.01 * A_a, V_b = 0.01 * V_a.$$

Since the wires enclosed A_b are twisted, the area vector of adjacent twists have the opposite direction. The cosine of the angle between the two vectors has the opposite sign.

If the areas of the twists match with 10% [e.g, $A_3 = A_4 \pm 10\%$], the effective area of A_b is only 0.1% of A_a .



Interactions between Nanomeasurements and Nanobuilding Design



Magnetic interaction Examples

$$V_a = \frac{dB}{dt} \bullet A_a$$

$$V = 377AB_0 \cos(377t) \text{ at } 60\text{Hz}$$

Peak Field B_0	Area A	Developed V	Error V @NMRR=60dB
$1\mu\text{T}$ [10mG]	1 cm^2	38nV	0.04nV
$10\mu\text{T}$ [100mG]	100 cm^2	38 μV	38nV
$100\mu\text{T}$ [1G]	1 cm^2	4 μV	4nV
10nT [0.1mG]	1 cm^2	0.4nV	0.0004nV

Interactions between Nanomeasurements and Nanobuilding Design

Magnetic interaction



Some key points regarding magnetic interactions:

For building designers:

- Loops is bad
 - Avoid loops in ac circuits carrying current
[they generate high magnetic fields]
 - Twisted pairs greatly reduce both ac generation and pickup
 - Magnetic coupling is proportional to frequency
- Keep power lines and communication lines away from experiment areas
- Avoid random dc field generators, such as dc elevators
- Analytical equipment [Mass Spec, E-Beam, SEM] requires 1-10mG [0.1-1 μ T] for proper operation

Interactions between Nanomeasurements and Nanobuilding Design

Magnetic Interaction



Some key points regarding magnetic interactions:

For experiment/process designers:

- Loops is bad
 - Keep the area enclosed by the physical circuit small
 - 1 Gauss in 1 cm² generates 4 μ V at 60Hz
- Measure fields with Flux-gate Magnetometer
 - Use this to determine existing fields near sensitive experiments
 - Analytical equipment [Mass Spec, E-Beam, SEM] requires 1-10mG [0.1-1 μ T] for proper operation
- Determine shielding effectivity at experiment:
 - Test reasonable shielding: Cell phone near experiment
 - Electric Drill
 - Put power cords near circuit
 - Use permeability shielding [μ -metal etc.] at experiment as needed

Process for Analyzing Interactions

- Determine coupling between the building and the experiment:
 - Roughly quantify the magnitude of disturbance**
[±1-2 decades]
 - Consider interferences within and outside of the measurement bandwidth**
- Based on desired error levels and instrument specifications,
Determine shielding requirements, based on measurements of experiment in situ
- Agree on acceptable levels of disturbance from the building:
 - Between user representatives and building designers.**
- Confirm that desired measurements CAN be made given the building design. **This means that it is POSSIBLE to shield the experiment well enough to make the measurement in the building.**