

Cost-effective EMC Design — by Working With the Laws of Physics



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We may have been taught physics and/or Maxwell's equations at Uni...

- but if so, it was never properly explained to us how this related to circuit design, power supply decoupling, PCB layout, shielding, filtering, etc...
- either to make circuits function well, or achieve EMC, to improve our employer's financial performance
- So, many electronic designers use techniques that add delays, costs, and reduce profitability...
 - e.g. requiring several design iterations to achieve functional spec's, then several more to achieve EMC...
 - resulting in low profits and high levels of financial risk



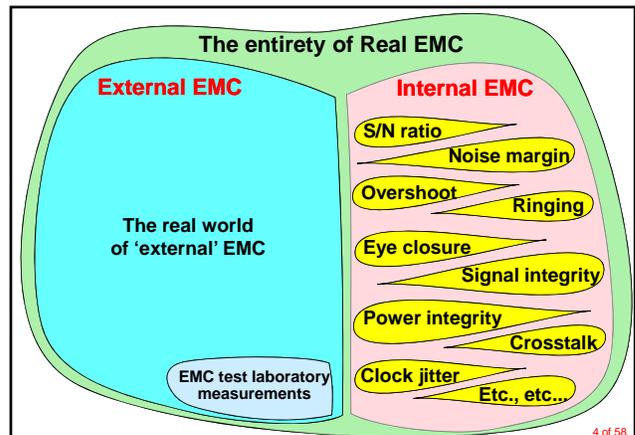
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It is all about electromagnetic compatibility (EMC)...

- Which can be "internal" or "external"...
 - EMC compliance (e.g. complying with the EMC Directive) is only a subset of the "external EMC" needed for customer satisfaction and low warranty costs
- The physics and Maxwell's equations are used, with some simplifications, by electromagnetic (EM) field simulators...
 - and they also lead to design principles that are *not* difficult to understand and use...
 - ▽ good EMC design engineers usually learn to visualise them



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Deriving easy EMC design principles

- The following slides summarise the physics and the Maxwell's...
 - ▽ *without using equations or difficult maths...*
 - leading to some design principles that are easy to visualise and easy to apply...
 - ▽ and proven over 30+ years to improve company financial performance...
 - and then apply them to an example electronic product



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AC versus DC

- The following EMC principles apply to all AC currents, whether they are associated with:
 - ▽ electrical power (DC or AC or RF, femtowatts to terawatts)
 - ▽ electronic signals (analogue, digital, switch-mode, RF, etc.)
 - ▽ noise (in any power supplies or signals)
- DC currents always flow "downhill" from the positive rail to 0V...
 - ▽ or uphill from the negative rail...
 - whereas AC and RF currents flow in any paths, regardless of DC voltage potentials, in any/all directions



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μ and ϵ continued...

- The routes taken by conductors, plus μ and ϵ , cause inductance (L) and capacitance (C)...
 - so **whenever** there is a fluctuating *voltage* (V) there is **always** an associated *current* (I)...
 - and vice-versa
- In insulators (e.g. PVC, air, FR4) μ and ϵ cause effects **similar to** inductance and capacitance...
 - so **whenever** there is a fluctuating *electric field* (E) there is **always** an associated *magnetic field* (H)
 - and vice-versa

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Permeability (μ) and permittivity (ϵ)

- Everything** in this universe has permeability (μ)...
 - associated with *inductive* energy, drawn as lines of magnetic (H) energy flow (flux)
- And** it also has permittivity (ϵ)...
 - associated with *capacitive* energy, drawn as lines of electric (E) energy flow (flux)
- And** it has resistivity (R) (except for superconductors)...
 - associated with energy *loss*, the conversion of EM energy flow into heat

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Everything that we think of as an AC voltage or current, is really a propagating EM wave...

- i.e. EM energy (Watts), propagating as a wave in the medium with a velocity, $v = 1/\sqrt{\mu\epsilon}$ m/s ...
 - at a speed close to 3.10^8 m/s when propagating in air/vacuum (but slower in other media)...
- and creating EM fields as it does so
- This is true for **every kind** of electrical activity...
 - whether mains 50Hz power, analogue, digital, switch-mode, PWM, radio-frequency (RF), microwaves, etc...
 - including all electrical or electronic "noises"

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The traditional way of representing an EM energy line vector (z) in 3D space, at an instant in time

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E and H fields associated with send and return conductors (shown in cross-section) (the EM power, P, is propagating along the conductors)

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Because of the Principle of Conservation of Energy...

- there is **always** a return current **into** any circuit node...
 - that is **identical in every way** to the send current out of that node, but opposite in phase
- The **send and return** currents from a circuit node (i.e. a propagating EM wave) are emitted **simultaneously**...
 - and propagate through the impedances of the various media (air, conductors, etc.)...
 - eventually meeting up to create what *we think of* as the send/return current loop

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EM power divides amongst all alternative paths according to their loop impedance

- In the “far field” of an EM source, E and H fields experience the “wave impedance”: $\sqrt{(\mu/\epsilon)}$...
 - in air or vacuum: $120\pi \Omega$ (approximately 377Ω)...
 - but always a lower Z in other media (PVC, FR4, etc.)
- But in the “near field” of an EM source, the wave Z can be much higher or lower than 377Ω ...
- And conductors add L, C and R, so can have impedances lower or higher than 377Ω

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The electricity does not all stay in the wire or PCB trace!

- Current flow splits among all possible loop paths...
 - whether they are conducted along metal, or induced/radiated through insulators (PVC, FR4, air, etc.)...
 - the proportion of current flowing in each parallel loop is inversely proportional to that loop’s impedance...
 - just like DC current splits between parallel capacitors
- EM energy propagation (i.e. all signals, data and power) only “cares about” loop impedances...
 - whether its currents flow in conductors, or insulators

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All power, signal and noise currents, (whether DM or CM) prefer to flow in the loops with the best EMC

- These are the loops that have the smallest areas...
 - therefore the smallest field patterns, therefore the best internal and external EMC...
 - although if a small loop suffers high-impedance resonance, it might not be the preferred path at that frequency
- All we have to do is make low-Z loops available, and the currents will naturally take them!
 - working with the laws of physics, instead of against them

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We could say that our products are trying to help us achieve good EMC!

- We often feel like our designs are fighting us over good EMC...
 - making our lives more difficult, as if the Laws of Physics were working against us
- But in fact, for any given arrangement of circuit conductors, shielding, etc....
 - Maxwell’s Equations ensure they are emitting the least EM fields that they can!

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Computer simulations of the return current path for a wire above a plane

A bent wire, 20mm above a chassis used as its return path

From Marco Klingner, “Modeling and Simulation of Powertrains for Electric and Hybrid Vehicles”, Workshop FR-AM-4-1, IEEE 2009 Int’l Symp. on EMC, Austin, TX, Aug 17-21, ISBN: 978-1-4244-4285-0 17 of 58

Return current path for wire above plane
 continued... (red dotted lines drawn by hand)

Showing the effects of frequency on the path taken by the return current (μ and ϵ dominate R above a few hundred Hz)

10 Hz	100 Hz
1 kHz	10 kHz
100 kHz	

No current in this area of the plane!

From Marco Klingner, “Modeling and Simulation of Powertrains for Electric and Hybrid Vehicles”, Workshop FR-AM-4-1, IEEE 2009 International Symposium on EMC, Austin, Texas, USA, Aug 17-21, ISBN: 978-1-4244-4285-0 18 of 58

All conductors are "accidental antennas"

- o "Antenna" means that the EM wave energy propagating along conductors...
 - ▾ that we call electrical/electronic power, signals, noise, etc. and measure as Volts and Amps...
- has a spatial field pattern...
- shaped by the impedances associated with (*what we are describing here as...*) its send/return current loop...
- which relate to the dimensions and structure of the conductors, their associated dielectrics (insulators), and all of their permeabilities and permittivities

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Accidental antennas continued...

- o When this EM energy "couples" with other conductors...
 - it creates "stray" currents and voltages in their impedances
- o This can be called "accidental antenna" behaviour...
 - except when we use it to create *intentional* antennas, for radio and wireless communications...
 - and other uses of radiated EM energy (e.g. medical diathermy, induction heating, etc.)

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The "accidental antenna" effect works in reverse too

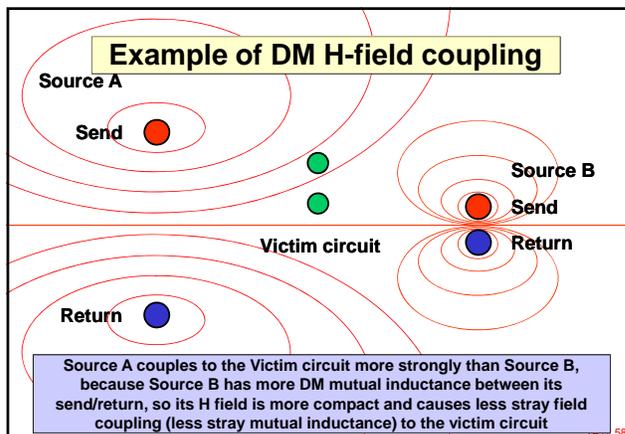
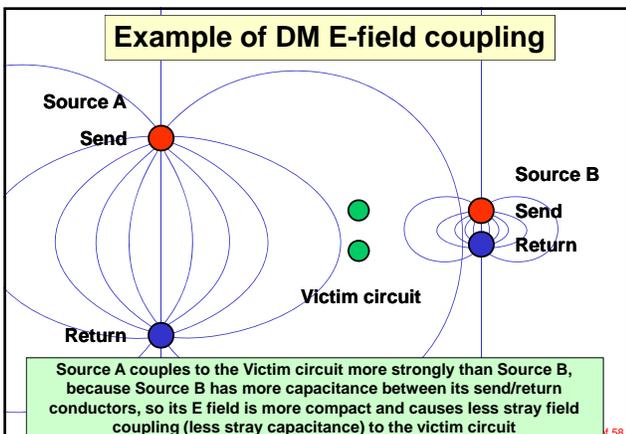
- o When a conductor is *exposed* to E, H or EM waves in its insulating medium (e.g. air)....
 - its electrical/electronic circuit experiences the same voltage and current noise as we would need to create if we wanted to generate the *exact same* field pattern and field strength at the surface of the conductor...
 - this is called the Principle of Reciprocity
- o So a conductor that causes EM emissions, will suffer noise "pick-up" in exactly the same way (i.e. designing for low emissions, improves immunity)

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Current loop shape defines field patterns

- o The larger the area of the send/return current loop, the larger its impedance (ignoring resonances for now), and the larger its E and H field patterns...
 - so its stray coupling with other circuits is larger and a higher percentage of the wanted power or signal is converted into "common mode" noise in different loop...
 - ▾ increasing the distortions and noises in wanted waveforms, and worsening both EM emissions and EM immunity
- o **So it is important to minimise the send/return current loop areas, for all circuits...**
 - to maximise both SI and EMC

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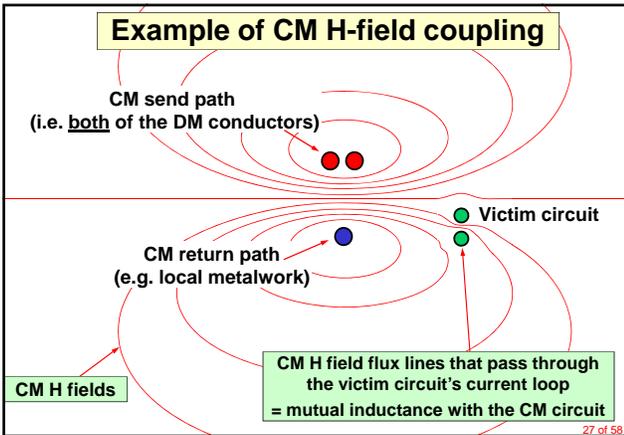
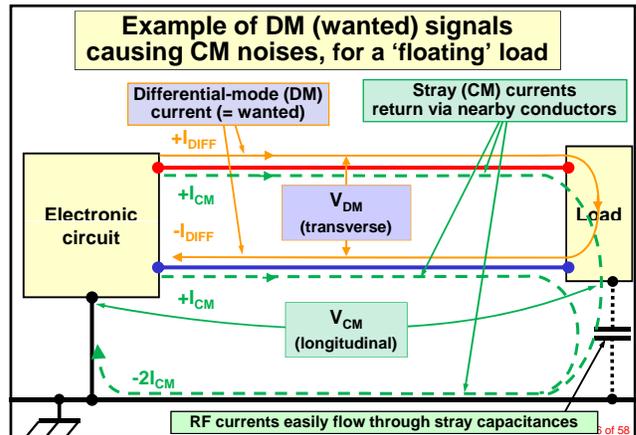
Power and signals in conductors have two different modes of wave propagation

- **Differential Mode** (also called transverse or metallic mode) caused by the “wanted” power and signals...
- **Common Mode** (also called longitudinal or antenna mode) caused by the stray, leaked, “unwanted” EM energy...
 - ▾ when a DM loop's EM fields couple with another conductor

o Some of the EM energy travels as CM current, also in a loop...

- which is almost always the main cause of EM emissions and immunity (i.e. the worst “accidental antenna” effects) over 1MHz - 1GHz

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Resonating conductors make perfect accidental antennas

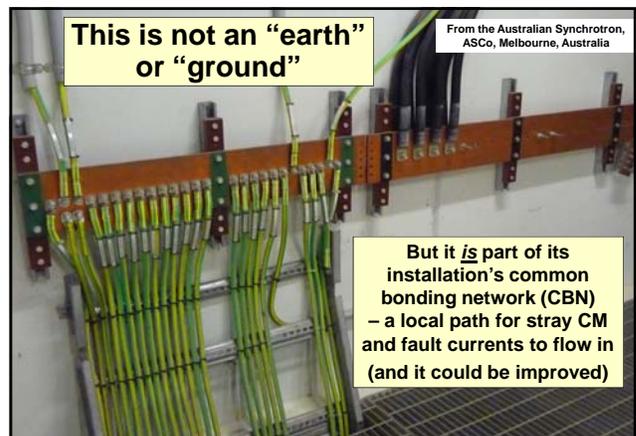
- o Two causes of resonance in conductive structures:
 - when the L and C impedances happen to be equal...
 - when geometry interacts with wavelength to create “standing waves”
- o At resonant frequencies, loop impedances go wild:
 - ▾ as low as the stray series resistance (mΩ), or as high as the stray shunt resistance (kΩ, MΩ)...
 - and this amplifies the accidental antenna effects (low Z increases H coupling, high-Z increases E coupling)...
 - ▾ by up to 100 times (40dB), sometimes even more

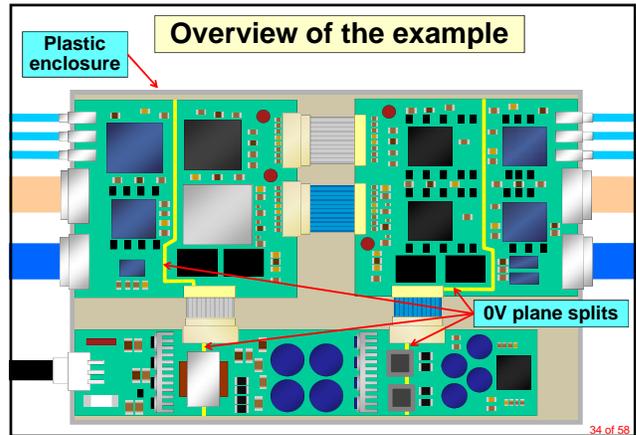
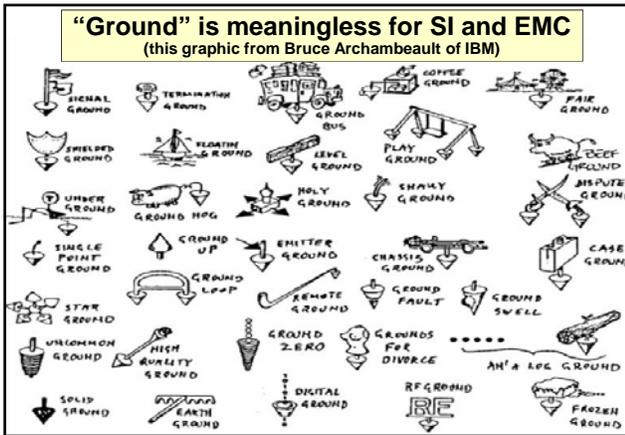
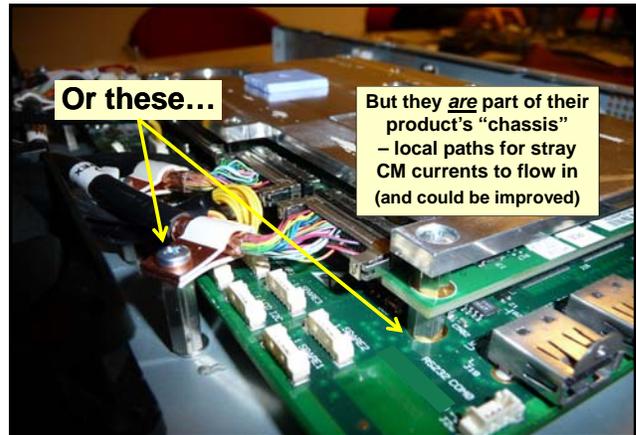
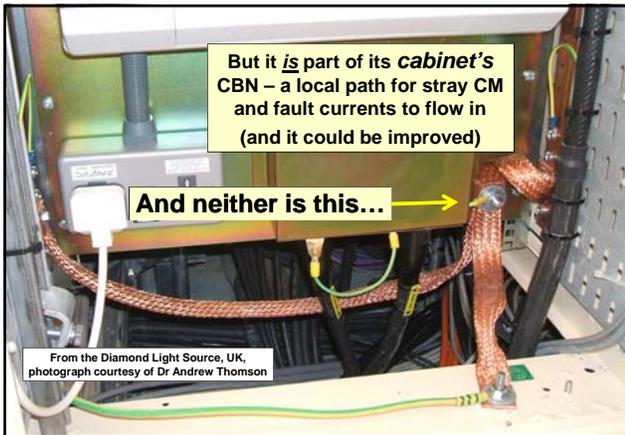
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“Earth” or “Ground” as a perfect sink for current or voltage cannot exist...

- o All conductors have impedance, and behave as accidental antennas...
 - so there can never be a perfect “sink” for EM energy at any frequency...
- o In any case, all currents flow in closed loops...
 - so even if a zero-impedance EM energy sink *could* exist...
 - ▾ (but it can't, even if using superconductors with no resistance)...
 - it *wouldn't* play any part in SI or EMC

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The assumptions made in its design

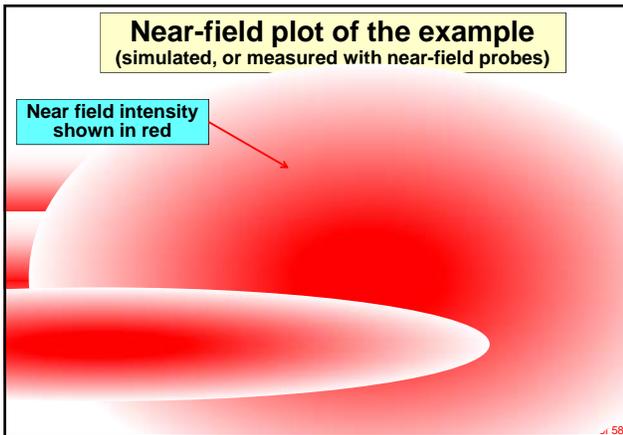
- Single-point "earthing" or "grounding", using 0V plane splits between (and on) the PCBs...
 - assumed to keep devices' circulating return currents confined to certain circuit areas, preventing crosstalk of noise between them (e.g. digital noise in analogue)...
 - known to be bad practice, when microprocessors and switch-mode converters are used, since 1980 (or earlier)
- Lowest BOM cost assumed to give the most profitable product...
 - known to be incorrect since 2000 (when time to market became the most important issue for a product's profitability)

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The real-life example continued...

- I see *many* designs like this every year...
 - they have poor functional performance at first, especially poor S/N ratios, unreliable software...
 - requiring many design iterations to solve, causing project delays, increased costs and reduced profitability
 - and they fail EMC tests at first, requiring many design iterations to solve...
 - causing more delays and more project costs, requiring filters and shielding that increase BOM cost, reducing profitability even more
 - and their higher-than-necessary levels of warranty returns erode profitability even more

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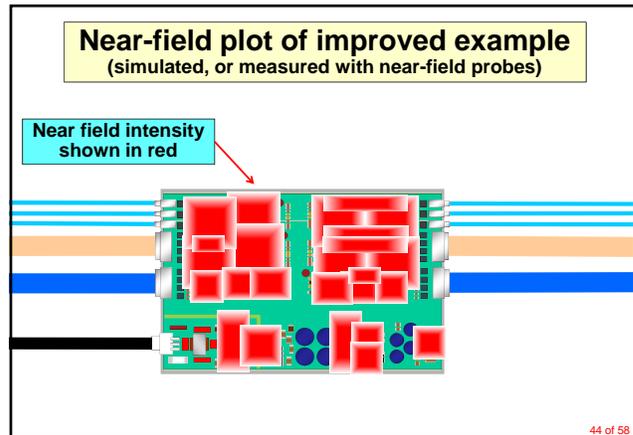
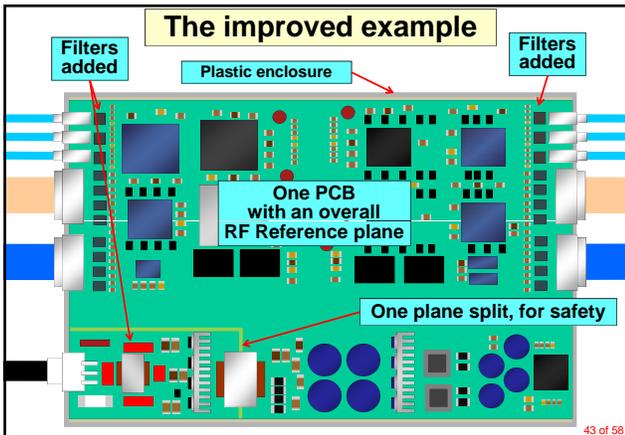
- What do such near-fields mean?**
- On the PCB – they are the wanted DM signals...
 - plus DM and CM crosstalk and noise, that cause reduced S/N ratios in analogue circuits, and reduced digital noise margins (unreliable software)
 - In EMC testing...
 - high levels of “far field” emissions, and poor immunity
 - In Real Life...
 - a lower proportion of satisfied customers (hence increased cost of sales) and higher levels of warranty costs
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- Making improvements**
- Understanding that *all* currents (including stray CM “noise” currents) flow in closed loops...
 - and that loop shape and area govern field patterns...
 - and that current prefers to flow in loops with less Z...
 - ∇ hence the smallest field patterns and the best internal and external EMC
 - means we can make a number of improvements to the circuit design and PCB layout...
 - to provide all DM and CM currents with smaller loops...
 - which they will naturally take: improving EMC
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- Improvement #1 – create an RF Reference**
- Replace the multiple PCBs with a single PCB...
 - that has a common conductor (almost always at 0V) over its entire area, called the *RF Reference*...
 - a solid, continuous, copper PCB plane, that lies underneath and extends beyond all devices and traces
 - which achieves very low impedance (Z)...
 - ∇ depends on devices and EMC spec’s, but always $\ll 1\Omega$...
 - over the frequency range that must be controlled to avoid causing/suffering EMI...
 - ∇ i.e. all of the DM frequencies created in its devices, and all of the frequencies in the operational environment
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- Improvement #2 – DC supply decoupling**
- Design the decoupling between DC power rails and RF Reference to achieve low Z...
 - ∇ depends on devices and EMC spec’s, but always $\ll 1\Omega$...
 - over the frequency range that needs to be controlled to prevent the product causing/suffering EMI
 - Now AC DM currents in the DC rails can flow in tiny loops very close to the devices that cause them...
 - so they do, and do not flow widely in the RF Reference or power distribution network...
 - making small areas of DM near-fields that create little CM
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- Improvement #3 – cable filtering**
- Add direct bonds or filters to the RF Reference on *all* traces connected to off-PCB conductors...
 - ∇ whatever their electrical/electronic/other purpose (including mechanical, hydraulic, pneumatic, etc.)...
 - at least using a capacitor to the RF Reference...
 - ∇ (often making more complex filters by combining capacitors with resistors and/or soft-ferrites, too many details for here)...
 - placed where the traces connect to the conductors...
 - to provide low-Z paths for CM currents that would otherwise “leak” from the PCB into the conductors...
 - ∇ Z depends on devices and EMC spec’s, but always $\ll 1\Omega$
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These good EMC design techniques work exactly as well for immunity, as they do for emissions...

- because they employ the fundamentals of electromagnetism...
- to make field patterns and wave propagation as compact as possible...
- dramatically reducing EM coupling, reducing emissions, and improving immunity...
- thereby improving: internal EMC (PI and SI); external EMC; and reliability

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Conclusions

- o All electrical and electronic activities are really EM energy travelling as waves...
 - and connecting to safety earth/ground has no effect on them so is *unimportant and unnecessary*
- o We can easily design circuits and PCBs to create small, low-Z current loops for both the wanted DM and the stray CM currents...
 - the EM waves naturally prefer to flow in these routes...
 - by working *with the laws of physics*, we automatically achieve very compact field patterns...
 - best for internal and external EMC, and financial success

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Cost-effective EMC Design — by Working *With* the Laws of Physics

the end

Find more information on this topic at interferencetechnology.com

For questions regarding this webinar or any of the topics we covered please email info@interferencetechnology.com


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Some useful references

- o "The Physical Basis of EMC"
 - Keith Armstrong, Nutwood UK, October 2010
 ISBN: 978-0-9555118-3-7
 purchase from www.emcacademy.org/books.asp
- o EMC Design Techniques for Electronic Engineers Chapter 2 (identical to "The Physical Basis of EMC" above)
 - Keith Armstrong, Nutwood UK 2010
 ISBN: 978-0-9555118-4-4
 purchase from www.emcacademy.org/books.asp
- o "Grounds for Grounding"
 - Elya B Joffe, Kai-Sang Lock, IEEE Press, John Wiley & Sons, Inc., 2010 ISBN: 978-04571-66008-8

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Some more slides....

- For if we have time, and/or to help answer questions....

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Skin Effect

- E-field coupling induces a displacement current on the surface of a metal object
- H-field coupling induces an eddy current flowing *in the metal itself*
 - creating a field opposing the incoming field (Lenze's Law)
- RF induced currents flow mostly near the surface of a metal conductor...
 - depending on its resistivity and permeability...
- this is called the **skin effect**...
 - and the higher the frequency and/or metal conductivity or permeability - the thinner the "skin" of the current

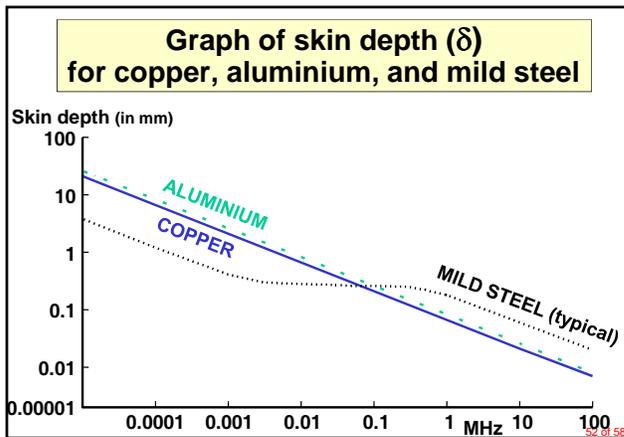
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Examples of cross-sectional current density in a copper sheet

Example at d.c Uniform current density

Example of surface currents at 1MHz ($\delta = 0.07\text{mm}$)

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RF currents cannot flow through a sheet of metal !

- Above a certain frequency, most of the current has to flow around metal **edges** (including the edges of holes, apertures, joints, gaps, seams)...
- No current loop can ever have zero impedance...
 - so some return current still flows in other paths, creating fields that couple noise into other circuits...
 - so we use skin effect to help contain DM and CM current loops, to further minimise field patterns...
 - especially effective if we can't make the loops small enough not to have high impedance resonances in the frequency range we need to control

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Skin effect and filter assembly

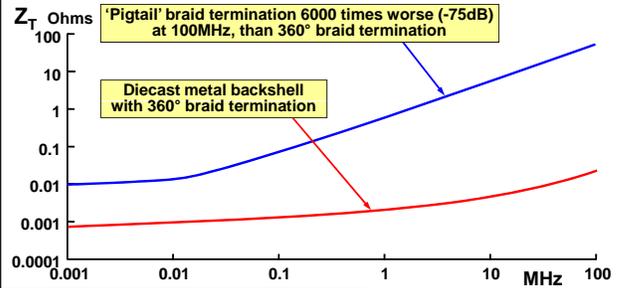
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Improvement #4 – cable shielding

- o Add shielding to **all** unfiltered and unbonded off-board conductors...
 - to contain the CM currents that would otherwise “leak” out of (or into) the conductors as EM fields
 - shielding can also be used in addition to filtering
- o Use 360° shielding throughout...
 - including the shields’ connections to the RF Reference
 - ▾ too many details to go into here, except don’t use pigtailed to connect cable shields

Pigtails are very bad for cable shields!

Example of measurements on 25-way subminiature D-type, developed from page 27 of “Analysis of Electromagnetic Shielding of Cables and Connectors (keeping currents/voltages where they belong)”, Lothar O. (Bud) Hoelt, PhD, IEEE, 2002



Lower Z_T = better shielding effectiveness (SE)

Improvement #5 – PCB shielding

- o The enclosure can be converted from plastic to metal (or metallised)...
 - and RF-bonded to the PCB’s RF Reference
- o Alternatively, shielding can be carried out at PCB level...
 - by electrically bonding metal (or metallised) boxes onto the RF Reference
- o Either will help contain EM fields that have not been sufficiently constrained...
 - by devices and design of circuits, decoupling and PCB

Skin effect and cable shielding

