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

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interference technology

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

- but 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 to 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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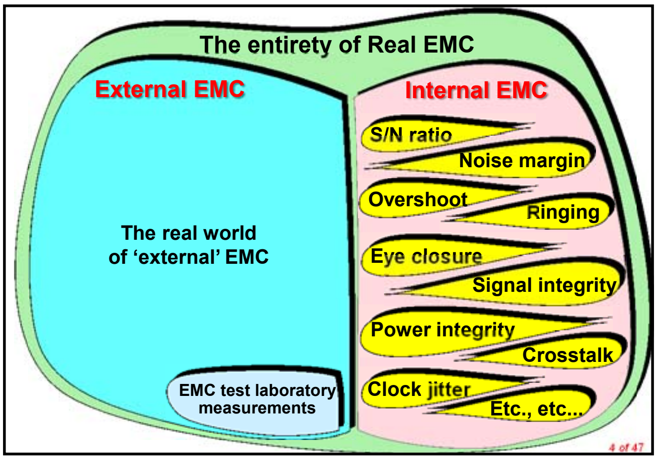

Deriving easy EMC design principles

■ 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 electromagnetic principles apply to *all* 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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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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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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Everything that we *think of* as an AC voltage or current, is really a propagating EM wave…

- i.e. EM energy (in Watts), propagating as a wave in the medium with a velocity, $v = 1/\sqrt{(\mu\varepsilon)}$ m/s …
  - at a speed close to 3.10⁸ 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 60Hz power, analogue, digital, switch-mode, PWM, radio-frequency (RF), microwaves, etc...
    - including all electrical or electronic "strays" or "noises"

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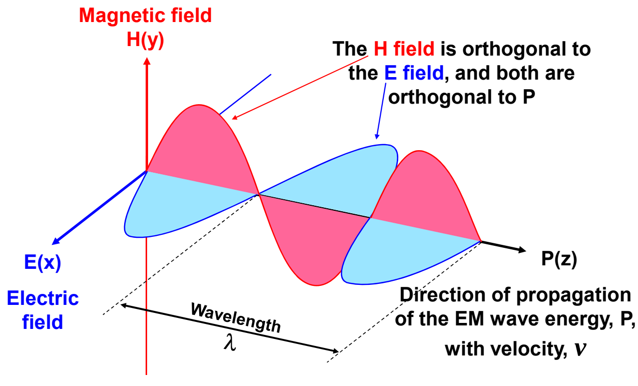
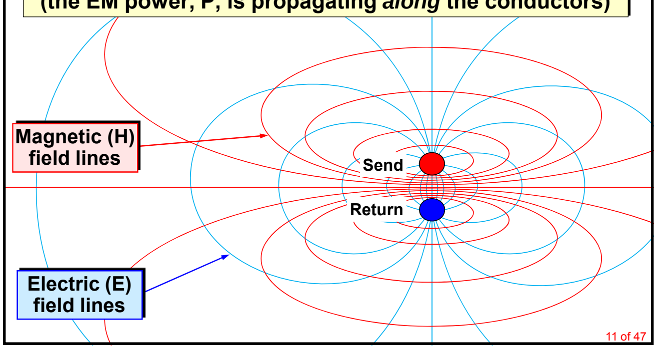


The traditional way of representing an EM energy line vector (z) in 3D space, at an instant in time

E and H fields associated with send and return conductors (shown in cross-section)

(the EM power, P, is propagating *along* the conductors)



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": √(μ/ε)…
  - in air or vacuum: 120π Ω (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 resistors
- 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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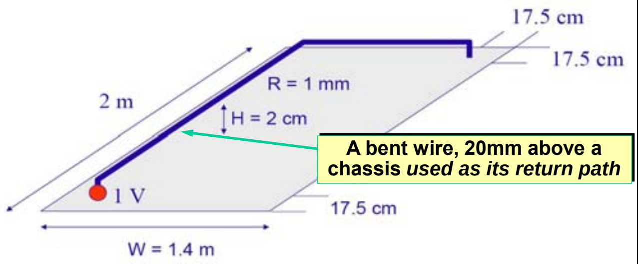
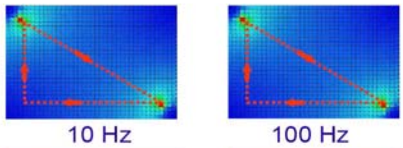
Computer simulations of the return current path for a wire above a plane

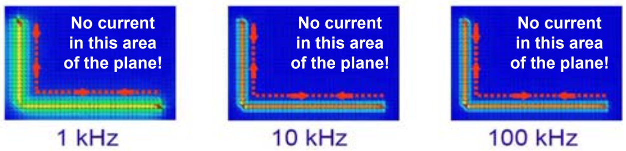


From Marco Klinger, "Modeling and Simulation of Powertrains for Electric and Hybrid Vehicles",, Workshop FR-AM-4-1, IEEE 2009 Int'l Symp. on EMC, Austin, TX, Aug 17-21, ISBN: 978-1-4244-4285-0

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)





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All conductors are "accidental antennas"

- "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...

- When this EM energy "couples" with other conductors…
  - it creates "stray" currents and voltages in their impedances
- 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

- 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
- So a conductor that causes EM emissions, will suffer noise "pick-up" in exactly the same way (i.e. designing for low emissions also improves immunity)

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Current loop shape defines field patterns

- 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
- So it is important to minimise the areas of the send/return current loops, for all circuits...
  - to maximise SI, PI and EMC

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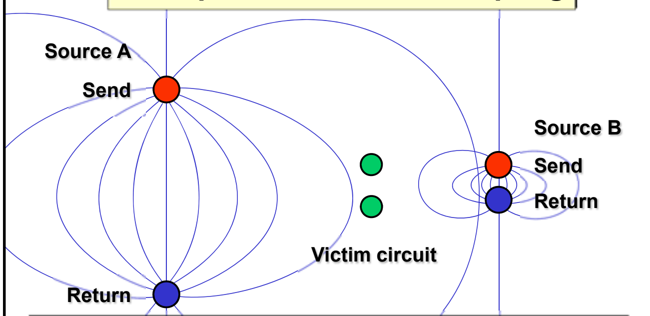
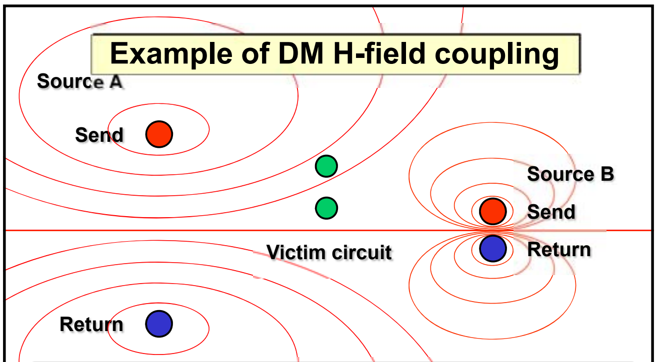
Example of DM E-field coupling



Source A couples to the Victim circuit more strongly than Source B, because Source B has more capacitance between its send/return conductors, so its E field is more compact and causes less stray field coupling (less stray capacitance) to the victim circuit

Example of DM H-field coupling



Source A couples to the Victim circuit more strongly than Source B, because Source B has more DM mutual inductance between its send/return, so its H field is more compact and causes less stray field coupling (less stray mutual inductance) to the victim circuit

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 stray, leaked, "unwanted" EM energy…
  - when a DM loop's EM fields couple with another conductor

■ **Some of the EM energy travels as CM current, which also flows in loops...**

- almost always the main cause of EM emissions (i.e. the worst "accidental antenna" effects) over 1MHz - 1GHz

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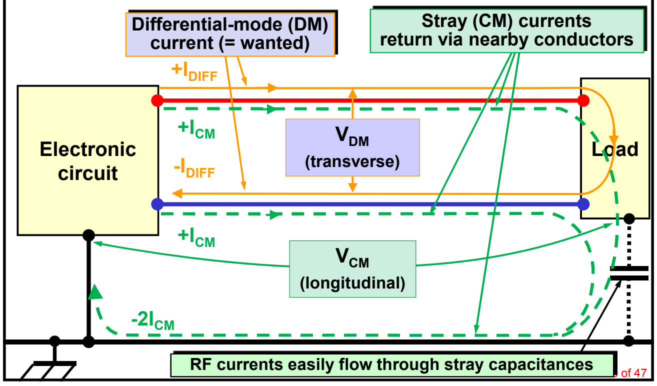
Example of DM (wanted) signals causing CM noises, for a 'floating' load



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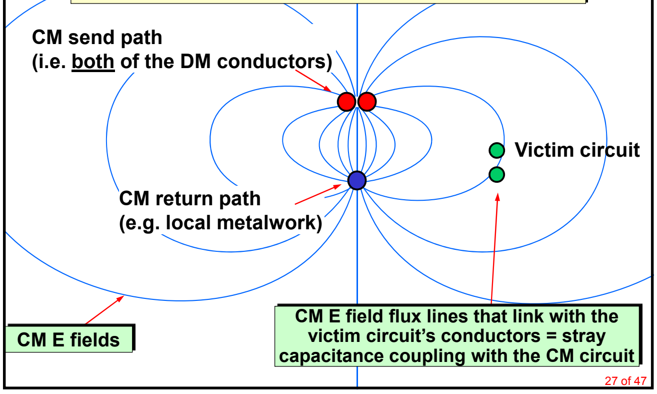
Example of CM E-field coupling



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Resonating conductors make perfect accidental antennas

■ **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"

■ **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...

■ ***All*** **conductors have impedance, and behave as accidental antennas…**

- so there can never be a perfect "sink" for EM energy at any frequency...

■ **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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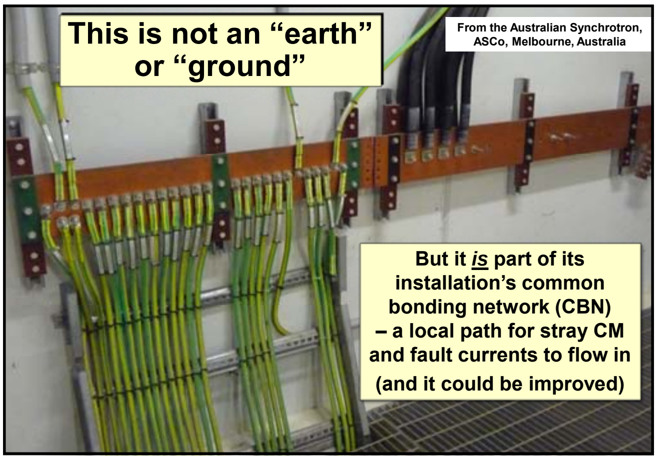

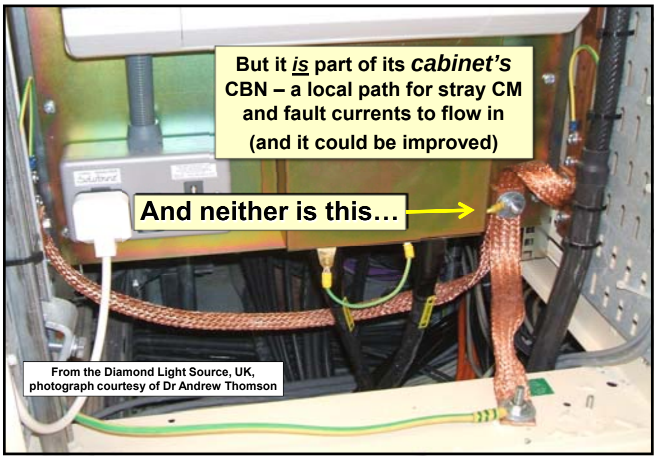

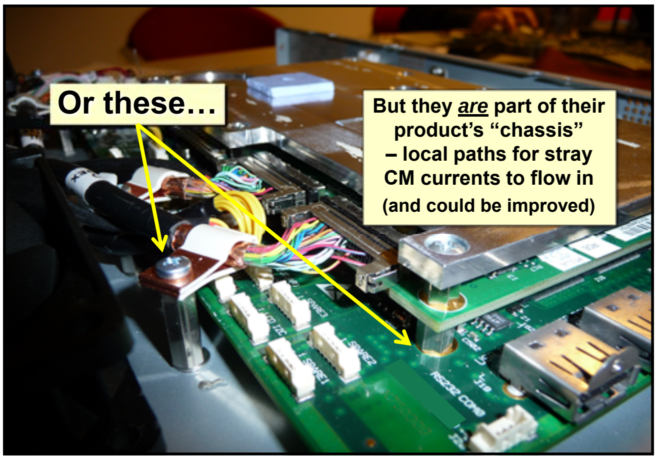

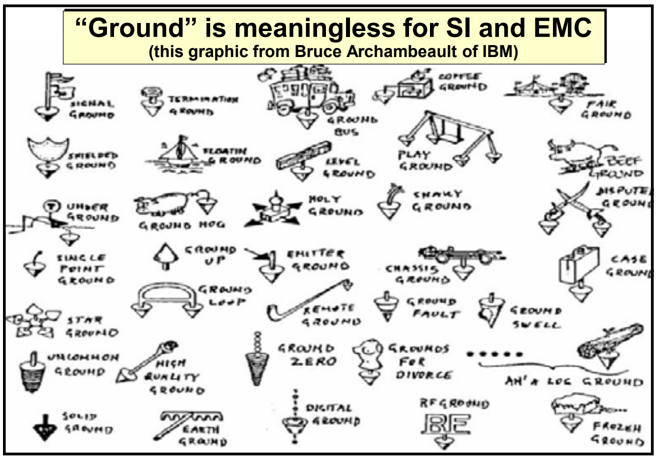

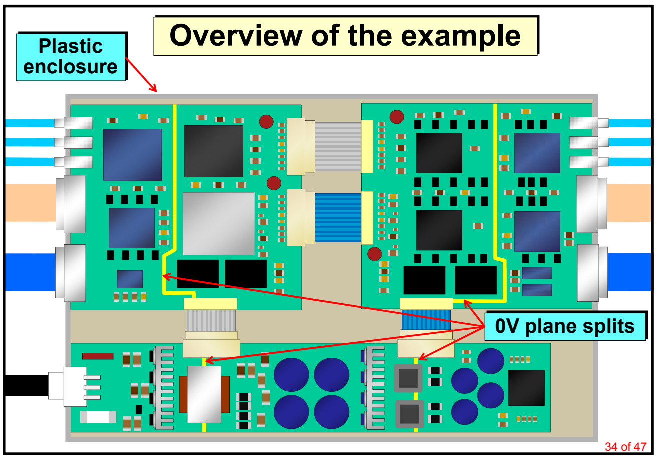

The assumptions made in its design

- 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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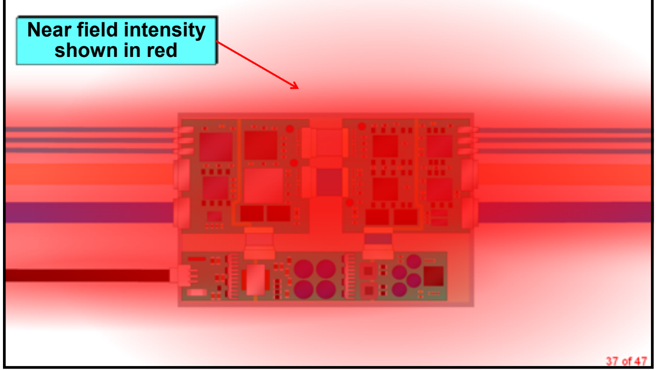
Near-field plot of the example
(simulated, or measured with near-field probes)



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, giving 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 <<1Ω…
  - 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…
    - the Z needed depends on devices and EMC spec's, but should generally be <<1Ω…
    - 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 cables…
    - 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 off-board cables…
  - to provide low-Z paths for CM currents that would otherwise "leak" from the PCB into the off-board cables…
    - The Z depends on devices and EMC spec's, but should be <<1Ω

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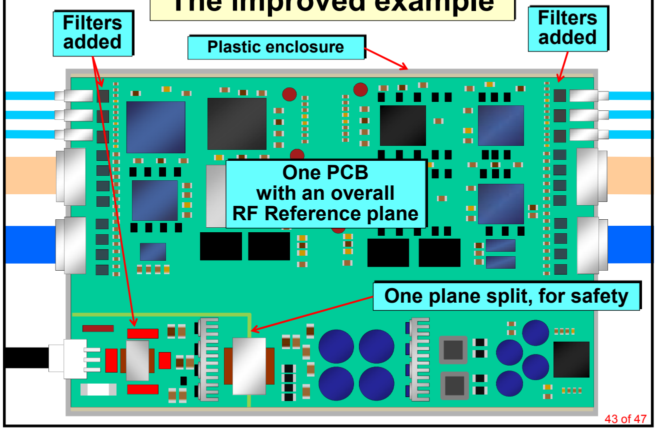
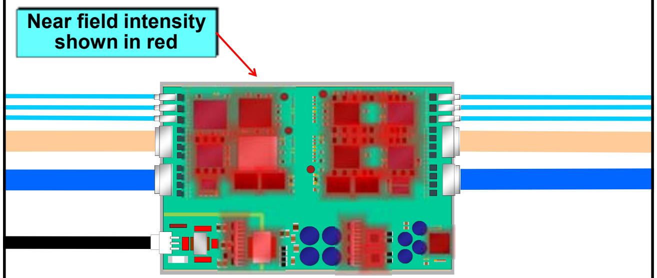
The improved example



Near-field plot of improved example

(simulated, or measured with near-field probes)



These good EMC design techniques work exactly as well for immunity, as they do for emissions…

– because they employ the fundamentals of electromagnetic propagation…

– 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

- All electrical and electronic activities and noises are really EM energy travelling as waves…
  – and connecting to safety earth/ground has no effect on them so is *unimportant* and *unnecessary*
- 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 for 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

- "The Physical Basis of EMC"
  – Keith Armstrong, Nutwood UK, October 2010
  ISBN: 978-0-9555118-3-7
  purchase from www.emcacademy.org/books.asp
- 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
- "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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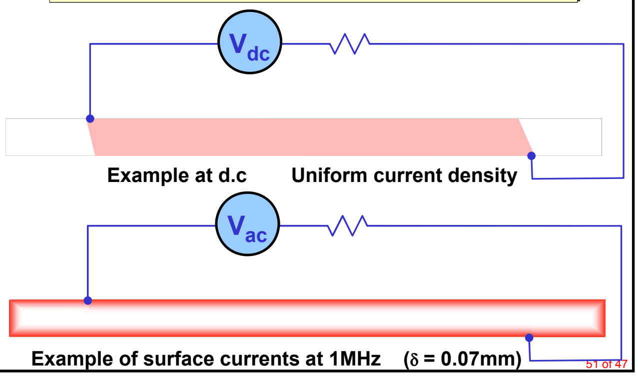
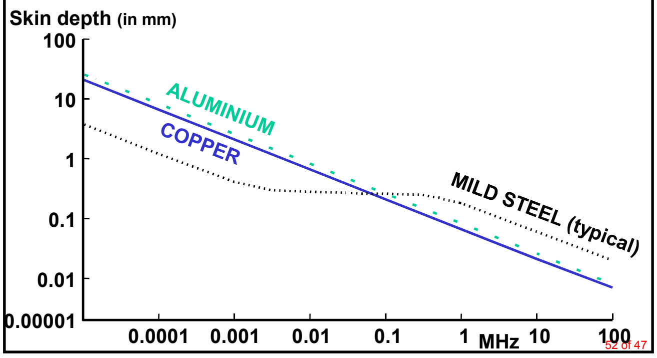
Examples of cross-sectional current density in a copper sheet



Graph of skin depth (δ) for copper, aluminium, and mild steel



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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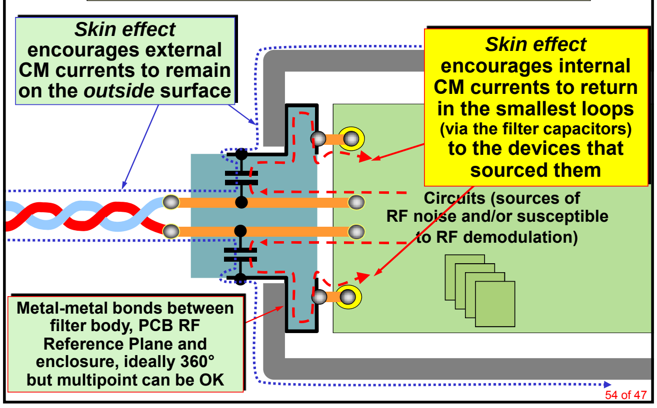
Skin effect and filter assembly



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Improvement #4 – cable shielding

- **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
- **Use 360° shielding throughout…**
  - including the shields' connections to the RF Reference
    - too many details to go into here, except don't use pigtails to connect cable shields

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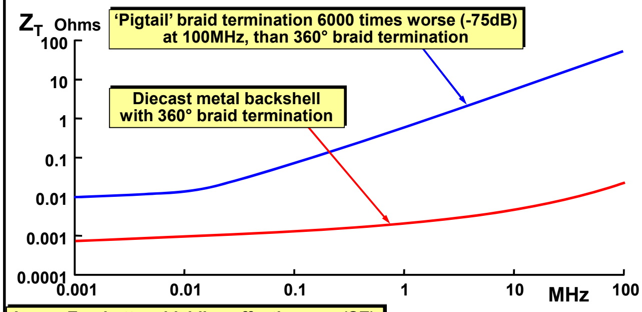
Pigtails are very bad for cable shields!

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) Hoeft, PhD, IEEE, 2002



Lower Z_T = better shielding effectiveness (SE)

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Improvement #5 – PCB shielding

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

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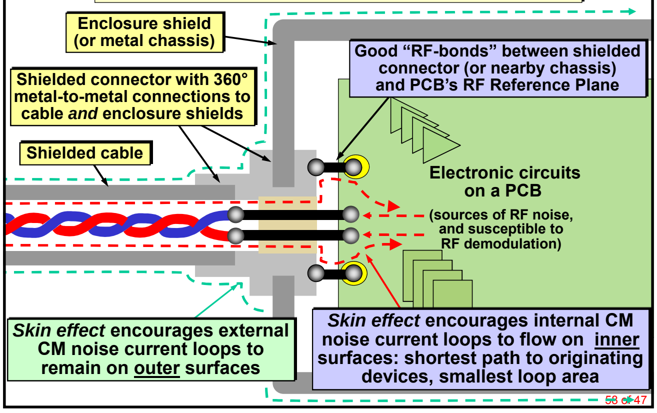
Skin effect and cable shielding



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