

EMI Troubleshooting Commandments

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“Whatever you do, do it to the purpose; do it thoroughly, not superficially. Go to the bottom of things. Any thing half done, or half known, is in my mind, neither done nor known at all. Nay, worse, for it often misleads.”

-Lord Chesterfield

“Everybody is ignorant, only on different subjects.”

-Will Rogers

“Let’s put the cookies on a shelf where we all can reach them.”

-Dave Ramsey

“The EMI problem is caused by the interaction of the power supply with my box.”

-EMI Test Customer

Topics

1. The source of the Commandments
2. Overview/Motivation
3. The Commandments are golden
4. Test early and often
5. THE EMI TROUBLESHOOTING COMMANDMENTS

Topics

1. The source of the Commandments

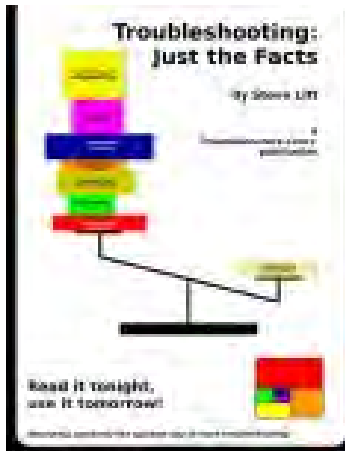
2. Overview/Motivation
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The Source of the Commandments (1)

“See if there’s gas in the tank, son, before you overhaul the carburetor.” *Richard Glenn Shelby*
(My Dad)



The Source of the Commandments (2)



www.troubleshooters.com

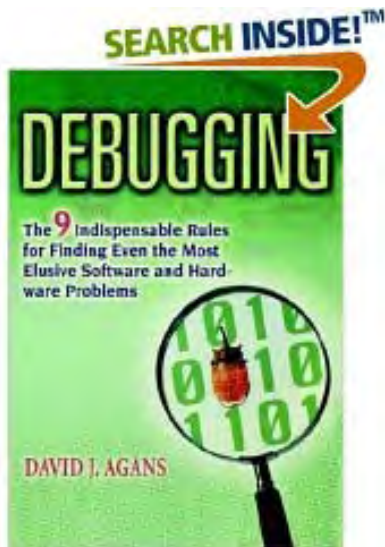
“Troubleshooting: Just the Facts”

Steve Litt

Publisher: Self-published

ISBN: To be determined

\$8.95 on www.troubleshooters.com



www.debuggingrules.com

“Debugging: The 9 Indispensable Rules for Finding Even the Most Elusive Software and Hardware Problems”

David J. Agans

Publisher: Amacom (September 12, 2006)

ISBN-10: 0814474578

ISBN-13: 978-0814474570

\$16.16 on Amazon

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Overview/motivation

- **Why** learn a process on how to logically troubleshoot EMI problems?
 - **Makes you focus on the fundamentals**
 - **Makes you follow a process**
 - Makes life easier
 - Makes you look like a genius
 - Reduces stress
 - When opportunity comes, you're the man/woman
- What this presentation is: troubleshooting *philosophy/fundamentals*, i.e. **How to get your mind right** (with apologies to Clayton Paul)
- What this presentation is not:
 - How to use specific EMI troubleshooting tools
 - Full of math
- Presentation based on “Grandpa” Shelby’s experience:
 - MIL-STD-461-based testing
 - 28Vdc/120Vdc dedicated return power systems
 - shielded boxes
 - shielded data cables
 - waiver process

If you must have math....

7.19 The angular momentum of a distribution of electromagnetic fields in vacuum is given by

$$\mathbf{L} = \frac{1}{4\pi c} \int d^3x \mathbf{x} \times (\mathbf{E} \times \mathbf{B})$$

where the integration is over all space.

(a) For fields produced a finite time in the past (and so localized to a finite region of space) show that, provided the magnetic field is eliminated in favor of the vector potential \mathbf{A} , the angular momentum can be written in the form

$$\mathbf{L} = \frac{1}{4\pi c} \int d^3x \left[\mathbf{E} \times \mathbf{A} + \sum_{j=1}^3 E_j (\mathbf{x} \times \nabla) A_j \right]$$

The first term is sometimes identified with the “spin” of the photon and the second with its “orbital” angular momentum because of the presence of the angular momentum operator $\mathbf{L}_{op} = -i(\mathbf{x} \times \nabla)$.

(b) Consider an expansion of the vector potential in the radiation gauge in terms of plane waves:

$$\mathbf{A}(\mathbf{x}, t) = \sum_{\lambda} \int \frac{d^3k}{(2\pi)^3} [\boldsymbol{\epsilon}_{\lambda}(\mathbf{k}) a_{\lambda}(\mathbf{k}) e^{i\mathbf{k}\cdot\mathbf{x} - i\omega t} + \text{c.c.}]$$

The polarization vectors $\boldsymbol{\epsilon}_{\lambda}(\mathbf{k})$ are conveniently chosen as the positive and negative helicity vectors $\boldsymbol{\epsilon}_{\pm} = (1/\sqrt{2})(\boldsymbol{\epsilon}_1 \pm i\boldsymbol{\epsilon}_2)$ where $\boldsymbol{\epsilon}_1$ and $\boldsymbol{\epsilon}_2$ are real orthogonal vectors in the x-y plane whose positive normal is in the direction of \mathbf{k} .

Show that the time average of the first (spin) term of \mathbf{L} can be written as

$$\mathbf{L}_{spin} = \frac{1}{2\pi c} \int \frac{d^3k}{(2\pi)^3} \mathbf{k} [|a_{+}(\mathbf{k})|^2 - |a_{-}(\mathbf{k})|^2]$$

Can the term “spin” angular momentum be justified from this expression? Calculate the energy of the field in terms of the plane wave expansion of \mathbf{A} and compare.

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These troubleshooting commandments are “golden”

- They are universal: apply them to any troubleshooting situation on any system
- Fundamental: provide a framework for and guide the choice of specific tools and techniques that apply to your system
- Essential: you can't troubleshoot effectively without following ALL of them EVERY TIME

“Chance favors the prepared mind.” *Louis Pasteur*
- Obvious, but not easy....

“They who want milk should not sit in the middle of the field and wait for a cow to back up to them.”
Lillian Katz
- Easy to remember, once you get in the habit of using them

“Habit is a cable; we weave a thread of it everyday, and at last we can not break it.” *Horace Mann*

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“Grandpa” Shelby’s Soapbox: Test Early and Often

“Fixing a qual unit is like overhauling an engine through the tailpipe.” *Grandpa Shelby*

- Don’t let the qualification/production unit be the first one to darken the door of the EMI chamber
- The earlier in the design cycle you involve EMI testing the more successful your project will be
- Waiver = $\text{Ignorance}_{req} + \text{Ignorance}_{emi} + \text{IEDP} + \text{SOS}$

where:

Ignorance_{req} is ignorance of the electrical and EMI requirements

Ignorance_{emi} is ignorance of EMI physics and EMI design

IEDP is Ignoring EMI Development Testing

SOS is “Success Oriented Scheduling” a.k.a. “let’s develop an unrealistic schedule by abandoning logic, close our eyes and ears, and wish a lot”

“I only changed these two things from the previous design. Those things can’t change the EMI characteristics, so it’s all good.” *EMI Test Customer*

“You got trouble comin’. Big trouble.” *Sheriff Buford T. Justice*

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The EMI Troubleshooting COMMANDMENTS

1. Adopt the right attitude
2. Acquire the right technical knowledge
3. Follow the right troubleshooting process

“Excellence is achieved by the mastery of fundamentals.” *Vince Lombardi*

**“The vital, successful people I have met all had one common characteristic.
They had a plan.”**
Marilyn Van Derbur

The EMI Troubleshooting COMMANDMENTS

1. Adopt the right attitude

2. Acquire the right technical knowledge
3. Follow the right troubleshooting process

Adopt the Right Attitude (1)

“You cannot always control your circumstances, but you can always control your own thoughts.” *Charles E. Popplestone*

- Troubleshooter’s Philosophy, Part 1:
Relax: Believe in the process and troubleshooting will be easy
- Troubleshooter’s Philosophy, Part 2:
Measure more, think less
- Troubleshooter’s Philosophy, Part 3:
Don’t try to fix it, just try to narrow it down
- Troubleshooter’s Mantra:
How can I narrow it down just one more time?

“Sticking to it is the genius.” *Thomas Edison*

Adopt the Right Attitude (2):

EMI is NOT voodoo

“Don’t count on your education to make you wise.” *John Pagent*

- EMI is:
 - Not taught in schools
 - Physics in action
 - All the things not included in the circuit diagram
 - Invisible
- The “voodoo effect” is caused by Dominant Effect (Clayton Paul)
 - Assume: at some frequency, total emissions are due to 2 mechanisms: $E_1 + E_2$
 - Assume: $E_1 \gg E_2$
 - If you apply an EMI mitigation technique (e.g., ferrite) that only works on E_2 , the total emissions are NOT reduced
 - You say “Ferrites don’t work. EMI is voodoo!”
 - Reality is that you weren’t mitigating the dominant effect
- When things get weird, remember: physics holds in every lab
 - $V = IR$
 - Ferrites work
 - Faraday cages contain electromagnetic energy

The EMI Troubleshooting COMMANDMENTS

1. Adopt the right attitude

**2. Acquire the right technical
knowledge**

3. Follow the right troubleshooting process

Acquire the Right Technical Knowledge

You need three types of technical knowledge for EMI troubleshooting:

1. Basic knowledge of electronics

- Circuits
- Filters
- Power supplies
- Test equipment

2. Sufficient knowledge of the equipment under test (EUT). How much?

- Enough to draw a block diagram of the system (mental model)
- Enough to know how it operates

3. Sufficient knowledge of EMI. How much?

- Basic EMI
- Know what's reasonable

Sufficient knowledge of the EUT (1)

- Develop the “Mental Model” of the equipment under test (EUT): draw block diagrams

- A useful mental model must have:
 1. Correct amount of detail: detailed enough to show potential tests and test points, but not so detailed that you drown in it
 2. Accuracy: if it’s not accurate, you’re chasing your tail
 3. Modularity: necessary to approximate a binary search
 4. Concreteness: big symbols, color, big legible writing (make it real to you)

- Use a multi-level Mental model as needed to avoid clutter

- Draw it out on PAPER in PENCIL

Sample Mental Model: Simple computer

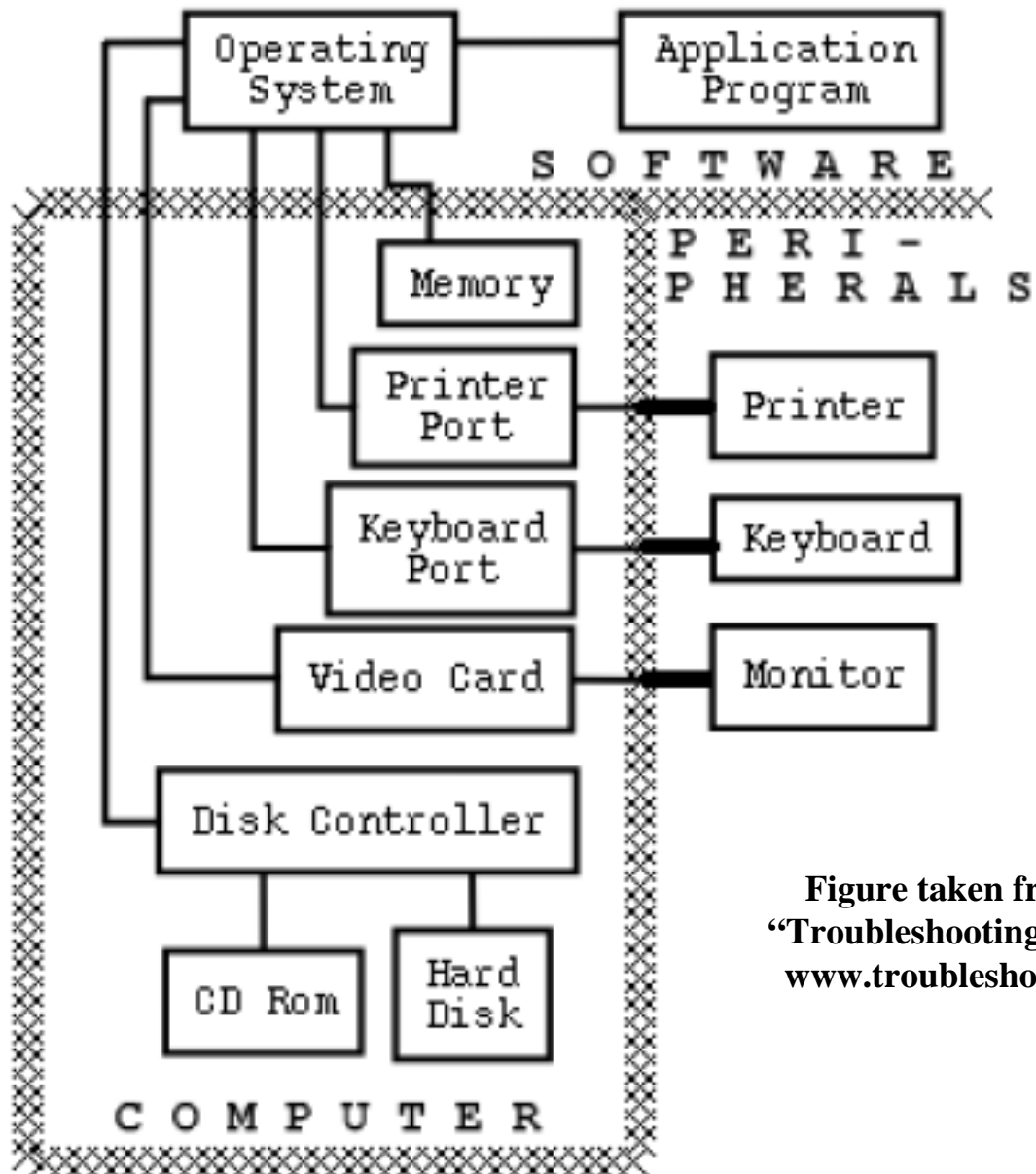


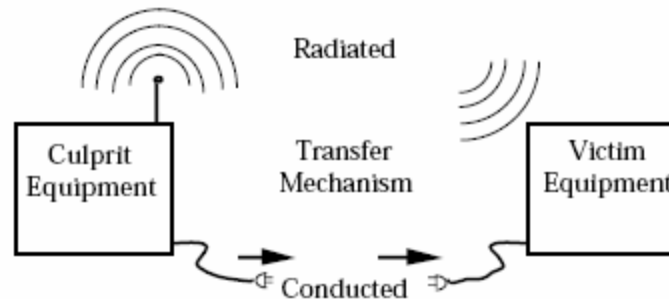
Figure taken from Litt, Steve, "Troubleshooting: Just the Facts", www.troubleshooters.com, 2007

Sufficient knowledge of the EUT (2)

- List of intentional system frequencies
- How components are connected together
- Operating modes
- Intended operation
- Look it up: don't guess at how something works

(VERY) Basic EMI Physics

- Source, coupling, receptor model



- Transfer mechanisms

- Common impedance
- Electric field (near-field)
- Magnetic field (near-field)
- Electromagnetic (far-field)

- Ideal EMI reduction order

- Reduce/eliminate source
- Reduce/eliminate transfer mechanism
- Make receptor more immune

- “Hertz hurts” in EMI: frequency makes life interesting

- Capacitors become inductors
- Inductors become capacitors
- You don't need wires to propagate signals

A good read:

Schmitt, Ron. “Electromagnetics Explained”, Newnes, 2002, ISBN 0-7506-7403-2

Know what's reasonable

- Know what's reasonable:
 - 120dBuV/m emission not likely from a test item that's not an intentional transmitter
 - Ferrites aren't going to reduce emissions 60dB
 - 100MHz scope isn't going to capture 1GHz signals

- Know your tools (and their limitations)
 - Preamplifier compression
 - Oscilloscope probe ground lead loop
 - **NEVER** put DC voltage into a spectrum analyzer/EMI receiver
 - Don't overload spectrum analyzer front end

- Look it up: don't guess at how something works

The EMI Troubleshooting COMMANDMENTS

1. Adopt the right attitude
2. Acquire the right technical knowledge

3. Follow the right troubleshooting process

Follow the right troubleshooting process

“Take first things first. That process often reduces the most complex human problems into manageable proportions.” *Mark Twain*

Use the following **process** to **focus** your attention on **the right thing at the right time**:

1. Get the symptom description
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5. Narrow it down: divide and conquer
 - A. Check the plug
 - B. Write it down
 - C. Change one thing at a time
 - D. Get a fresh view
6. Implement the fix
7. Test: If you didn't fix it, it ain't fixed
8. Celebrate
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Commandment #1: Get the symptom description

- If you didn't do the test, get the symptom description from the person who did
- Ask W4/H: who, what, when, where, how
 - What is the symptom/failure?
 - How do you reproduce it?
 - Timing: when did it start to occur?
 - Timing: what other things happened around that time?
 - What mode was the equipment under test (EUT) in?
 - What things appear related?
 - Commonalities/differences related to when it does/doesn't occur
- **DO NOT ask "Why"**
 - Try to get just the facts, not opinions
 - Record assumptions as opinions, NOT facts

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Commandment #2: Make it fail

“Sometimes things can go right only by first going very wrong.” *Edward Tenner*

- Reproduce the symptom: why?
 - Provides a baseline
 - So you can look at it
 - So you can focus on the cause
 - So you can tell if it's fixed

- Put the EUT into the failing mode and document your steps: make it repeatable

- Start at the beginning: make sure the EUT is in the same mode that caused the failure, same cables are connected, same antenna polarization, etc.

- Use the system that's failing, not one “exactly like it”

- Know that “that” *can* happen: when you don't know what's causing the problem don't rule out things by “thinking”

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Commandment #3: Quit thinking and look

“It is a capital mistake to theorize before one has data. Insensibly one begins to twist facts to suit theories, instead of theories to suit facts.” *Arthur Conan Doyle*

“No farmer ever plowed a field by turning it over in his mind.” *George E. Woodbury*

- Quit thinking and look: don't guess, take the time to look at the failure
 - Thinking is easy
 - Looking with appropriate instrumentation is hard

- If you guess at how something is failing...
 - You may fix something that isn't the real problem
 - When you're done disproving all your bad guesses, you **STILL** have to fix the problem

- But....
 - Good guesses are allowed, especially if you understand the system well
 - Guess only to focus the search
 - Don't trust your guesses too much: if instrumentation doesn't confirm your guess, back up and look at your mental model again

Follow the right troubleshooting process

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Commandment #4: Perform appropriate corrective maintenance

“The secret of success is to do the common things uncommonly well.” John D. Rockefeller

- Appropriate = items that are relatively quick and easy, likely to fix the symptom, and probably should be done anyway
- “Relatively quick and easy” = quick and easy compared to the probable work in using more elaborate diagnostic tests
- **Make sure the EUT construction actually matches the design drawings**
- Be sure to only change one thing at a time and test after each fix
- Make what’s there as good as you can before you start troubleshooting
- Fix the problems you know about: “We know part "x" of the system isn’t working right, but it couldn’t possibly affect what we’re seeing.”
- Don’t get carried away: don’t be a perfectionist and waste time on things that aren’t likely to cause problems

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Commandment #5: Narrow it Down/Divide and Conquer (1)

“Many strokes, though with a little axe, hew down and fell the hardest timber’d oak.”

William Shakespeare

- Divide and conquer = binary search and the process of elimination to quickly find the root cause (quickly as opposed to random guesses)
- Use diagnostic tests to repeatedly eliminate half of the remaining system as the residence for the root cause

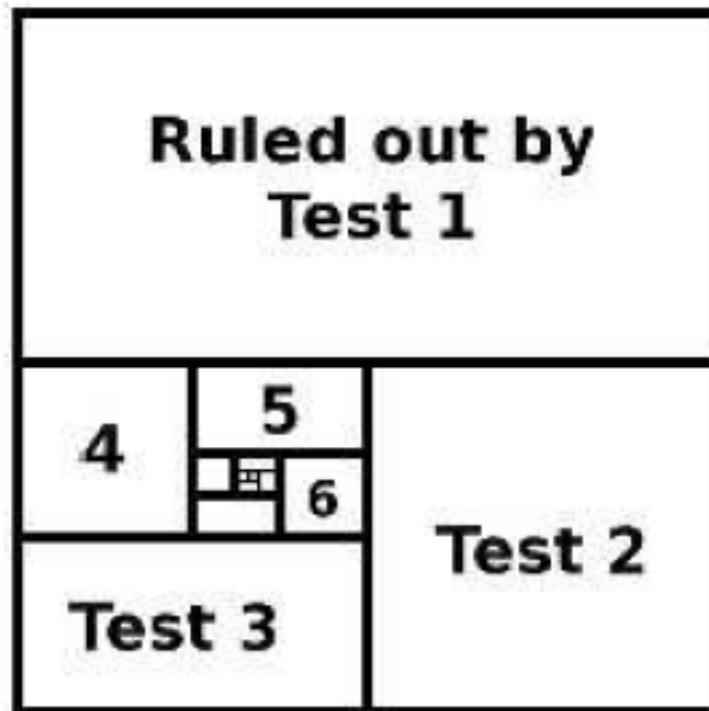


Figure taken from Litt, Steve,
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www.troubleshooters.com, 2007

Commandment #5: Narrow it Down/Divide and Conquer (2)

- Binary search is the ideal, but is almost never achieved
- Binary search can be approached by considering each diagnostic test according to the quadruple tradeoff:
 1. **Safety** (don't do anything to harm the EUT or yourself)
 2. **Even divisions** (how close to half can you get)
 3. **Ease** (how easy to run test A vs. test B, both of which might yield a system division)
 4. **Likelihood** (how likely is this test to yield a system division)
- Experience/instinct is good, but test **all** your assumptions
 - Proceeding on a wrong assumption = “The Big Mistake”
 - “The Big Mistake” = Wasting time digging around in the wrong part of the system

Sample narrowing tactics

- Measure the ambient environment
 - Turn off the equipment under test (EUT) - radiated
 - Turn off the ground support equipment (GSE) - radiated
 - Measure conducted emissions using a resistor drawing the same current as the EUT to see the test house power supply signature

- Change the EUT
 - Turn off parts of the EUT (if possible)
 - Check bonding of EUT housing mating surfaces
 - Put the EUT into different modes
 - Disconnect EUT cables one at a time (with EUT off, then repower)

- Use EMI diagnostic tools to look at relative amplitudes
 - Use "sniffer" probes to look at radiated emissions
 - Use current probes to measure currents on cable shields

- Check the EMI measurement system
 - Perform a measurement system check
 - Insert attenuator between preamp and EMI receiver

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Commandment #5A: Check the Plug

“See if there’s gas in the tank, son, before you overhaul the carburetor.” *Richard Glenn Shelby*

- Check the obvious
 - Is it plugged in?
 - Is some part of the EUT malfunctioning?
 - Are the inputs and outputs filtered?
 - Has an I/O filter been bypassed due to poor layout?

- Question your assumptions, especially for really wacky problems

- Test the tool: make sure the multimeter battery is good

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Commandment #5B: Write it down

“If it isn’t written down, it didn’t happen.” *some lawyer*

- Write down what you did
 - In what order and what happened
 - **SLOW DOWN**: Don’t get in a hurry in the heat of battle and quit recording details
 - Compare results to previous diagnostic test results

- Understand that any detail could be the important one: don’t skip recording it because you don’t think it’s important

- The shortest pencil is longer than the longest memory

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Commandment #5C: Change one thing at a time

“The world doesn’t come to clever folks, it comes to the stubborn, obstinate, one-idea-at-a-time people.”

Mary Roberts Rinehart

- Use a rifle, not a shotgun
 - Stop after each shot
 - Look at the target to see where the bullet hit

- Grab the submarine’s brass bar with both hands: if you change several things at once you may never get back to the initial set of failing conditions

- Keep your “fixes” in as you continue to troubleshoot until you find the real fix

- When you find the real fix, back out the other changes you made one at a time to make sure they don’t change anything

- Always make a baseline measurement at the start of each test day to make sure nothing changed overnight

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Commandment #5D: Get a Fresh View

“Form the habit of making decisions when your spirit is fresh... to let dark moods lead is like choosing cowards to command armies.” *Charles Horton Cooley*

- Take a break
 - Go get some ice cream
 - Sleep on it
- Ask for fresh insights from someone not in your rut
- Talk to a mannequin: verbalizing the problem helps you to see things you may have missed
- Know that help is all around you
 - Ask an expert about a part of the EUT you don't understand
 - Listen to the voice of experience
 - Don't be proud
- Report symptoms, not theories: **don't pollute the helper**

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Commandment #6: Implement the fix

- Implement the “gross” fix first to demonstrate it fixes the problem: don't worry about practical implementation at this point
- Use good workmanship
- Make it the best you can
- Use good design practices
 - Don't inadvertently bypass a filter
 - Use good shield/cable bonding

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Commandment #7: Test: If you didn't fix it, it ain't fixed

- Every problem has a root cause: make sure you've found it
- Things to test:
 - Did the symptom(s) go away?
 - Did you fix the root cause?
 - Did you create any other problems?
 - Did you back out all other troubleshooting "fixes" one a time to make sure they don't affect anything?
- Recreate the symptom: break it, fix it, break it again
- Now (and only now) do you start thinking about how to practically implement the "gross" fix: tweak and fiddle as long as they'll let you
- Intermittence: Know that it NEVER just goes away by itself

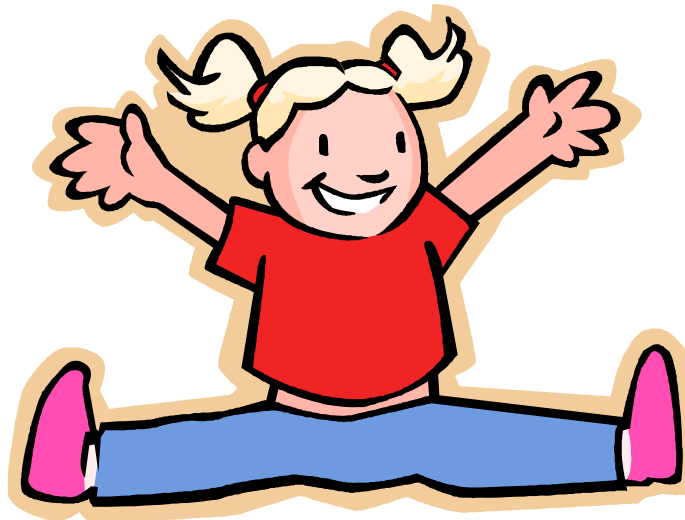
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Commandment #8: Celebrate

- Take pride after every successful fix to avoid burnout
- Don't get the "big head"
- Celebrate the team effort: don't be discouraged if you're not the one who came up with the ultimate fix



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5. Narrow it down: divide and conquer
 - A. Check the plug
 - B. Write it down
 - C. Change one thing at a time
 - D. Get a fresh view
6. Implement the fix
7. Test: If you didn't fix it, it ain't fixed
8. Celebrate

9. Prevent future occurrence

Commandment #9: Prevent future occurrence

“One thorn of experience is worth a whole wilderness of warning.” *James Russell Lowell*

“Learning from experience is a faculty almost never practiced.” *Barbary Tuchman*

“Every success I know has been reached because the person was able to analyze defeat and actually profit by it in the next undertaking.” *William Marston*

- Write down lessons learned
- Develop design guidelines
- Communicate lessons learned to your designers and management

So....

What did we talk about?

The EMI Troubleshooting COMMANDMENTS

1. Adopt the right attitude
2. Acquire the right technical knowledge
3. Follow the right troubleshooting process

“Excellence is achieved by the mastery of the fundamentals.” *Vince Lombardi*

**“The vital, successful people I have met all had one common characteristic.
They had a plan.”** *Marilyn Van Derbur*

Follow the right troubleshooting process

“Take first things first. That process often reduces the most complex human problems into manageable proportions.” *Mark Twain*

Use the following **process** to **focus** your attention on **the right thing at the right time**:

1. Get the symptom description
2. Make it fail
3. Quit thinking and look
4. Perform appropriate corrective maintenance
5. Narrow it down: divide and conquer
 - A. Check the plug
 - B. Write it down
 - C. Change one thing at a time
 - D. Get a fresh view
6. Implement the fix
7. Test: If you didn't fix it, it ain't fixed
8. Celebrate
9. Prevent future occurrence

“It is common sense to take a method and try it; if it fails, admit it frankly and try another. But above all, try something.”

-Franklin D. Roosevelt

“Spectacular achievement is always preceded by unspectacular preparation.”

-Robert Schuller

“Permanence, perseverance, and persistence in spite of all obstacles, discouragements and impossibilities; it is this that in all things distinguishes the strong soul from the weak.”

-Sir Francis Drake

“That’s all I have to say about that.”

-Forrest Gump