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reliability designed, reliability delivered

Design for Reliability: A Condition for Successful Product Introduction

November 19, 2015 IMEC Heverlee, Belgium

What is Design for Reliability (DfR)?

- Reliability is the measure of a product's ability to
  - ...perform the specified function
  - ...at the customer (with their use environment)
  - ...over the desired lifetime

- Design for Reliability is a process for ensuring the reliability of a product or system during the design stage before physical prototype
  - Often part of an overall Design for Excellence (DfX) strategy

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Warning: DfR Solutions' DfR vs. Others' DfR

- DfR: Focus is on activities before prototype
- Others: Focus is on the entire product lifecycle (HALT, root-cause analysis, reliability growth)

- DfR: Focus is on preventing single point of failures
- Others: Focus is on system-level failures and failure modes (safety)

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Why Design for Reliability (DfR)?

- The foundation of a successful product is a robust design
  - Provides margin
  - Mitigates risk from defects
  - Satisfies the customer

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Who Controls Electronic Hardware Design?

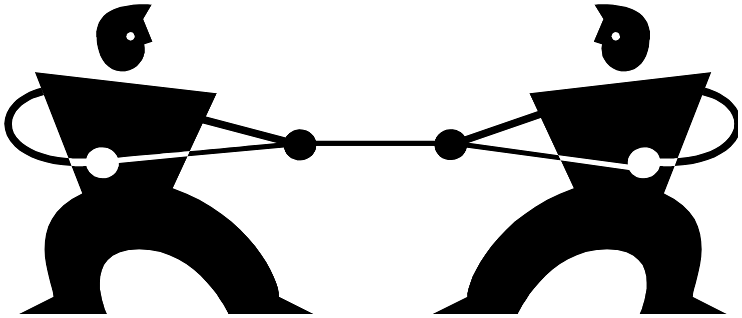
Electrical Designer

- Circuit Schematic
- Component selection
  - Bill of materials (BOM)
  - Approved vendor list (AVL)

Mechanical Designer

- PCB Layout and Outline
- Other aspects of electronic packaging

Both parties play a critical role in minimizing hardware mistakes during new product development



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When Do Mistakes Occur?

- Insufficient exchange of information between electrical design and mechanical design
- Poor understanding of supplier limitations
- Customer expectations (reliability, lifetime, use environment) are not incorporated into the new product development (NPD) process

There can be many things that "you don't know you don't know"

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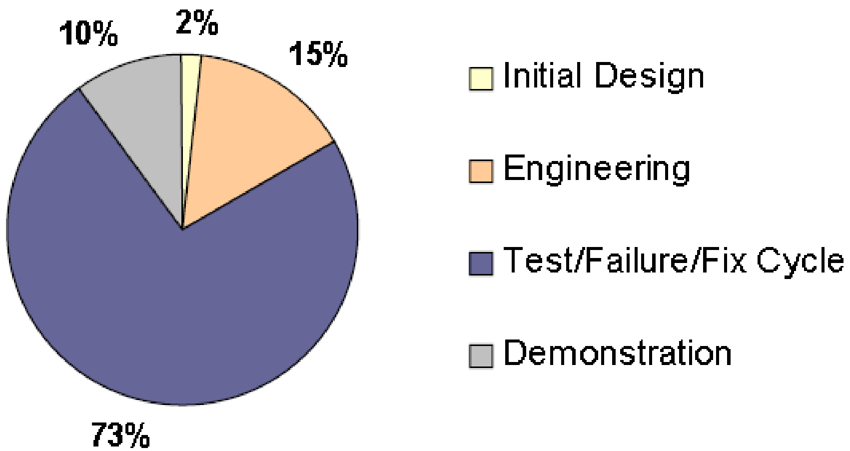
Why DfR: Faster / Cheaper

- Traditional OEMs spend almost 75% of product development costs on test-fail-fix

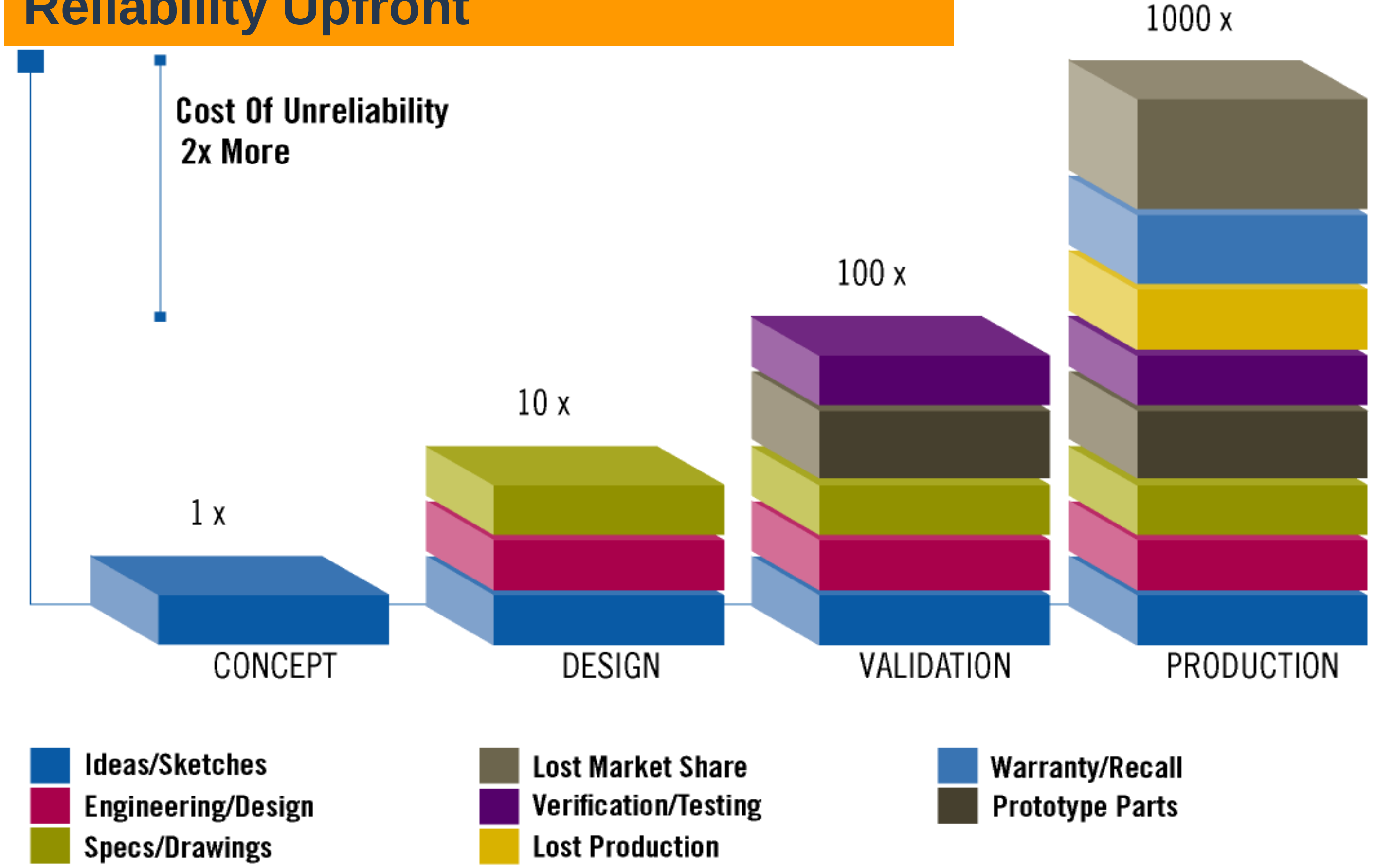


- Electronic OEMs that use design analysis tools
  - Hit development costs 82% more frequently
  - Average 66% fewer re-spins
  - Save up to $26,000 in re-spins

Gene Allen and Rick Jarman .Collaborative R&D; (New York John Wiley&Sons. Inc. 1999). 17.
Aberdeen Group, Printed Circuit Board Design Integrity: The Key to Successful PCB Development, 2007 http://new.marketwire.com/2.0/rel.jsp?id=730231

Why DfR: Earlier is Cheaper

Reduce Costs by Improving Reliability Upfront



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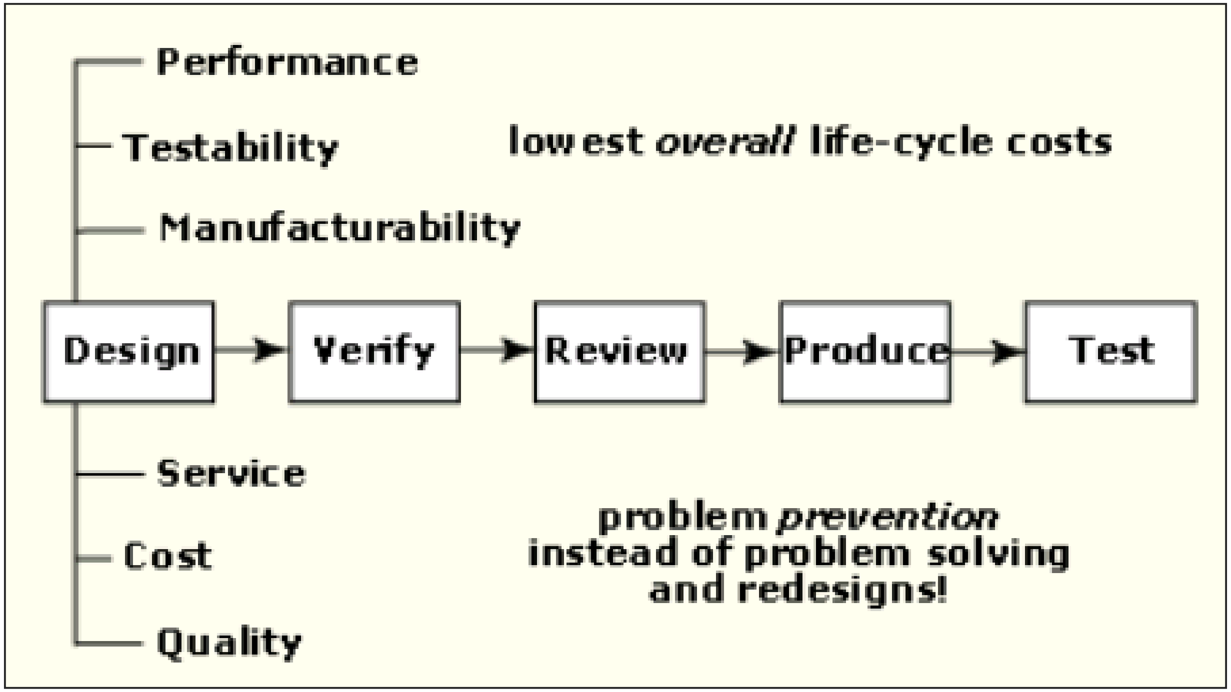
How DfR?

- Successful DfR efforts require the integration of product design and process planning into a cohesive, interactive activity known as Concurrent Engineering



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DfR Implementation

- Many organizations have developed DfR Teams to speed implementation
  - Success is dependent upon team composition and gating functions

- Challenges: Classic design teams consist of electrical and mechanical engineers trained in the ‘science of success’
  - DfR requires the right elements of personnel and tools

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DfR Team

- Component engineer
- Physics of failure expert (mechanical / materials)
- Manufacturing engineer
  - Box level (harness, wiring, board-to-board connections)
  - Board / Assembly
- Engineer cognizant of environmental legislation
- Testing engineer (proficient in ICT / JTAG / functional)
- Thermal engineer (depending upon power requirements)
- Reliability engineer?
  - Depends. Many classic reliability engineers provide **limited** value in the design process due to over-emphasis on statistical techniques and environmental testing

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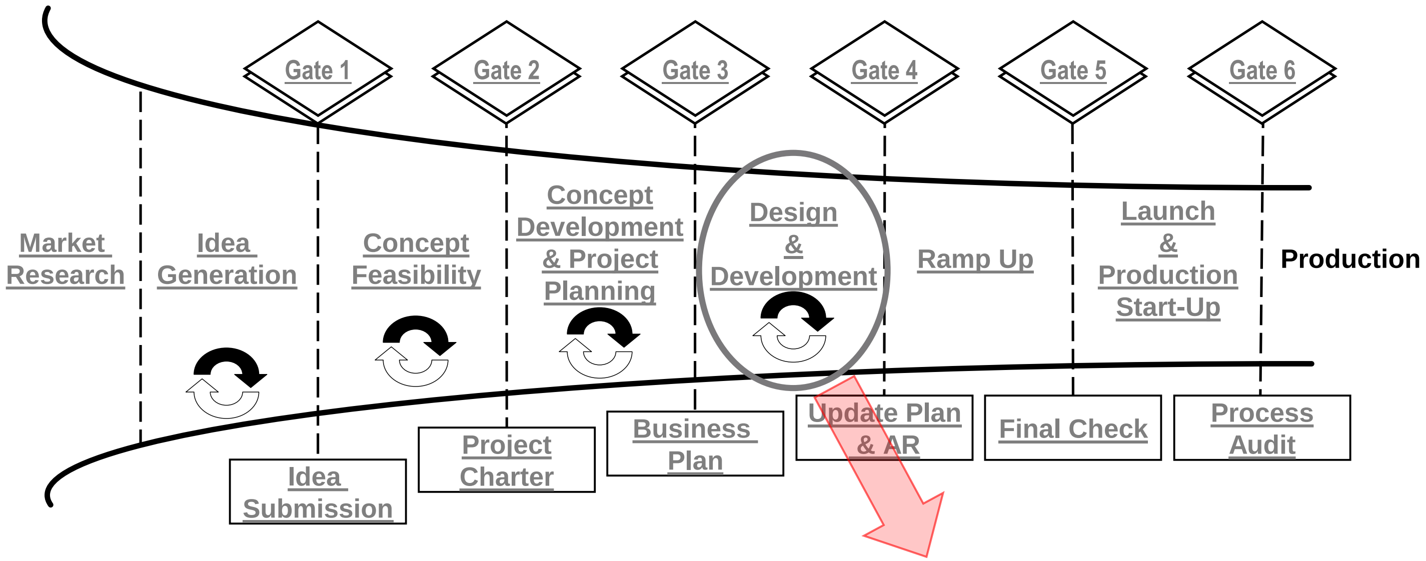
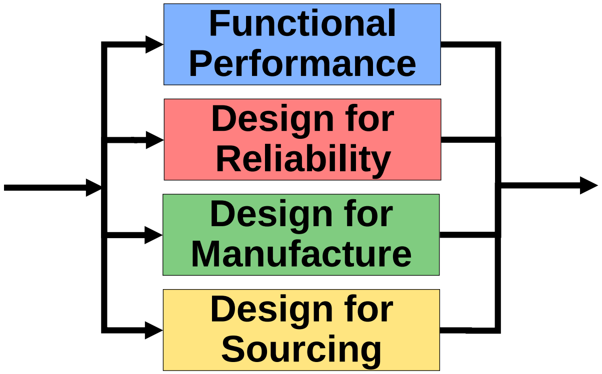
Gating DfR



- Goal: Simultaneously optimizing the design
- Reality: Need for specific gating activities (design reviews)



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List of DfR Tools and Techniques (Wikipedia)

Many tasks, techniques and analyses are specific to particular industries and applications. Commonly these include:

- Built-in test (BIT) (testability analysis)
- Failure mode and effects analysis (FMEA)
- Reliability hazard analysis
- Reliability block-diagram analysis
- Dynamic Reliability block-diagram analysis[6]
- Fault tree analysis
- Root cause analysis
- Sneak circuit analysis
- Accelerated testing
- Reliability growth analysis
- Weibull analysis
- Thermal analysis by finite element analysis (FEA) and / or measurement
- Thermal induced, shock and vibration fatigue analysis by FEA and / or measurement
- Electromagnetic analysis
- Statistical interference
- Avoidance of single point of failure
- Functional analysis and functional failure analysis (e.g., function FMEA, FHA or FFA)
- Predictive and preventive maintenance: reliability centered maintenance (RCM) analysis
- Testability analysis
- Failure diagnostics analysis (normally also incorporated in FMEA)
- Human error analysis
- Operational hazard analysis /
- Manual screening
- Integrated logistics support

List of DfR Tools and Techniques (DfR Solutions)

- Failure Mode Analysis
  - Failure Mode Effect Analysis (FMEA), Fault Tree/Tolerance Analysis (FTA), Design Review by Failure Mode (DRBFM), Sneak Circuit Analysis (SCA)
- Reliability Prediction - Empirical
- Design Rules
- Design for Excellence
  - Design for Manufacturability (DfM), Design for Testability (DfT)
- Tolerancing (Mechanical, Electrical)
- Simulation and Modeling (Stress)
  - Thermal, Mechanical, Electrical/Circuit
- Simulation and Modeling (Damage)
  - EMI/EMC, EOS/ESD, Physics of Failure, Derating

Failure Mode Analysis

- A process of identifying potential failure modes and appropriate mitigations early in the design process
  - Likely the most common DfR tool for reliability engineers

- These are generic DfR tools
  - A Strength and Weakness

- Strength: Can provide amazing insight
- Weakness: Can be a boring, monotonous, no-value, check-the-box activity

- ***"Unfortunately, reliability engineering has been afflicted with more nonsense than any other branch of engineering."***
- Pat O'Connor (Author Practical Reliability Engineering).

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Failure Mode Effects Analysis (FMEA)

- The classic failure mode analysis technique
  - Developed after World War II
- Forces the team to identify failure modes and their severity, their probability of occurrence, and their detectability
- Executed as both a design analysis (DFMEA) and a process analysis (PFMEA)

FMEA (cont.)

- Conservative, regulated industries love FMEA
  - Very concerned about safety
  - Very concerned about having a written record of being concerned about safety

- Other industries are less certain
  - DFMEA can take too long (personal computer company completed DFMEA three months after product launch)
  - PFMEA provided by suppliers can be boilerplate

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Valuable FMEAs

- For a FMEA to be valuable, two things need to happen
- One, the form should be fluid
  - Functional block, geometry, etc.
  - Scoring can be linear, actual measurements, etc.
- Two, actions that can be measured through statistical process control should be identified
  - It is not a one and done

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DfR Outline

- **DfR at Concept / Block-Diagram Stage**
  - Specifications
- Part Selection
  - Derating and uprating
- Design for Manufacturability
  - Reliability is only as good as what you make
- **Wearout Mechanisms and Physics of Failure**
  - Predicting degradation in today's electronics

DfR at Concept Stage

Concept / Block Diagram

- Can DfR mistakes occur at this stage?
  - No……….and Yes
- Failure to capture and understand product specifications at this stage lays the groundwork for mistakes at schematic and layout
- Important specifications to capture at concept stage
  - **Reliability goals**
  - Use environment
  - Dimensional constraints

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Reliability Goals

- Reliability is the measure of a product's ability to
  - …perform the specified function
  - …at the customer (with their use environment)
  - …over the desired lifetime
- Typical reliability metrics: Desired Lifetime / Product Performance
- Desired lifetime
  - Defined as when the customer will be satisfied
  - Should be actively used in development of part and product qualification
- Product performance
  - Returns during the warranty period
  - Survivability over lifetime at a set confidence level
  - Try to avoid MTBF or MTTF

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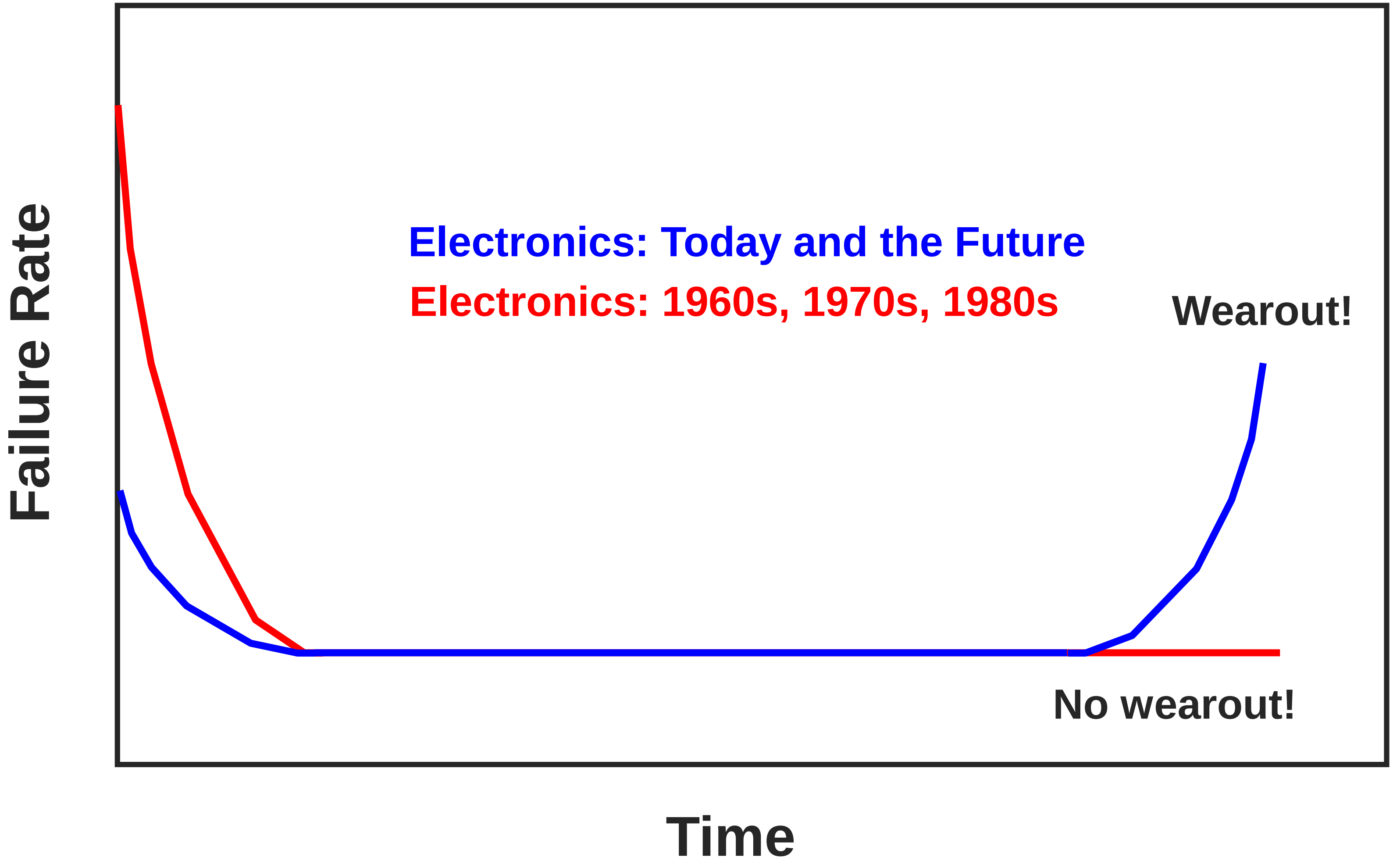
Why is Desired Lifetime Important?



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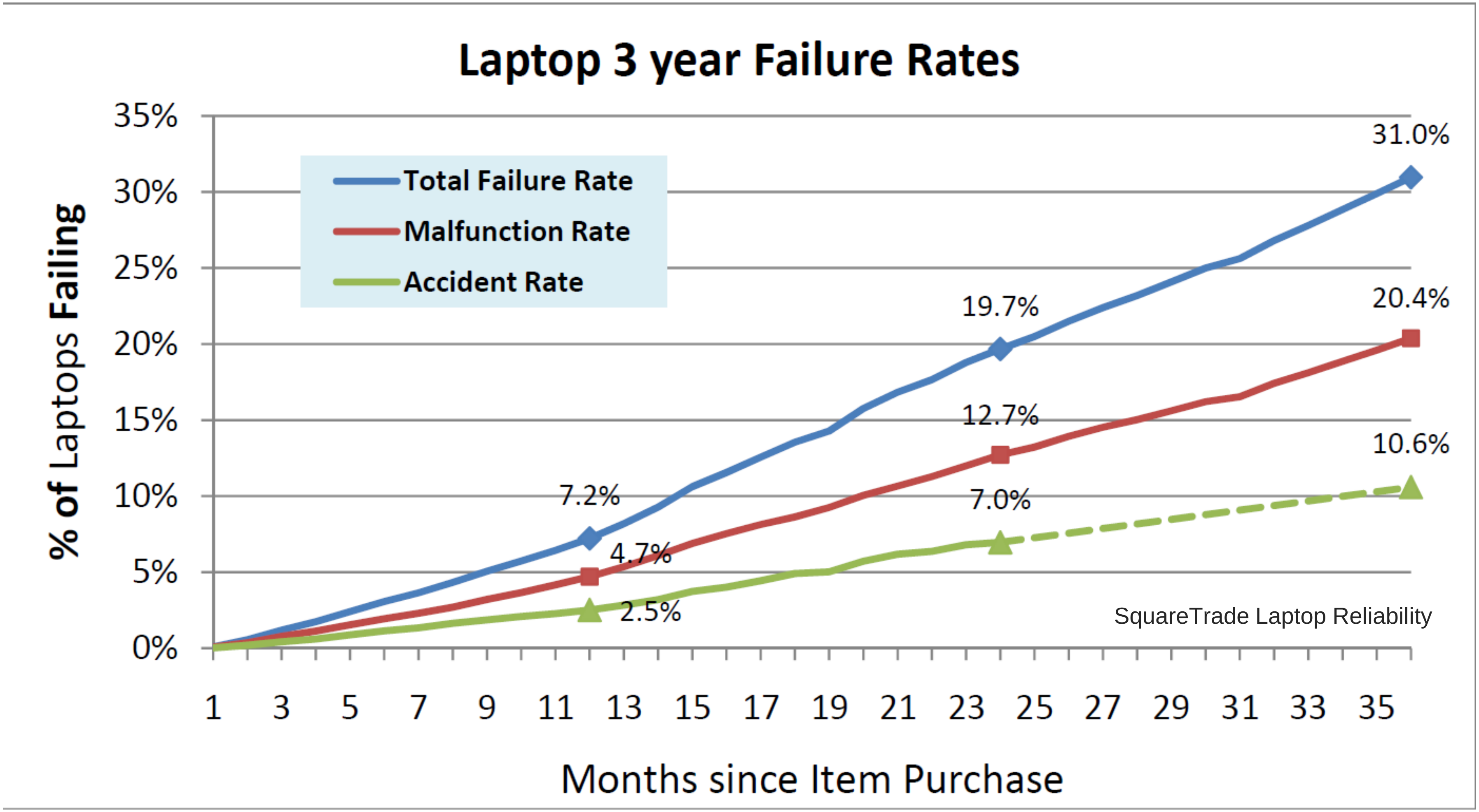
Warranty Returns: Laptops (cont.)



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Warranty Returns: iPad

Figure 2. Non-Accident Failure Reasons - iPad1 and 2

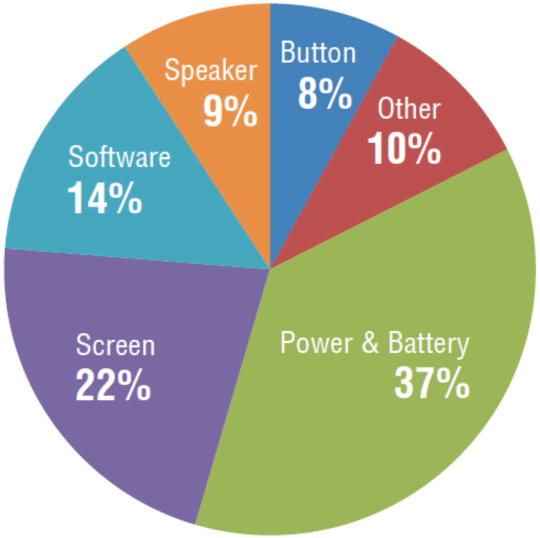
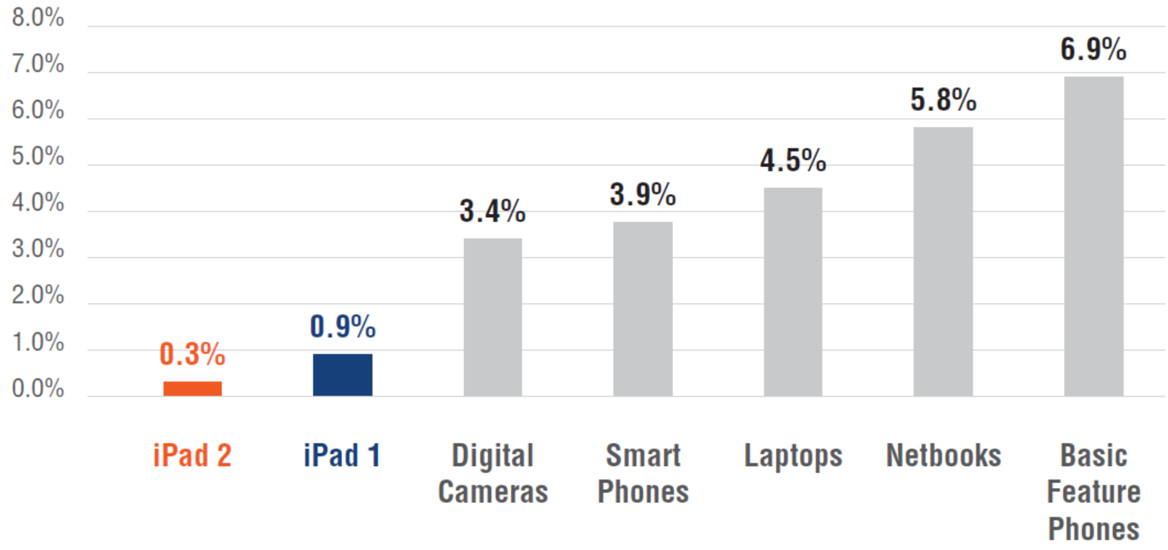


Figure 3. 12 Month Malfunction Rates of Common Portable Electronics



- Truly revolutionary: A consumer electronic as reliable (or more) than typical high-reliability electronics
  - Key Drivers: More robust software, elimination of moving parts (fans, keyboard, hard drive)

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Warranty Returns: Automotive Modules

- Many manufacturers of automotive electronic modules track by incidents per thousand vehicles (IPTV)(over some time interval, typically 1 year)
  - Desired IPTV highly dependent on safety and propulsion
- Hyundai Brake http://www.hyundaiproblems.com/investigations/Genesis/2012/
  - 25-30 IPTV (a problem)
  - 0.3 IPTV (no a problem)
- GM Antilock Brake http://money.cnn.com/2005/05/03/Autos/gm_investigation/
  - 0.32 IPTV (a problem)
  - 0.03 IPTV (no problem)
- Saturn Power Steering http://www.carcomplaints.com/Saturn/Ion/2006/investigations/
  - 14 IPTV (a problem)
- Nissan Transmission http://www-odi.nhtsa.dot.gov/cars/problems/defect/results.cfm?action_number=PE13029&SearchType=QuickSearch&summary=true
  - 50 IPTV (a problem)
  - 0.6 IPTV (no problem)
- Axles (4 to 14 IPTV) http://www.mysanantonio.com/business/fool/article/Diversifying-Away-From-General-Motors-4306695.php

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Product Performance: Survivability

- Some companies set reliability goals based on survivability
  - Often bounded by confidence levels
  - Example: 95% reliability with 90% confidence over 15 years

- Advantages
  - Helps set bounds on test time and sample size
  - Does not assume a failure rate behavior (decreasing, increasing, steady-state)

- Disadvantages
  - Can be re-interpreted through mean time to failure (MTTF) or mean time between failures (MTBF)

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Limitations of MTTF/MTBF

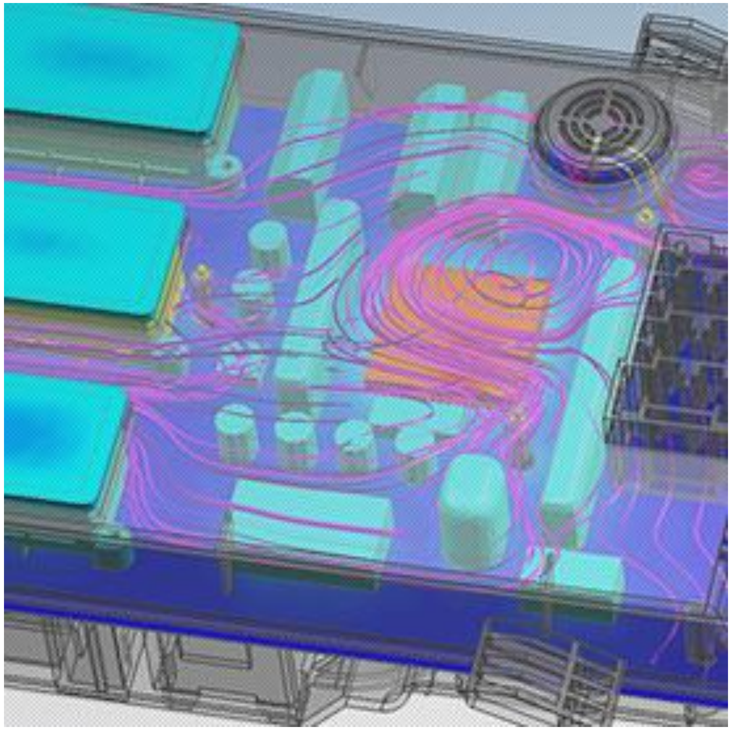
- MTBF/MTTF calculations tend to assume that failures are random in nature
  - Provides no motivation for failure avoidance
- Easy to manipulate numbers
  - Tweaks are made to reach desired MTBF
  - E.g., quality factors for each component are modified
- Often misinterpreted
  - 50K hour MTBF <u>does not mean</u> no failures in 50K hours
- Better fit towards logistics and procurement, not failure avoidance

Wearout Mechanisms and Physics of Failure (PoF)

What is Physics of Failure (PoF)?

- Also known as reliability physics

- Common Definition:
  - The process of using modeling and simulation based on the fundamentals of physical science (physics, chemistry, material science, mechanics, etc.) to predict reliability and prevent failures



Physics of Failure: Modeling and Simulation

- What are we modeling / simulating?
- Packaging + Reliability (t > 0) = Material Movement
  - Diffusion
  - Creep
  - Fatigue

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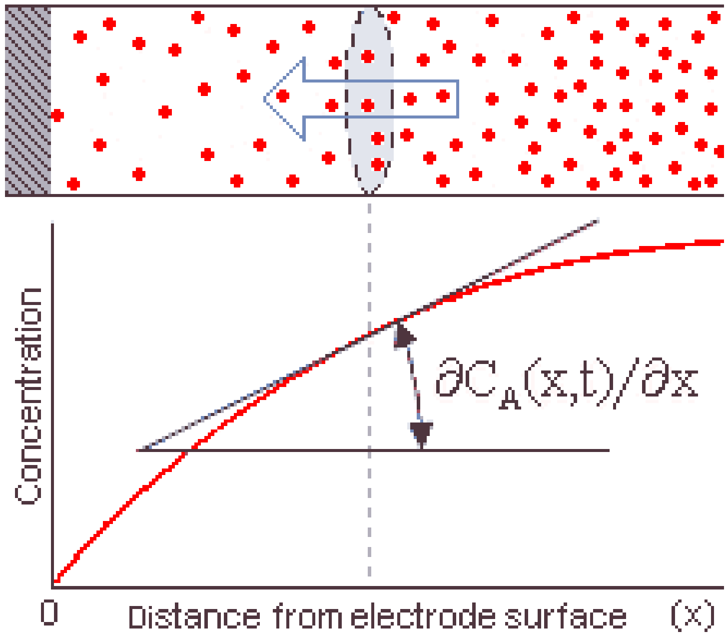
Diffusion

- Motion of electrons, atoms, ions, or vacancies through a material
  - Typically driven by a concentration gradient (Fick's Law)

$$J_A(x,t) = -D_A \frac{\partial C_A(x,t)}{\partial x}$$

$$n(x,t) = n(0)\left[1 - 2\left(\frac{x}{2\sqrt{Dt\pi}}\right)\right]$$



  - Can be driven by other forces (electromotive force, stress)

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PoF-Based Reliability Prediction

- Most physics-of-failure (PoF) based models are semi-empirical
  - The basic concept is still valid
  - Requires calibration
- Calibration testing should be performed over several orders of magnitudes
  - Allows for the derivation of constants
- The purpose of PoF is to limit, but not eliminate, the influence of material and geometric parameters
  - E.g., Solder: Testing must be re-performed for each package family (ball array devices, gullwing, leadless, etc.)

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Physics of Failure (PoF) Algorithms

$$\tau_{HCI} \propto \exp[\frac{b_{HCI}}{V_D}] \cdot \exp[\frac{E_{aHCI}}{kT}]$$

$$L = L_r \left(\frac{V_r}{V_0}\right) \times 2^{\left(\frac{T_r - T_A}{10}\right)}$$

$$T_f \propto \exp\left(\frac{\sim 0.51eV}{kT}\right) \times \exp(\sim -0.063\% RH)$$

$$\tau_{TDDB} \propto \exp[-b_{TDDB} \cdot V_G] \cdot \exp[\frac{E_{aTDDB}}{kT}]$$

$$\mathrm{N_f^{-0.6} D_f^{0.75}} + 0.9 \frac{\mathrm{S_u}}{\mathrm{E}} \left[\frac{\exp(\mathrm{D_f})}{0.36}\right]^{0.1785 \log \frac{10^5}{\mathrm{N_f}}} - \Delta\varepsilon = 0$$

$$\frac{t_1}{t_2} = \left(\frac{V_2}{V_1}\right)^n \exp \frac{E_a}{K_B}\left(\frac{1}{T_1} - \frac{1}{T_2}\right)$$

$$\tau_{EM} \propto (J)^{-n} \cdot \exp[\frac{E_{aEM}}{kT}]$$

$$\tau_{NBTI} \propto \exp[-b_{NBTI} \cdot V_G] \cdot \exp[\frac{E_{aNBTI}}{kT}]$$

$$(\alpha_2 - \alpha_1) \cdot \Delta T \cdot L = F \cdot \left(\frac{L}{E_1 A_1} + \frac{L}{E_2 A_2} + \frac{h_s}{A_s G_s} + \frac{h_c}{A_c G_c} + \left(\frac{2 - \nu}{9 \cdot G_b a}\right)\right)$$

Can be mind-numbing! What to do?

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PoF and Wearout

- What is susceptible to long-term degradation in electronic designs?
  - Ceramic Capacitors (oxygen vacancy migration)
  - Memory Devices (limited write cycles, read times)
  - **Electrolytic Capacitors** (electrolyte evaporation, dielectric dissolution)
  - Film Capacitors
  - Resistors (if improperly derated)
  - Silver-Based Platings (if exposed to corrosive environments)
  - Relays and other Electromechanical Components
  - **Light Emitting Diodes (LEDs) and Laser Diodes**
  - Connectors (if improperly specified and designed)
  - Tin Whiskers*
  - **Integrated Circuits (EM, TDDB, HCI, NBTI)**
  - **Interconnects (Creep, Fatigue)**
    - Plated through holes
    - Solder joints

Industry-accepted models exist

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Ceramic Capacitor Lifetime Prediction

- Ceramic caps are typically not expected to experience 'wearout' during normal operation

$$\frac{t_1}{t_2} = \left(\frac{V_2}{V_1}\right)^n \exp\frac{E_a}{K_B}\left(\frac{1}{T_1} - \frac{1}{T_2}\right)$$

- where t is time, V is voltage, T is temperature (K), n is a constant (1.5 to 7; nominally 4 to 5), E_a is an activation energy (1.3 to 1.5) and K_B is Boltzman's constant (8.62×10^{-5} eV/K)
- Lifetime may be limited for extended value capacitors
  - Sub-2 micron dielectric thickness
  - Greater than 350 layers (increased failure opportunity)

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Inconsistency in Parameters (Different Failure Mechanisms)

Organization	Voltage Exponent, n	Activation Energy, Ea (eV)	Comments
DfR	2.5	0.9	Based on case studies with clients
Panasonic	3	0.31	Roughly equivalent to 2X / 15C
Murata	3	0.57	Roughly equivalent to 2X / 8C
Venkel	3	0.8	Roughly equivalent to 10X / 20C
Intel	4.6	1.27	Average from seven types of X6S capacitors
Kemet-A	5.9	1.14	Average from three types of X7R capacitors
Kemet-B	3.4	1.43	Average from four types of X5R capacitors

Temperature (K)	383	418	433	433	433
Temperature (C)	110	145	160	160	160
Voltage	18.9	12.6	37.8	37.8	37.8
Capacitor	0603/10uF/6.3V	0603/10uF/6.3V	0603/10uF/6.3V	0805/22uF/6.3V	1206/47uF/6.3V
HALT Life (minutes)	192	15	0.75	23	4
Model	Time to Failure at 38C and 3.3V (years)				
DfR	16	4	8	250	43
Panasonic	2	0	1	18	3
Murata	35	17	84	2,561	445
Venkel	273	355	2,698	82,739	14,389
Intel	8,279	2,512	66,723	2,046,184	355,858
Kemet-A	32,155	4,142	404,915	12,417,401	2,159,548
Kemet-B	3,132	2,321	19,234	589,845	102,582
0603 / DfR	6,482	1,997	47,067	1,443,400	251,026

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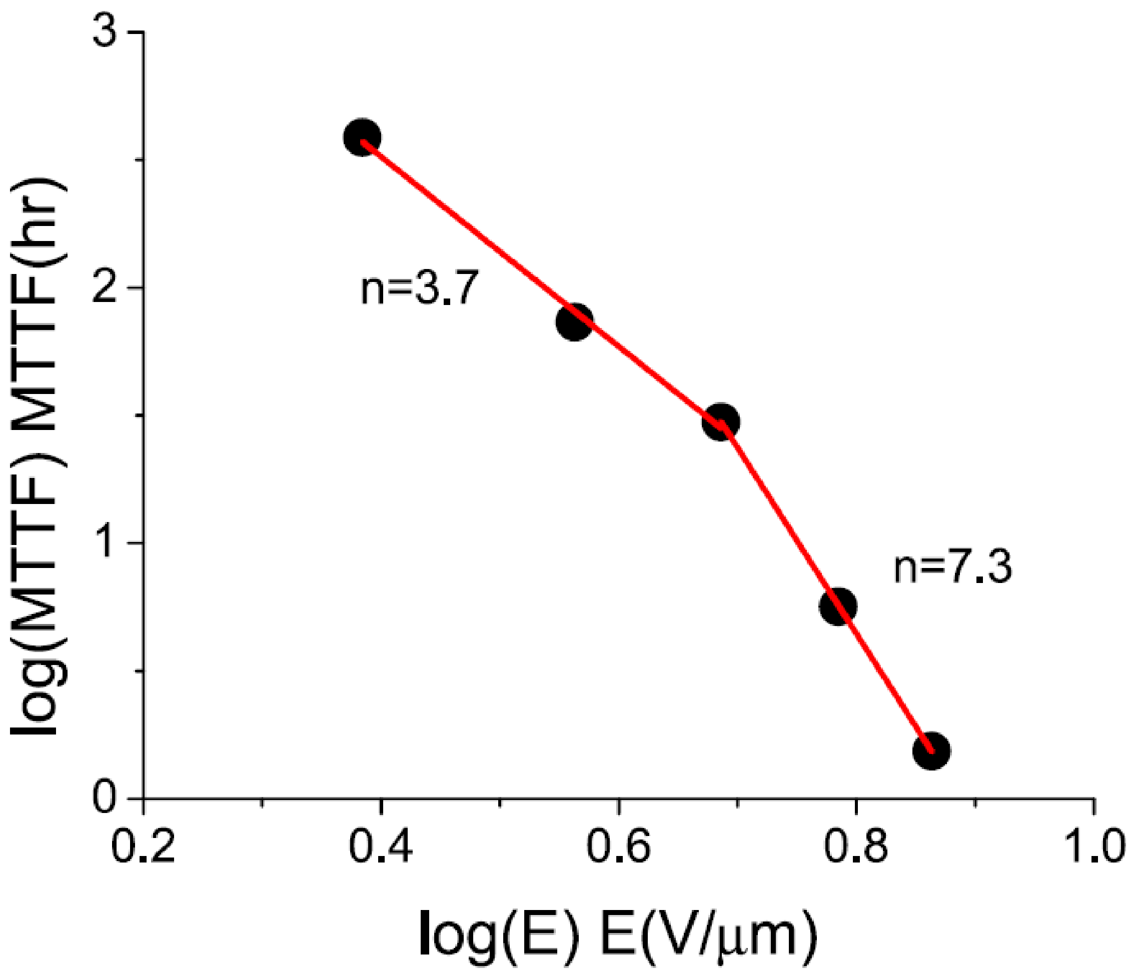
Inconsistency in Parameters (cont.)



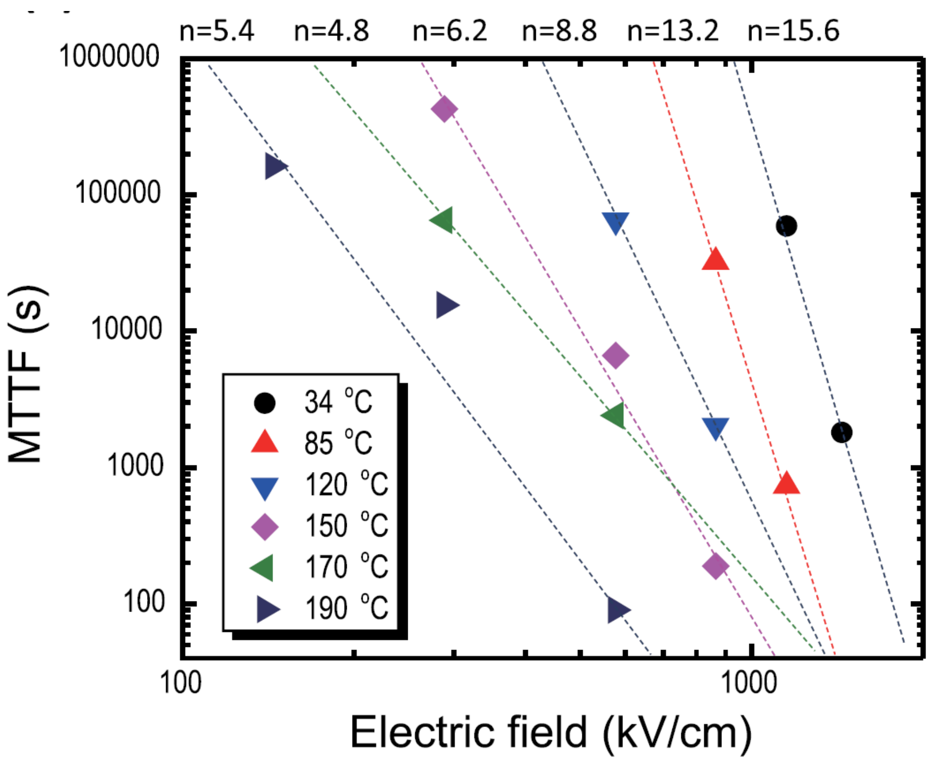
True Physics of Failure!

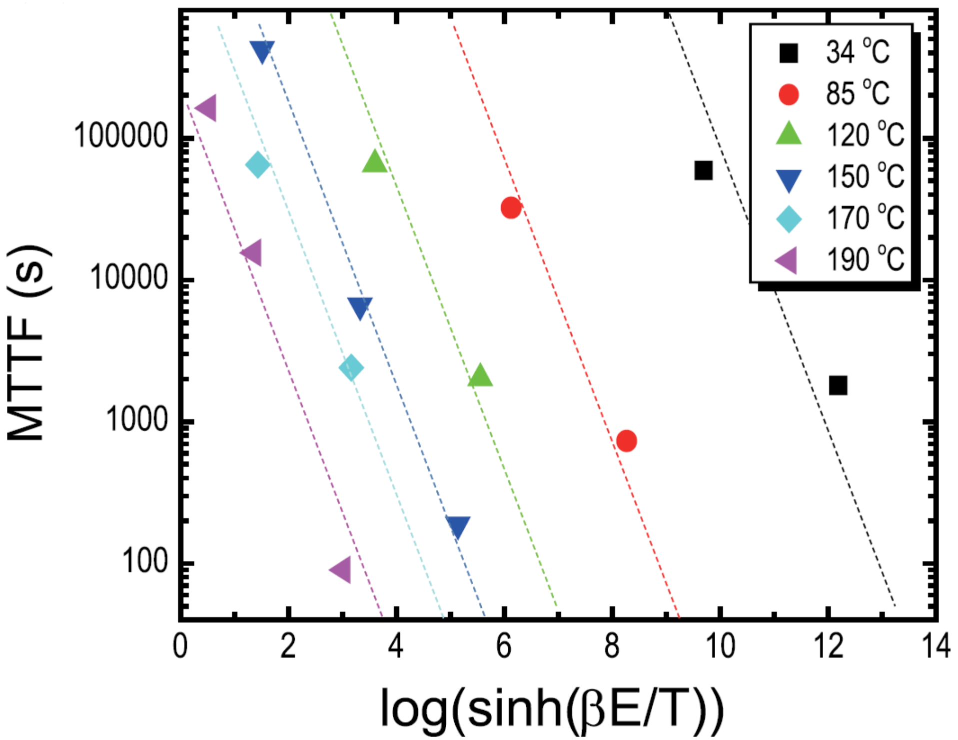
$$t = \rho_{crit} / a\upsilon N q \cdot \left(\exp \frac{-E_A}{k_B T} \sinh \frac{q a E_{App}}{2 k_B T} \right)^{-1}$$

- $\rho_{critical}$ is a critical ionic charge level, a is the characteristic hoping distance, υ is the jump frequency of the oxygen vacancy, N is concentration of oxygen vacancies, q is ionic charge of the point defect, EA is activation energy, kB is Boltzmann's constant, T is temperature, Eapp is applied electric field

Randall, et. al., J. App. Phy (2013)

Physics of Failure, Simplified





$$\log(t_1) = C(T) - \log[\sinh(\beta E_1/T)]$$

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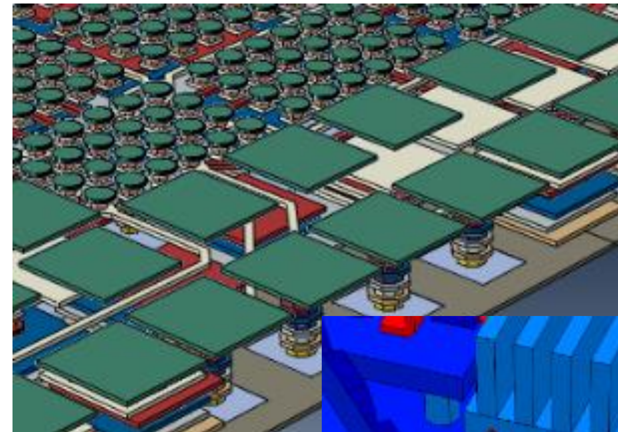
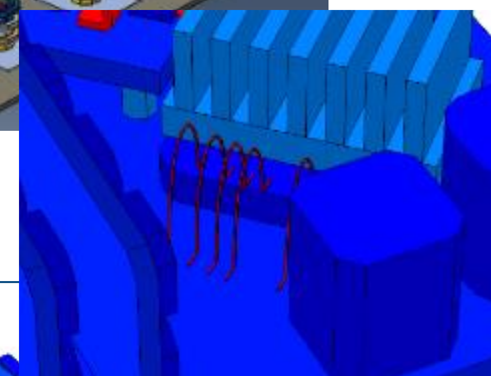
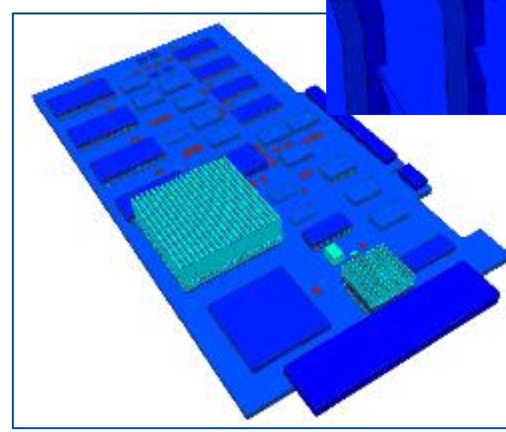
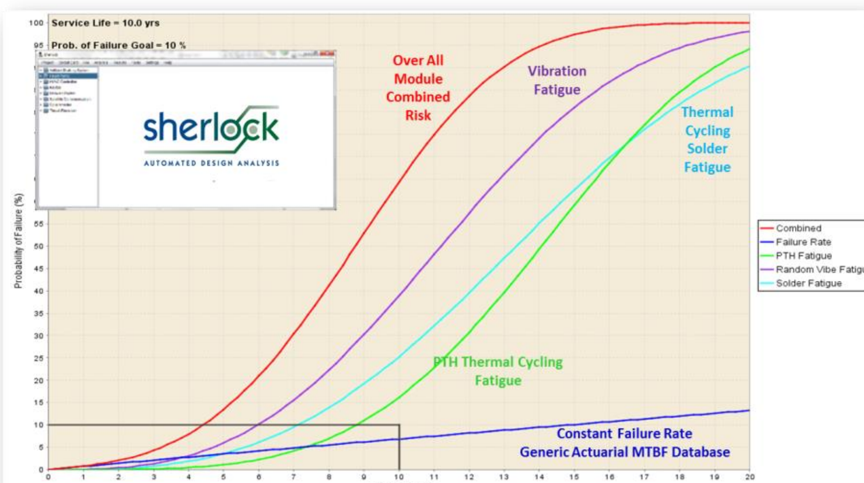
Physics of Failure – Sherlock

- Need for standardized physics of failure tool + easy access to necessary data (translation)
- Increasing requirement across supply chains
  - Boeing, GM, Embraer, Volkswagen, BAE Systems, etc.









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Summary

- To avoid design mistakes, be aware that functionality is only the beginning
- Be aware of industry best practices
  - When to use heuristic rules; when to use physics of failure
- Maximize knowledge of your design as early in the product development process as possible
- Do not overly rely on supplier statements
  - Their view: Reliability is application dependent

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