Electrical, Electronic and Electromechanical (EEE) Parts in the New Space Paradigm: *When is Better the Enemy of Good Enough?*

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Unclassified

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Acronyms

- Analog to Digital Converter (ADC)
- Advanced Encryption Standard (AES)
- Agile Mixed Signal (AMS)
- ARM Holdings Public Limited Company (ARM)
- Bayesian Networks (BN)
- Controller Area Network (CAN)
- Controller Area Network Flexible Data-Rate (CAN-FD)
- Cache Coherent Interconnect (CCI)
- a device or program that compresses data to enable faster transmission and decompresses received data (Codec)
- chemistry of failure (COF)
- Commercial Off The Shelf (COTS)
- Cyclic Redundancy Check (CRC)
- Communications Security Establishment (CSE)
- Camera Serial Interface 2nd Generation (CSI2)
- Control Unit (CU)
- Display Control Unit (DCU)
- Double Data Rate (DDR3 = Generation 3; DDR4 = Generation 4)
- identify and remove errors from computer hardware or software (DEBUG)
- Direct Memory Access (DMA)
- Digital Signal Processing (DSP)
- Dynamic Signal Processing Instrument (dSPI)
- Dual Channel (Dual Ch.)
- Error-Correcting Code (ECC)
- error detection and correction (EDAC)
- Electrical, Electronic, and Electromechanical (EEE)
- Equipment Monitor And Control (EMAC)
- Epitaxy, the deposition of a crystalline overlayer on a crystalline substrate (epi)
- electrostatic discharge (ESD)
- Event Timers (eTimers)
- Fluidized Catalytic Cracking Unit (FCCU)
- FlexRay Communication Controller (FlexRay)
- Gigabyte (Gb)
- Global Industry Classification (GIC)
- Government (Gov't)
- Graphics Processing Unit (GPU)
- Goddard Space Flight Center (GSFC)
- Goal Structuring Notation (GSN)
- Transceiver Type (GTH/GTY)
- High Density Digital Input/Output (HDIO)
- High-Dynamic-Range (HDR)
- High Performance Input/Output (HPIO)
- input/output (I/O)
- Inter-Integrated Circuit (I2C)
- Joint Photographic Experts Group (JPEG)
- independent caches organized as a hierarchy (L2 Cache)
- low earth orbit (LEO)
- Local Interconnect Network Flexible (LinFlex)
- Long-Memory (L-mem)
- Low Power (LP)
- Memory/Logic Built-In Self-Test (M/L BIST)
- model based mission assurance (MBMA)
- Model-Based Systems Engineering (MBSE)
- Mobile Industry Processor Interface (MIPI)
- Microprocessor Unit (MPU)
- Negated AND or NOT AND (NAND)
- National Aeronautics and Space Administration (NASA)
- NASA Electronic Parts and Packaging (NEPP)
- Not OR logic gate (NOR)
- on-chip RAM (OCM)
- Peripheral Component Interconnect Express (PCIe)
- Peripheral Component Interconnect Express Generation 2 (PCIe Gen2)
- Physics of Failure (POF)
- PS-GTR is a type of transceiver (PS-GTR)
- Research and Development (R&D)
- Radiation Hardened (Rad Hard)
- Random Access Memory (RAM)
- Red, Green, and Blue (RGB)
- Successive-Approximation-Register (SAR)
- Serial Advanced Technology Attachment (SATA)
- Secondary Control Unit (SCU)
- Secure Digital embedded MultiMediaCard (SD/eMMC)
- Secure Digital High Capacity (SD-HC)
- Single Event Effect (SEE)
- System Memory Management Unit (SMMU)
- Systems on a Chip (SOC)
- Serial Peripheral Interface (SPI)
- Size, weight, and power (SwaP)
- System Modeling Language (SysML)
- tightly-coupled memory (TCM)
- Total Ionizing Dose (TID)
- triple-modular redundancy (TMR)
- Temperature-Sensor (T-Sensor)
- Universal Asynchronous Receiver/Transmitter (UART)
- Universal Serial Bus (USB)
- watchdog timer (WDT)
- Freescale Zipwire interface (Zipwire)
- communication (comm)
- Fabrication Plant (fab)
- Supply Chain Brain (SCB), supply chain management information resource
- Ground (GND)
- linear energy transfer (LET)

Abstract

- As the space business rapidly evolves to accommodate a lower cost model of development and operation via concepts such as commercial space and small spacecraft (aka, CubeSats and swarms), traditional EEE parts screening and qualification methods are being scrutinized under a risk-reward trade space. In this presentation, two basic concepts will be discussed:
  - The movement from complete risk aversion EEE parts methods to managing and/or accepting risk via alternate approaches; and,
  - A discussion of emerging assurance methods to reduce overdesign such as emerging model based mission assurance (MBMA) and Small Mission concepts.
- Example scenarios will be described as well as consideration for trading traditional versus alternate methods.

Outline

- The Changing Space Market
  - Commercial Space and “Small” Space
- EEE Parts Assurance
- Modern Electronics
  - Magpie Syndrome
- Breaking Tradition: Alternate Approaches
  - Higher Assembly Level Tests
  - Use of Fault Tolerance
- Mission Risk and EEE Parts
- Summary

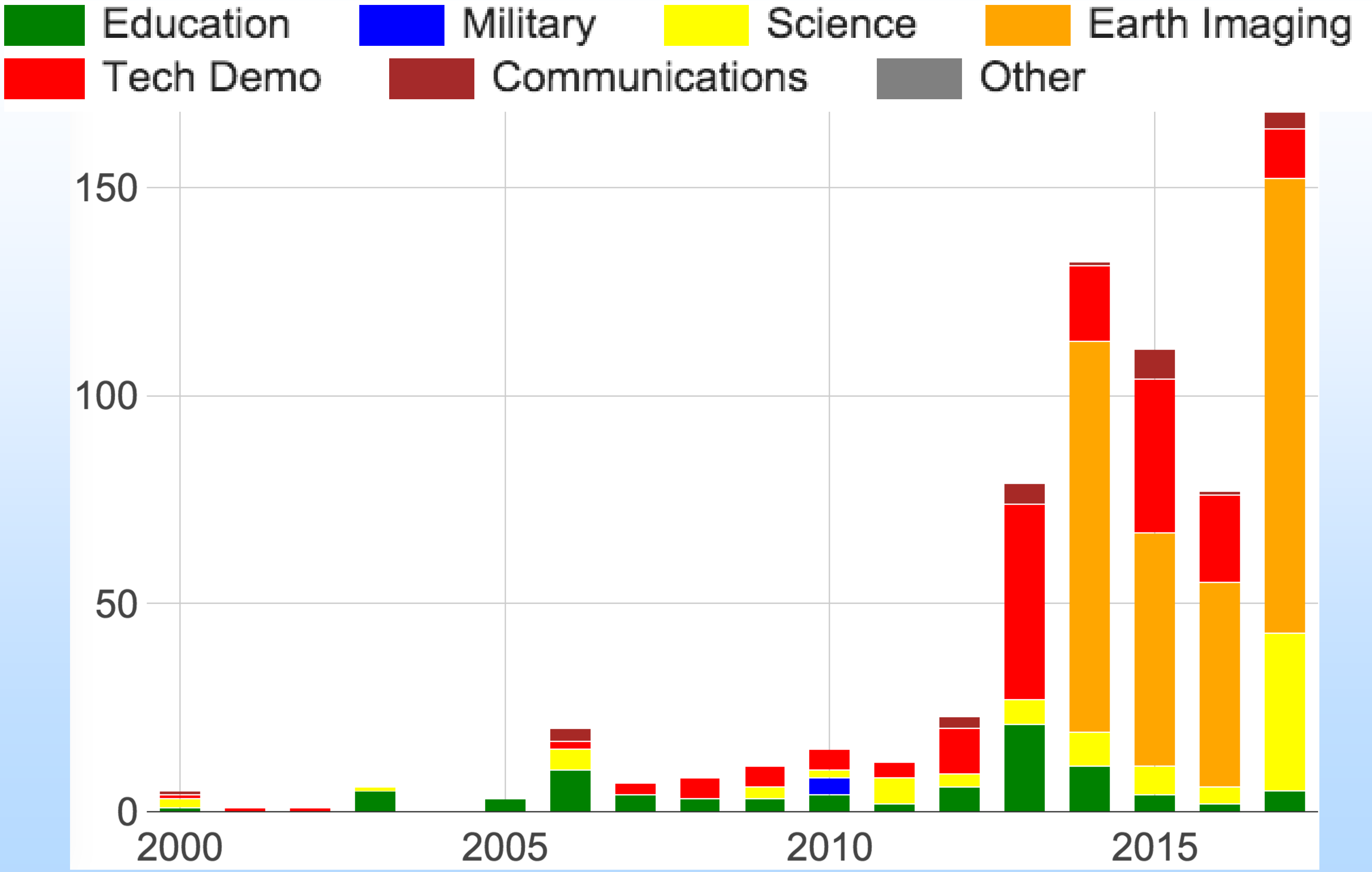
Hubble Space Telescope courtesy NASA

Space Missions:

How Our Frontiers Have Changed

- **Cost constraints and cost "effectiveness" have led to dramatic shifts away from traditional large-scale missions (ex., Hubble Space Telescope).**
- **Two prime trends have surfaced:**
  - ***Commercial space ventures* where the procuring agent "buys" a service or data product and the implementer is responsible for ensuring mission success with limited agent oversight. And,**
  - ***Small Missions* such as CubeSats that are allowed to take higher risks based on mission purpose and cost.**
- **These trends are driving the usage of non traditional electronic part types such as those used in automotive systems as well as "architectural reliability" (aka, resilience) approaches for mission success.**

CubeSat by Mission Type



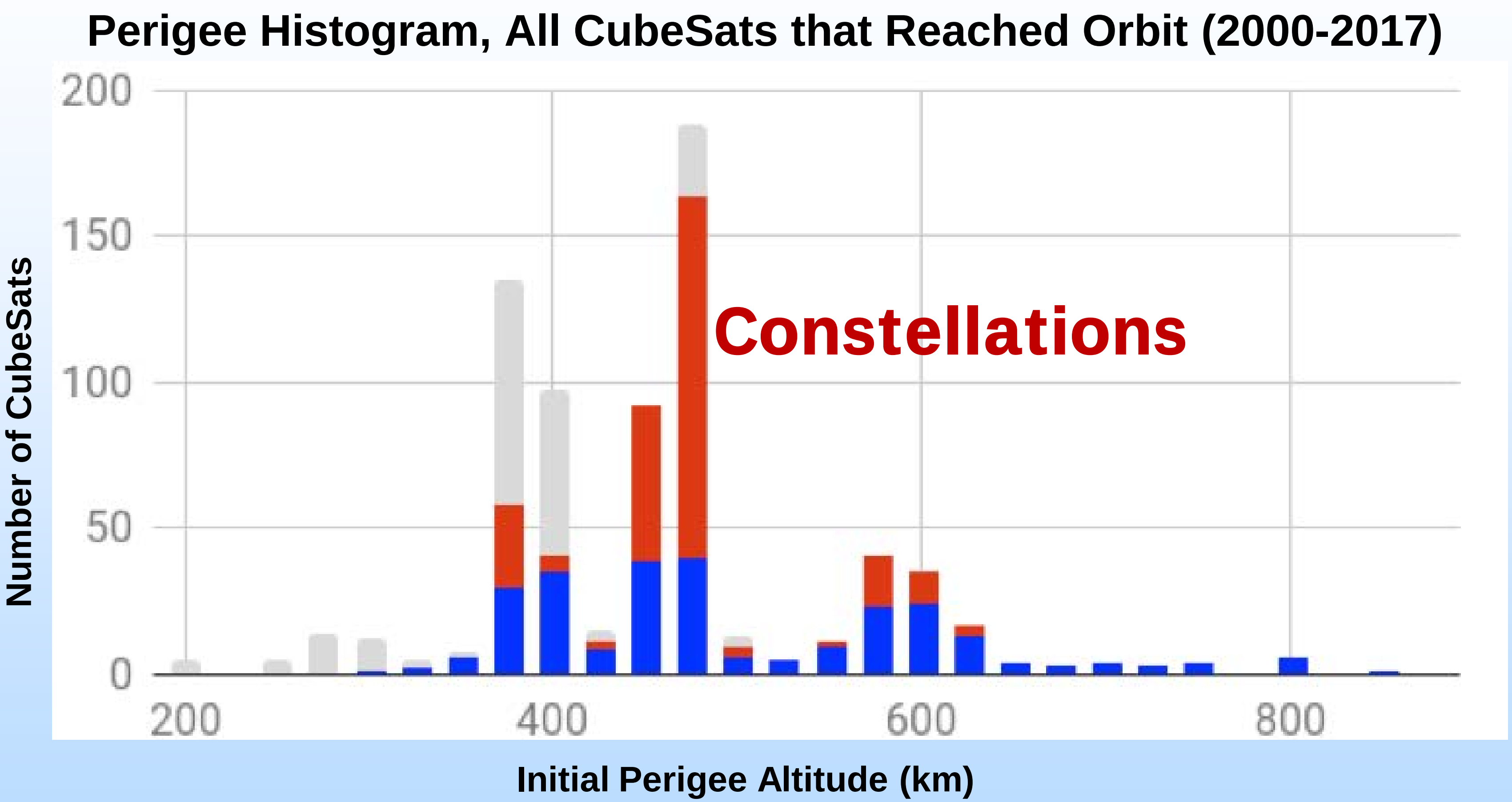
After Swartwout, 2017 NASA Electronics Parts and Packaging (NEPP) Electronics Technology Workshop (ETW), NASA Goddard Space Flight Center, Greenbelt, MD, June 26-29, 2017.

Taxonomy #1: The mindset of the developer

- **Hobbyist**
  - **No real experience in the field**
  - **Building for fun & future profit**
  - **Ad hoc practices**
- **Industrialist**
  - **Experienced builders of big spacecraft**
  - **Building under gov't contract**
  - **Standard space system practices, with some truncation**
- **Crafter**
  - Experienced builders of small spacecraft
  - Working under contract
  - **Streamlined practices, experientially developed**
- **(Smallsat) Constellations**
  - Providing a geographically-distributed service (imaging, comm)
  - **Mission can be met with an ad hoc (?!?) implementation of orbits**
  - Spacecraft/launch costs are effectively free (I did say "effectively")

After Swartwout, 2018 NASA Electronics Parts and Packaging (NEPP) Electronics Technology Workshop (ETW), NASA Goddard Space Flight Center, Greenbelt, MD, June 18-21, 2018.

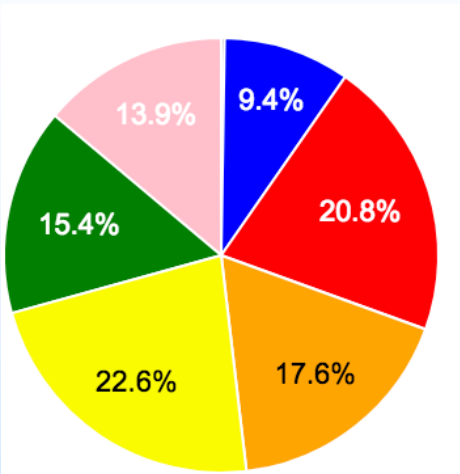
Who is Responsible for This?



After Swartwout, 2018 NASA Electronics Parts and Packaging (NEPP) Electronics Technology Workshop (ETW), NASA Goddard Space Flight Center, Greenbelt, MD, June 18-21, 2018.

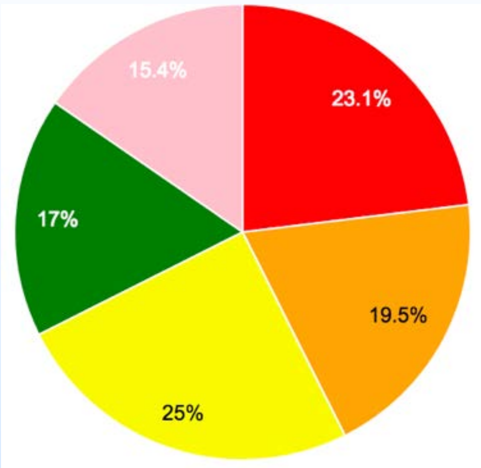
CubeSat Mission Status, 2000-2017 (No constellations)

All Missions (403)

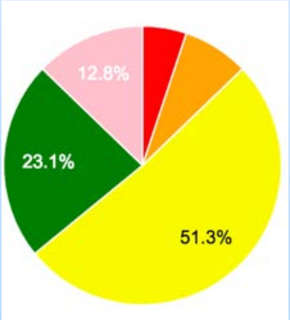


- Prelaunch
- Launch Fail
- DOA
- Early Loss
- Partial Mission
- Full Mission
- Unknown

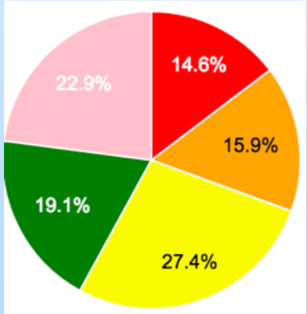
All missions reaching orbit (364)



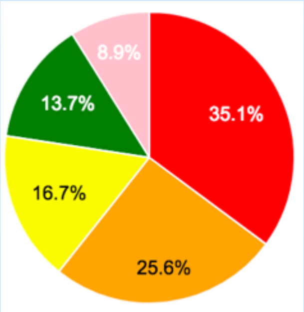
Industrialists (39)



Crafters (157)



Hobbyists (168)



After Swartwout, 2018 NASA Electronics Parts and Packaging (NEPP) Electronics Technology Workshop (ETW), NASA Goddard Space Flight Center, Greenbelt, MD, June 18-21, 2018.

EEE Parts Assurance

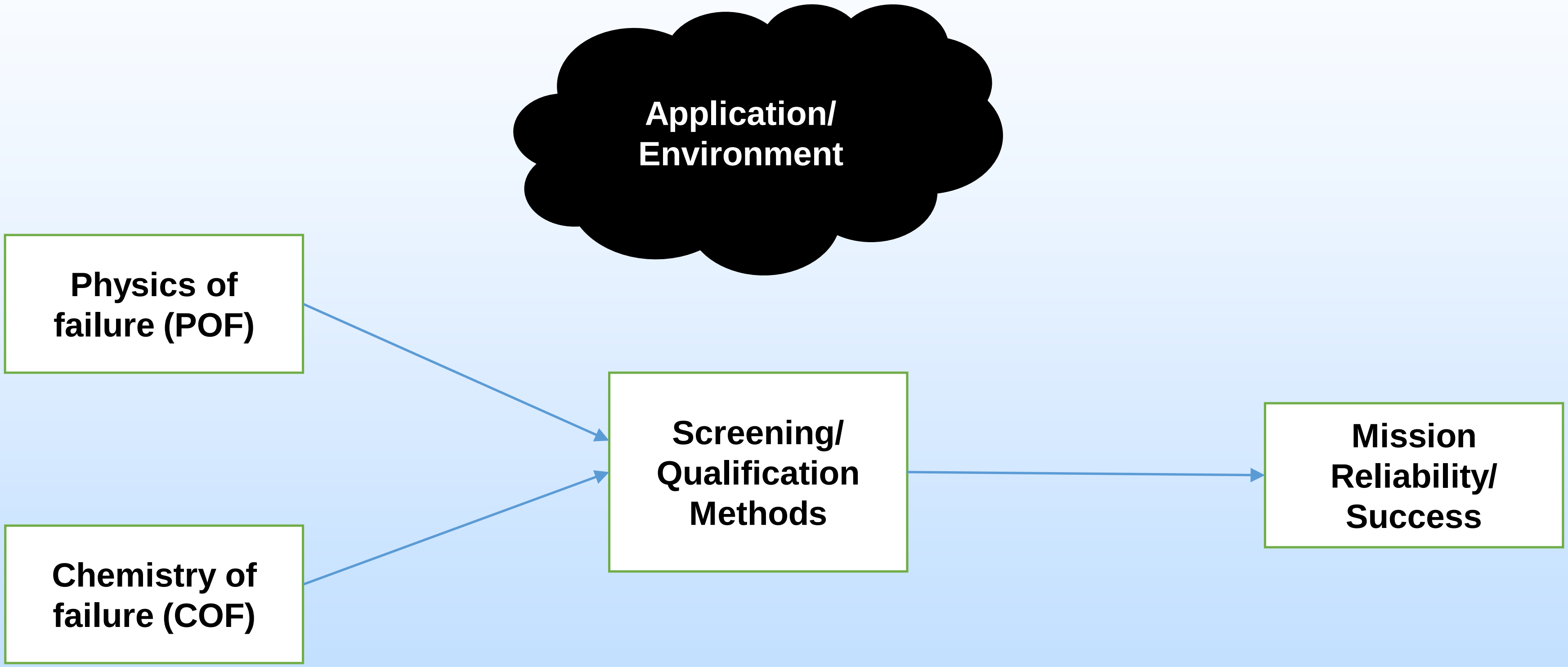
Assurance for EEE Parts

- ***Assurance* is knowledge of**
  - **The supply chain and manufacturer of the product**
  - **The manufacturing process and its controls**
  - **The physics of failure (POF) and chemistry of failure (COF) related to the technology.**
  - **Statistical process and inspection via**
    - **Testing, inspection, physical analyses and modeling.**
      - » **Audits, process data analysis, electrostatic discharge (ESD), …**
  - **Test/Qualification/Screening methods**

– **Understanding the application and environmental conditions for device usage.**

- **This includes factors such as:**
  - **Radiation, Lifetime, Temperature, Vacuum, etc., and,**
  - **Device application and appropriate derating criteria.**

Taking a Step Back…



It's not just the technology,

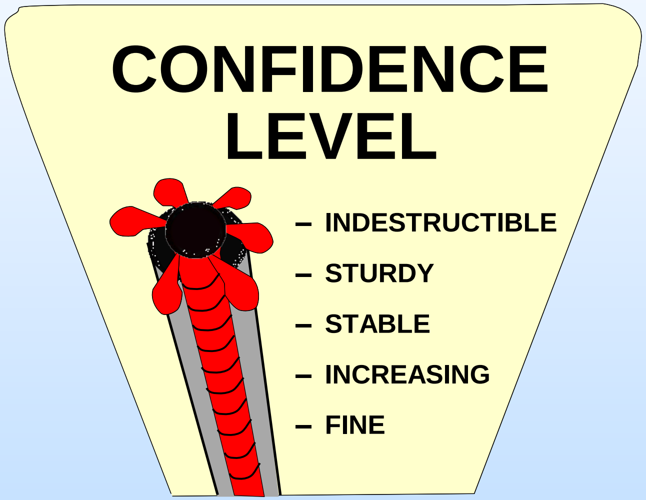
but how to view the need for safe insertion into space programs.

Reliability and Availability

- **Definitions**
  - **Reliability (Wikipedia)**
    - **The ability of a system or component to perform its required functions under stated conditions for a specified period of time.**
      - ***Will it work for as long as you need?***
  - **Availability (Wikipedia)**
    - **The degree to which a system, subsystem, or equipment is in a specified operable and committable state at the start of a mission, when the mission is called for at an unknown, *i.e.*, a random, time. Simply put, availability is the proportion of time a system is in a functioning condition. This is often described as a mission capable rate.**
      - ***Will it be available when you need it to work?***
- **Combining the two drives mission requirements:**
  - ***Will it work for as long as and when you need it to?***

What does this mean for EEE parts?

- *Understanding* of a device's failure modes and causes drives
  - Higher *confidence* level that it will perform under the mission environments and lifetime
  - *High confidence* = "it has to work"
    - High confidence in both reliability and availability.
  - *Less confidence* = "it may work"
    - Less confidence in both reliability and availability.
    - It may still work, but prior to flight there is less certainty that it will.



Traditional EEE Parts Approach to *Confidence*

- **Part level screening**
  - **Electronic component screening uses environmental stressing and electrical testing to identify marginal and defective components within a procured lot of EEE parts.**
- **Part level qualification**
  - **Qualification processes are designed to statistically understand/remove known reliability risks and uncover other unknown risks inherent in a part.**
    - **Requires significant sample size and a comprehensive suite of piecepart testing (insight) = *High Confidence***

However, tradition doesn't match the changing space market

(time to market, risk profiles, etc...).

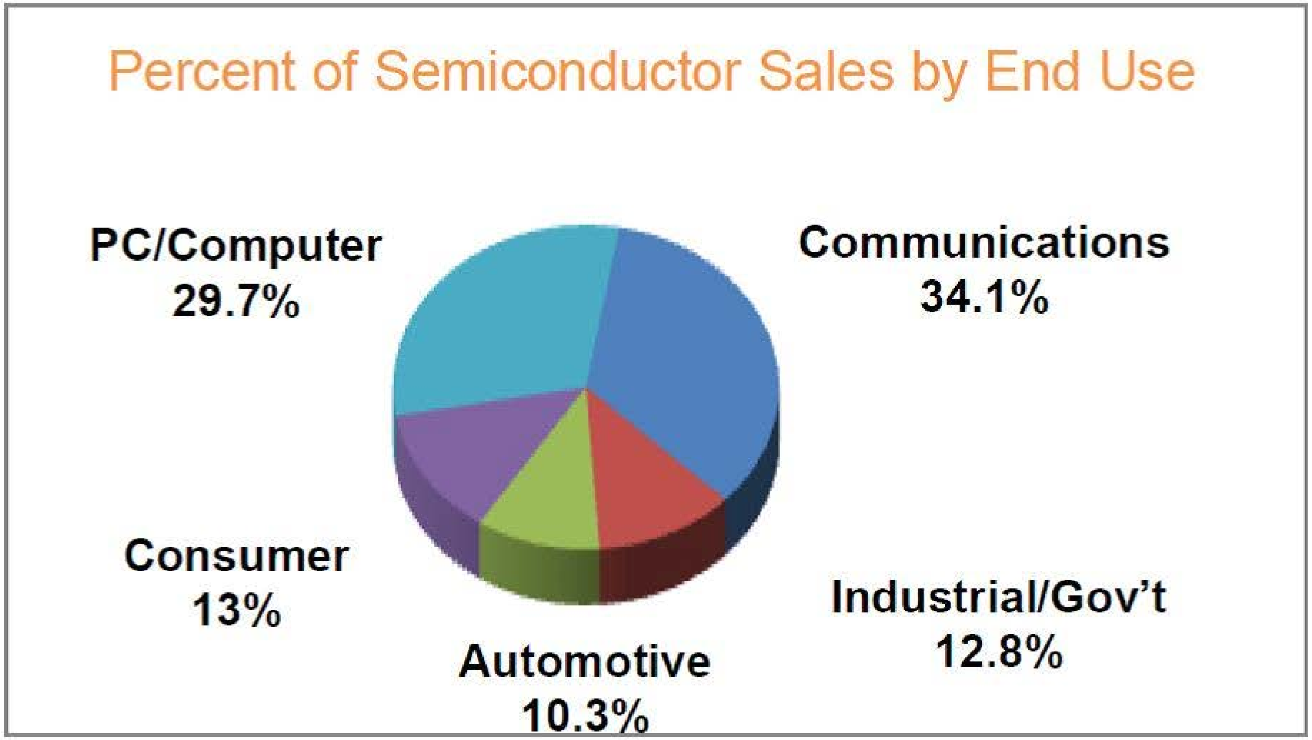
Alternate EEE parts approaches that *may* be "good enough" are being used.

(Discussed later in presentation.)

Modern Electronics

A History Lesson

2015 Global Semiconductor Market: $335 Billion



Source: WSTS End Use Report, 2015
Note: Military is <1% and is included in Industrial/Gov't

Military and Aerospace share is estimated at ~$3.1B in 2015.

Aerospace is a small percentage of this amount.

For comparison, in 1975

the Military and Aerospace market share was ~$50%!

EEE parts are available in “grades”

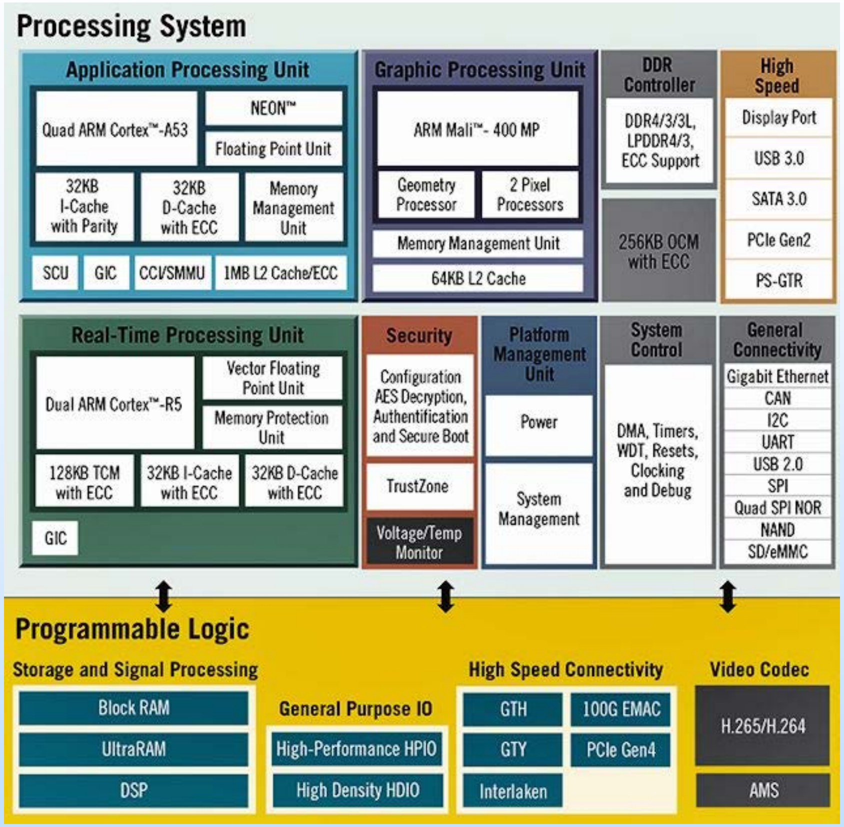
- **Grades – Designed, certified, qualified, and/or tested for specific environmental characteristics.**
  - **E.g., Operating temperature range, vacuum, radiation, exposure,…**
- **Example grades:**
  - **Aerospace, Military, Space Enhanced Product, Enhanced Product, Automotive, Medical, Extended-Temperature-Commercial, and Commercial (often called commercial off the shelf - COTS).**
  - ***Aerospace Grade* is the traditional choice for space usage, but has relatively few available parts and their performance lags behind commercial counterparts (speed, weight, and power - SWaP).**
    - ***Designed and tested for radiation and reliability for space usage.***
- **NASA uses a wide range of EEE part grades depending on multiple factors including technical, programmatic, and risk.**

The Magpie Syndrome:
The Electrical Designer's Dilemma

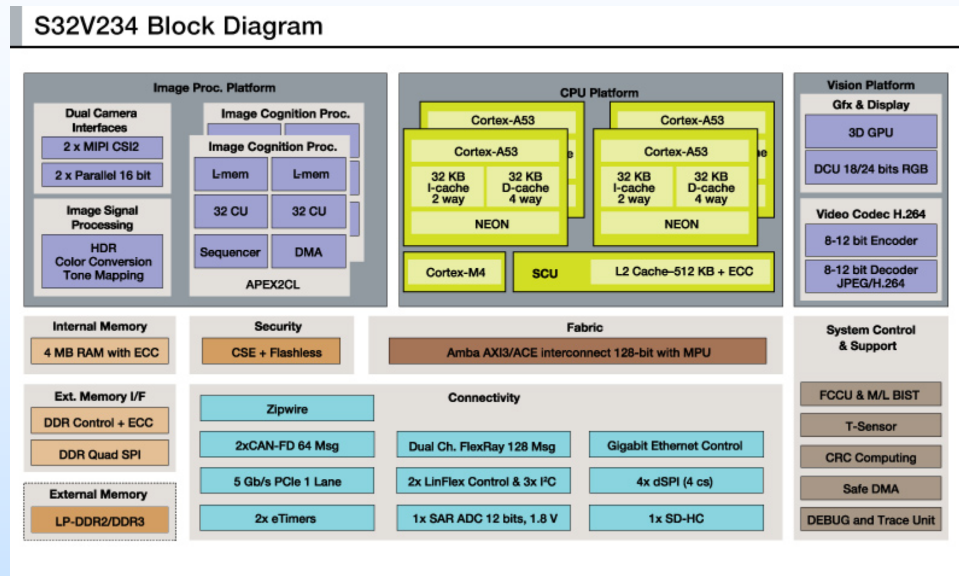
- **Magpie's are known for being attracted to bright, shiny things.**
- **In many ways, the modern electrical engineer is a Magpie:**
  - ***They are attracted to the latest commercial state-of-the-art devices and EEE parts technologies.***
    - **Usually any grade of EEE parts that aren't qualified for space nor radiation hardened.**
  - **These bright and shiny parts may have very attractive performance features that aren't available in higher-reliability parts:**
    - **Size, weight, and power (SwaP),**
    - **Integrated functionality,**
    - **Speed of data collection/transfer,**
    - **Processing capability, etc…**

Graphic from Clip Arts Free net.

Example Magpie EEE Parts

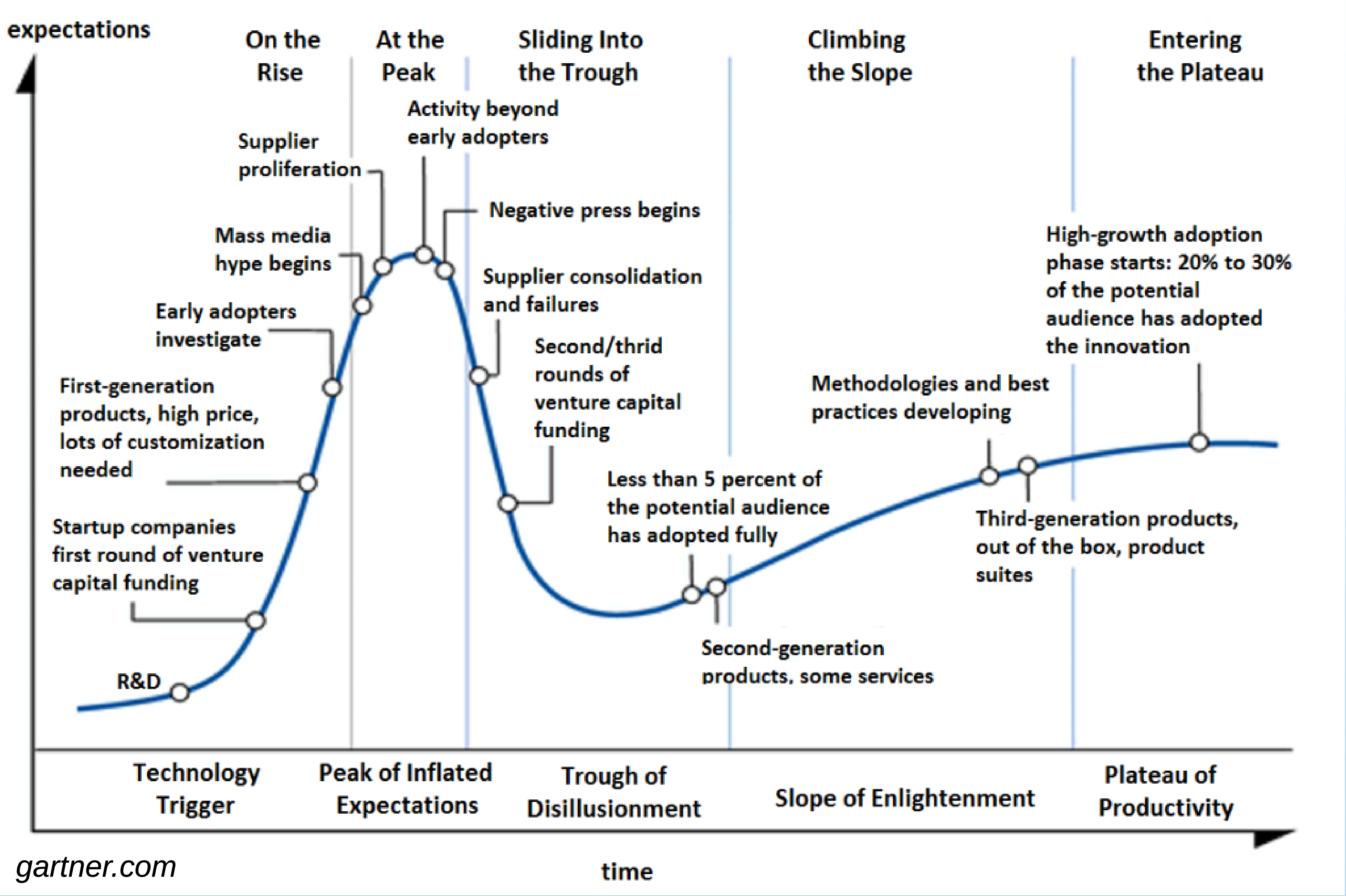


Xilinx Zynq UltraScale+
Multi-Processor System on a Chip (MPSoC) -
16nm CMOS with Vertical FinFETS
Xilinx.com



Advanced Driver Assistance System (ADAS)
Sensor Fusion Processor
Freescale.com

Gartner Hype Cycle –
Reality of Shiny New Things



Magpie Constraints

- But Magpies aren't designed for space flight
  - Just some aviary (bird) aviation at best!
- Sample differences include:
  - Temperature ranges,
  - Vacuum performance,
  - Shock and vibration,
  - Lifetime, and
  - Radiation tolerance.

Graphic from Free Vector Art.

- Traditionally, *"upscreening"* at the part level has occurred.
  - Definition: A means of assessing a portion of the inherent reliability of a device via test and analysis.
    - It does not increase reliability!
  - Note: Discovery of a part not passing upscreening is a regular occurrence.

Example Considerations for When a Magpie Flies

- **Aerospace (or at least Military grade) alternatives are not available,**
  - **Ex., SWaP or specific function or procurement schedule,**
- **Mission has a relatively short lifetime or benign space environment exposure,**
  - **Ex., 3 month CubeSat mission in LEO,**
- **System can assume risks (even unknown ones!),**
  - **Ex., a technology demonstration mission,**
- **Sufficient device upscreening (per mission requirements) and system validation are performed to obtain high enough confidence level for risk posture,**
- **Sufficient system level assurances based on fault tolerance/resilience, higher assembly level test, and validation.**
  - **Note: This is a systems engineering trade that takes a multi-disciplinary review.**
- **Out of scope for this talk: use of flight data for "qualification".**

Product Grades "Decoder Ring"

Quality / Reliability

R. Baumann, "From COTS to Space Electronics: Improving Reliability for Harsh Environments," 2016 Single Event Effects (SEE) Symp. and the Military and Aerospace Programmable Logic Devices (MAPLD) Workshop, May 23-26, 2016.

	COTS / COTS+		Enhanced Intermediate Grades			Space Grade	
	Commercial	AEC-Q100	EP	QMLQ	Space EP	QML-V	QMLV-RHA
Packaging	PLASTIC	PLASTIC	PLASTIC	CERAMIC	PLASTIC	CERAMIC	CERAMIC
Single Controlled Baseline	NO	NO	YES	YES	YES	YES	YES
Bond wires	Au or Cu	Au or Cu	Au	Al	Au	Al	Al
Pure Sn Used	YES	YES	NO	NO	NO	NO	NO
Burn-in Performed	NO	NO	NO	NO	NO	YES	YES
Radiation Tested	NO	NO	NO	NO	YES	YES	YES
Radiation Assured	NO	NO	NO	NO	YES	NO	YES
Temperature Range	-40 to 85ºC	-40 to 125ºC (only grade 1)	-55 to 125ºC (majority)	-55 to 125ºC	-55 to 125ºC (majority)	-55 to 125ºC	-55 to 125ºC
100% 3 Temp Test	NO	NO	NO	YES	25, 125ºC	YES	YES
Extra Qual/Process Monitors	NO	YES	YES	YES	YES	YES	YES
Life Test per lot	NO	NO	NO	NO	NO	YES	YES

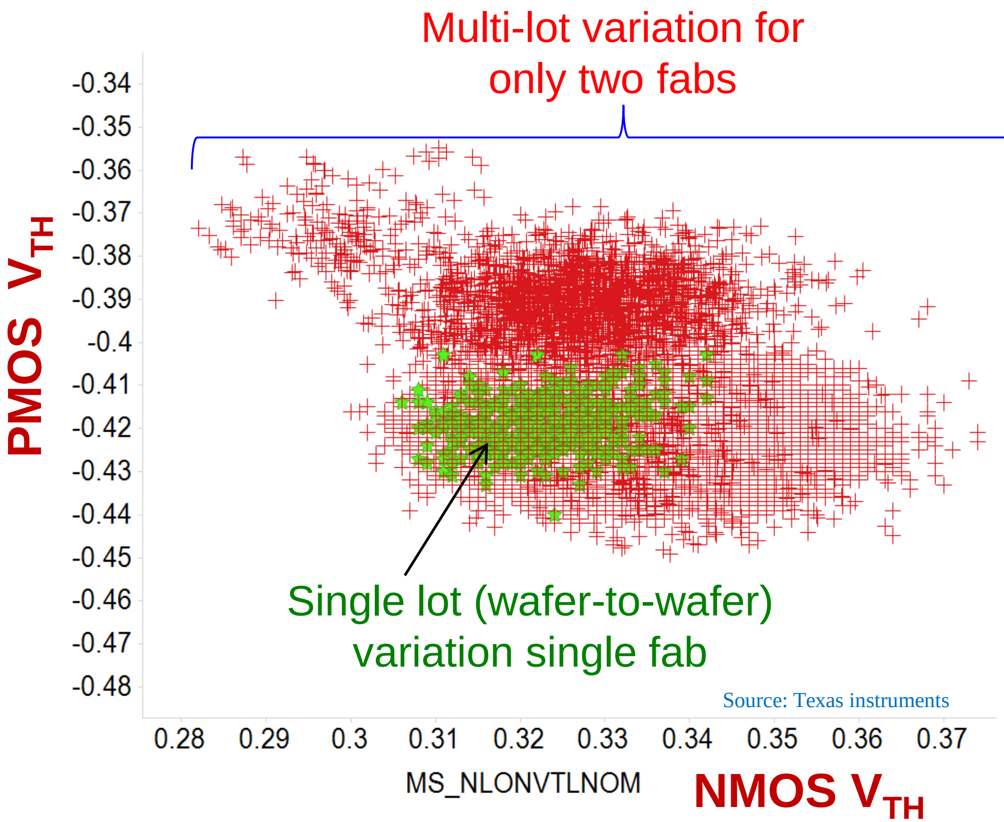
The move to the middle!

After Baumann, Radiation Effects on Components and Systems (RADECS) conference, Gothenburg, Sweden, September 16-21, 2018.

Multi-Fab Variability Example

- Why Single Controlled Baseline is Important

- **Fab-to-Fab**
  - Usually worse than Lot-to-Lot
  - Fab equipment set / version
  - Fab layout / cycle time
  - Fab recipe / starting material
  - Fab metrology coverage
  - Fab controls / methods
  - Revisions / shrinks
  - Design sensitivity / component choice
- **Lot-to-Lot**
  - Usually worse than wafer-to-wafer
  - Process has a natural variation
  - Processes / Equipment drifts over time
  - Process tweaks to boost yield



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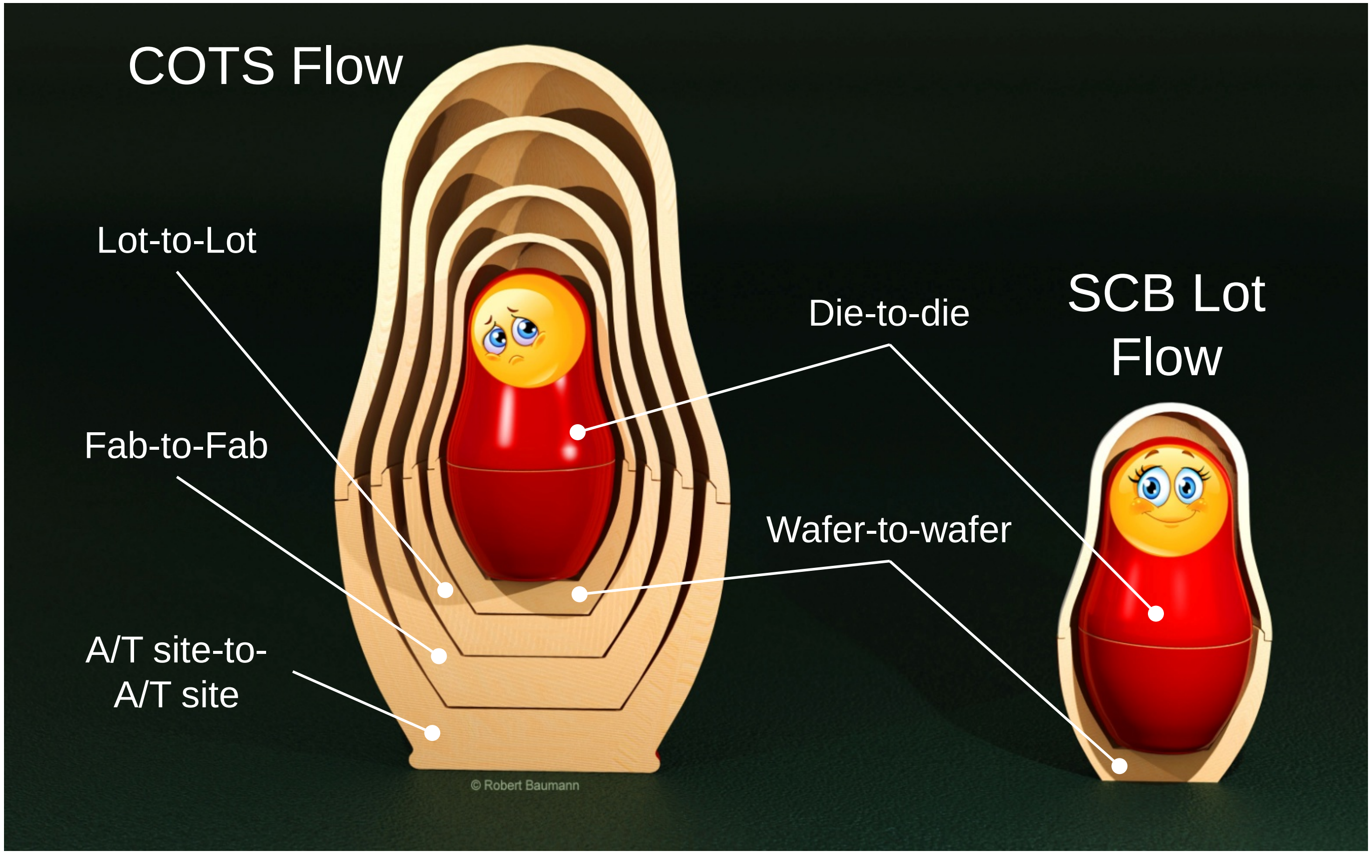
Variation and the “Matryoshka Paradigm”



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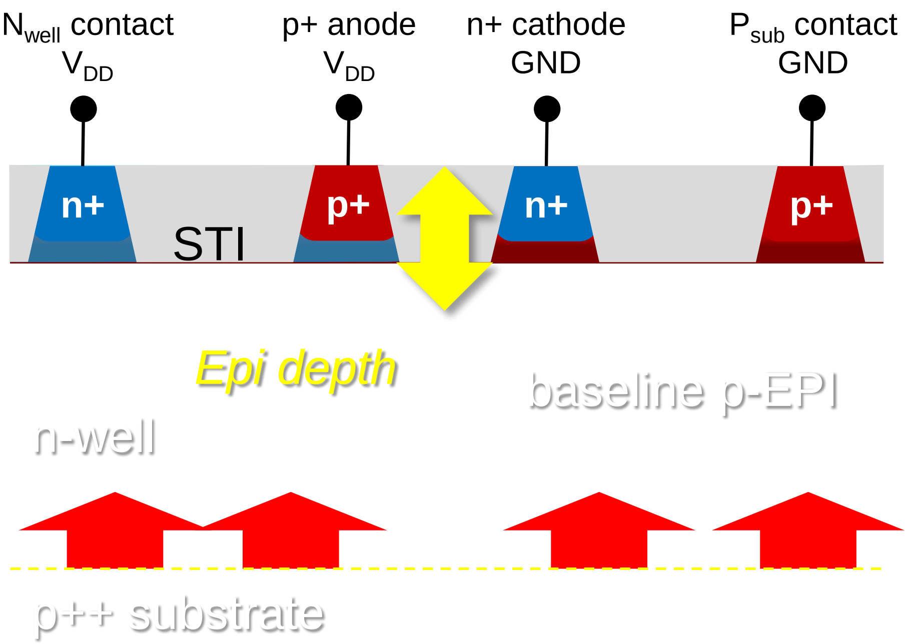
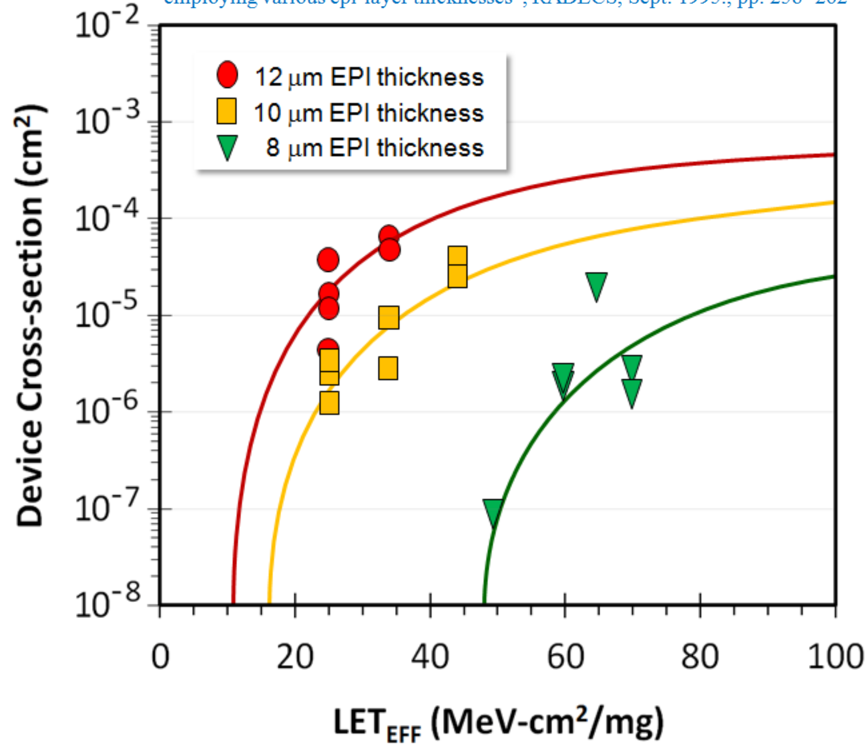
Mitigation of Single Event Latchup by Process

Example Variation Impact on Radiation Tolerance



from K. LaBel, et al., "Single event effect characteristics of CMOS devices employing various epi-layer thicknesses", RADECS, Sept. 1995., pp. 258- 262



Substitute standard p substrate with highly-doped substrate w thin baseline EPI

After Baumann, Radiation Effects on Components and Systems (RADECS) conference, Gothenburg, Sweden, September 16-21, 2018.

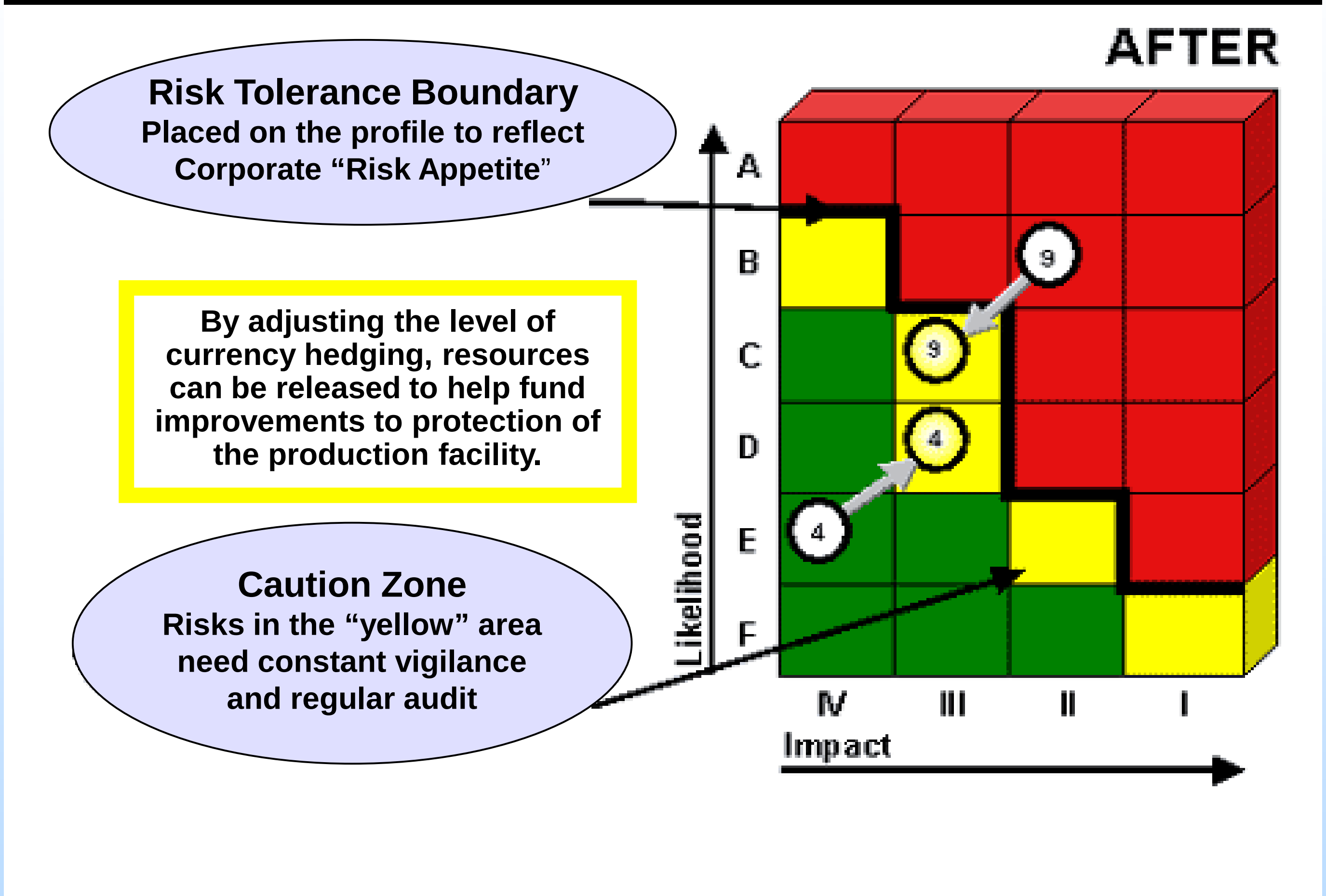
Mission Risk and EEE Parts

Understanding Risk

- **The risk management requirements may be broken into three considerations**
  - **Technical/Design – "The Good"**
    - **Relate to the circuit designs not being able to meet mission criteria such as jitter related to a long dwell time of a telescope on an object**
  - **Programmatic – "The Bad"**
    - **Relate to a mission missing a launch window or exceeding a budgetary cost cap which can lead to mission cancellation**
  - **Radiation/Reliability – "The Ugly"**
    - **Relate to mission meeting its lifetime and performance goals without premature failures or unexpected anomalies**
- ***Each mission must determine its priorities among the three risk types***

Graphic from Free Vector Art.

Background: Traditional Risk Matrix



Likelihood Scale:	A: Very High	B: High	C: Occasional	D: Low	E: Very Low	F: Almost Impossible
Impact Scale:	I: Catastrophic	II: Critical	III: Significant	IV: Marginal		

Space Missions: EEE Parts and Risk

- **The determination of acceptability for device usage is a complex trade space.**
  - **Every engineer will "solve" a problem differently:**
    - **Ex., software versus hardware solutions.**
- **The following chart proposes an alternate mission risk matrix approach for EEE parts based on:**
  - ***Environment exposure*, **
  - ***Mission lifetime*, and,**
  - ***Criticality* of implemented function.**
- **Notes:**
  - **"COTS" implies any parts grade that is not space qualified and radiation hardened.**
  - **Level 1 and level 2 refer to traditional space qualified EEE parts.**

Notional EEE Parts Selection Factors

Criticality	Low	Medium	High
High	Level 1 or 2 suggested. COTS upscreening/ testing recommended. Fault tolerant designs for COTS.	Level 1 or 2, rad hard suggested. Full upscreening for COTS. Fault tolerant designs for COTS.	Level 1 or 2, rad hard recommended. Full upscreening for COTS. Fault tolerant designs for COTS.
Medium	COTS upscreening/ testing recommended. Fault-tolerance suggested	COTS upscreening/ testing recommended. Fault-tolerance recommended	Level 1 or 2, rad hard suggested. Full upscreening for COTS. Fault tolerant designs for COTS.
Low	COTS upscreening/ testing optional. Do no harm (to others)	COTS upscreening/ testing recommended. Fault-tolerance suggested. Do no harm (to others)	Rad hard suggested. COTS upscreening/ testing recommended. Fault tolerance recommended

Environment/Lifetime

A Few Details on the "Matrix"

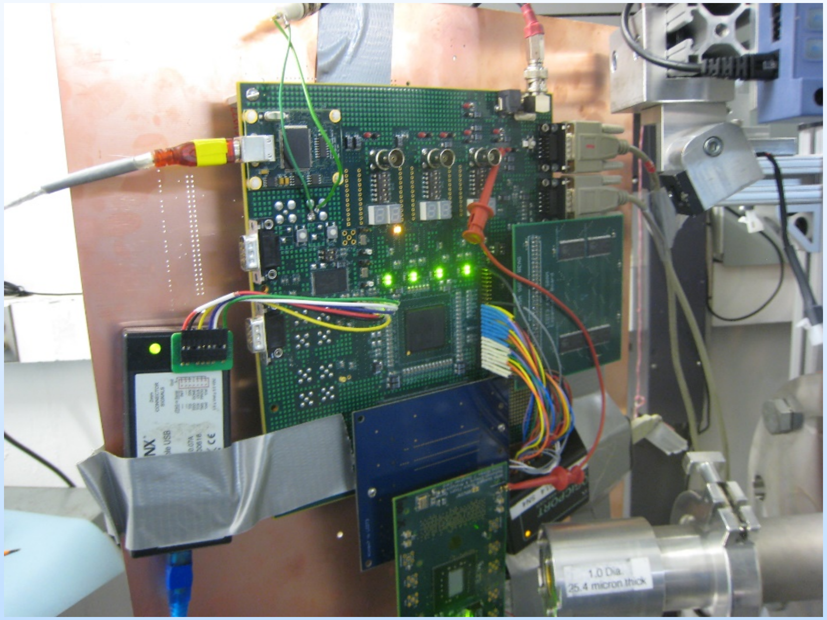
- When to test:
  - "Optional"
    - Implies that you might get away without this, but there's residual risk.
  - "Suggested"
    - Implies that it is good idea to do this, and likely some risk if you don't.
  - "Recommended"
    - Implies that this really should be done or you'll definitely have some risk.
  - Where just the item is listed (like "full upscreening for COTS")
    - This should be done to meet the criticality and environment/lifetime concerns.
- All fault tolerance/resilience must be validated.
- The higher the level of risk (i.e., more risk) that a mission deems acceptable,
  - The greater the consideration for performing "alternate" assembly level testing versus traditional part level (reduced confidence approaches).

Good mission planning identifies where on the matrix a EEE part lies.

Breaking Tradition:

Alternate Approaches to EEE Parts Assurance

Assembly Testing: Can it Replace Testing at the Parts Level?



NASA GSFC Picture of FPGA tester.

We can test devices,

but how do we test systems?

Or better yet, systems of systems on a chip (SOC)?

Not All Assemblies are Equal

- Consider two distinct categories of assemblies:
  - Off the shelf (you get what you get) such as COTS, and,
  - Custom (possibility of having specific "design for test")
    - Still won't be as complete as single part level testing, but it does reduce some challenges.
- For COTS assemblies, some specific concerns include:
  - Bill-of-materials may not include lot date codes or device manufacturer information.
  - Individual part application may not be known or datasheet unavailable.
  - The possible variances for "copies" of the "same" assembly:
    - Form, fit, and function EEE parts may mean various manufacturers, or,
    - Other variation as discussed earlier (lot-to-lot, fab-to-fab).

Selected Challenges for Testing Assemblies

- Limited statistics versus part level approaches due to sample size.
- Inspection constraints.
- Reliability acceleration factors
  - Temperature testing limited to “weakest” part.
  - Voltage testing may be limited by on-board/on-chip power regulation.
- Limited test points and I/O = inadequate visibility of errors/failures/faults.
- Inadequate fault coverage testing.
- System operation.
  - Ex., Using nominal flight software versus a high stress test approach.
- Error propagation
  - An error occurs, but does not propagate outward until some time later due to system operations such as those of an interrupt register.
- Fault masking during radiation exposure
  - Too high a particle rate or too many devices being exposed simultaneously.

Using Fault Tolerance to Improve "Reliability/Availability"

- **Operational**
  - Ex., no operation in the South Atlantic Anomaly (proton hazard)
- **System**
  - Ex., redundant boxes/busses or swarms of nanosats
- **Circuit/software**
  - Ex., error detection and correction (EDAC) scrubbing of memory devices by an external device or processor
- **Device (part)**
  - Ex., triple-modular redundancy (TMR) of internal logic within the device
- **Transistor**
  - Ex., use of annular transistors for Total Ionizing Dose (TID) improvement
- **Material**
  - Ex., addition of an epi substrate to reduce Single Event Effect (SEE) charge collection (or other substrate engineering)

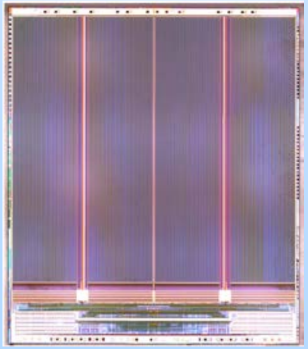
Good engineers can invent infinite solutions, but the solution used must be adequately validated.

It's easy to show a working block diagram, it's hard to provide sufficient validation details.

Possible Exceptions:
Is Radiation Testing Always Required for COTS?

- **Operational**
  - Ex., The device is only powered on once per orbit and the sensitive time window for a single event effect is minimal
- **Acceptable data loss**
  - Ex., System level error rate (availability) may be set such that data is gathered 95% of the time.
    - Given physical device volume and assuming every ion causes an upset, this worst-case rate may be acceptable.
- **Negligible effect**
  - Ex., A 2 week mission may have a very low Total Ionizing Dose (TID) requirement.

Memory picture courtesy NASA/GSFC, Code 561



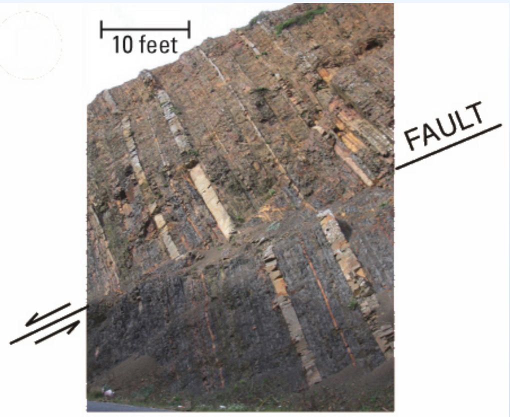
A flash memory may be acceptable without testing if a low TID requirement exists or not powered on for the large majority of time.

Is knowledge of EEE Parts Failure Modes Required To Build a Fault Tolerant System?

- **The system *may* work, but is there adequate confidence in the system to meet reliability and availability after launch?**
- **In no particular order:**
  - **What are the "unknown unknowns"?**
    - **Can we account for them?**
  - **How do you adequately validate a fault tolerant system for space?**
    - ***<u>This is a critical point.</u>***
  - **How do you calculate risk with unscreened/untested EEE parts?**
  - **Do you have a common mode failure potential in your design?**
    - **I.e., a design with identical redundant strings rather than having independent redundant strings.**

Summary: Assembly Testing and Fault Tolerance

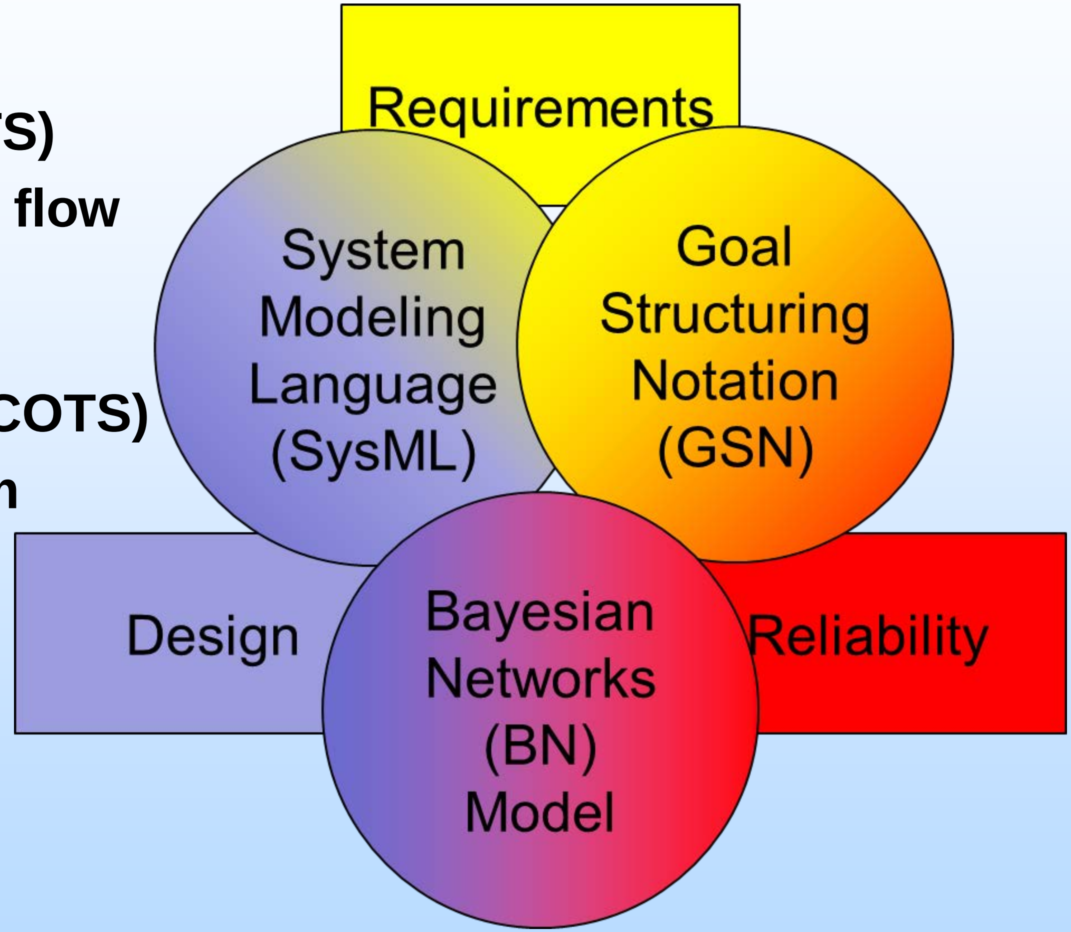
- **While clearly ANY testing is better than none, assembly testing has limitations compared to the individual EEE part level.**
  - **This is a risk-trade that's still to be understood.**
  - **No *definitive* study exists comparing this approach versus traditional parts qualification and screening.**
- **Fault tolerance needs to be validated.**
  - **Understanding the fault and failure signatures is required to design appropriate tolerance.**
  - **The more complex the system, the harder the validation is.**
- **NOTE: NEPP is in final development of a proton test guideline for assemblies**



NEPP View of SmallSat Assurance

Model Based Mission Assurance (MBMA)

- **Motivation**
  - **Commercial parts (COTS)**
  - **Document-centric work flow to model-based system engineering**
  - **System mitigation (for COTS)**
  - **Single source of system design parameters**



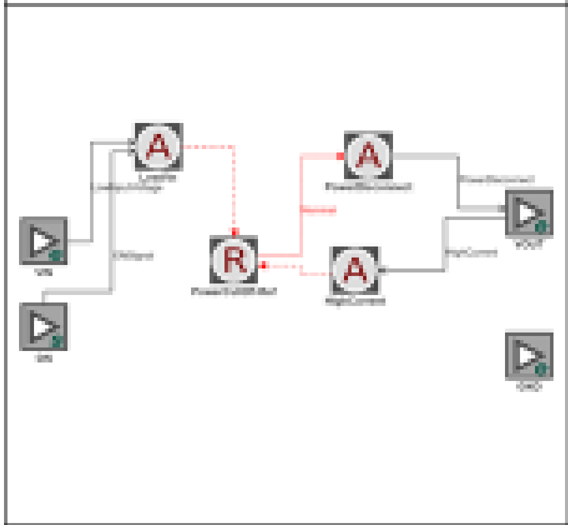
https://modelbasedassurance.org/

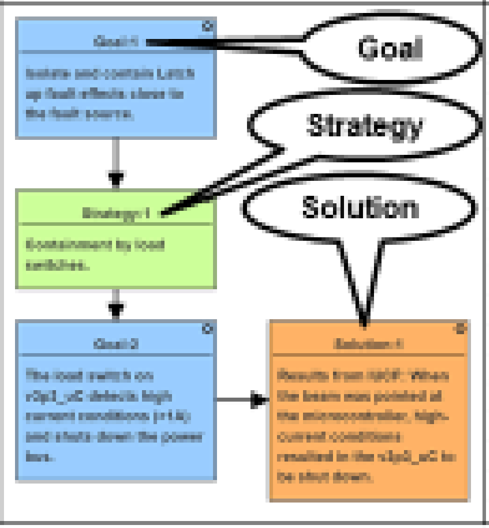
Overview of Modeling Languages Used - Model Based Systems Engineering (MBSE)

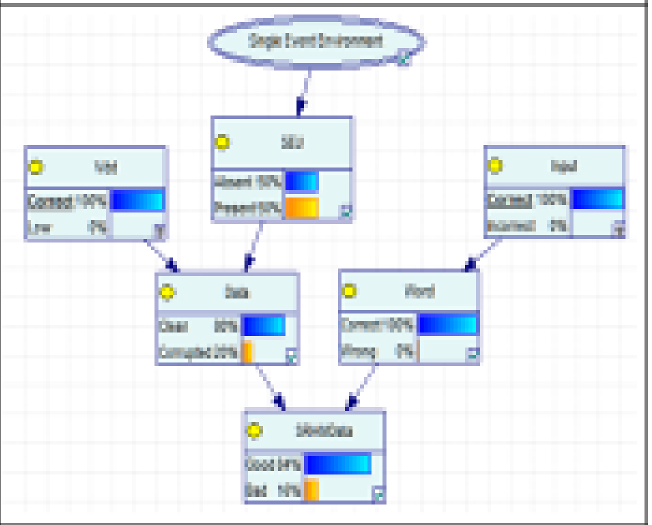
Overview of Modeling Languages Used

Vanderbilt Engineering

SysML	GSN	Bayes Net
• Specification of systems through standard notation • Added fault propagation paths	• Visual representation of argument • Goals, Strategies, and Solutions	• Nodes describe probabilities of states • Calculate conditional probabilities from observations







Presented at NASA Electronic Parts and Packaging (NEPP) Technical Interchange Meeting (TIM), Vanderbilt University, Nashville, TN, August 29-30, 2017. 10

Rebekah Austin, Vanderbilt University, used by permission.

Summary

- **In this talk, we have presented:**
  - **An overview of considerations for alternate EEE parts approaches:**
    - **Technical, programmatic, and risk-oriented**
      - **Every mission views the relative priorities differently.**
- **As seen below, every decision type may have a process.**
  - **It's all in developing an appropriate one for your application and avoiding "buyer's remorse"!**

Five stages of Consumer Behavior

P. Kotler and G. Armstrong, "Consider Purchase Decision Process Model Reference," Principles of Marketing, 2001.