Designing for Sustainability in Electronics - If not now, when?... and how?

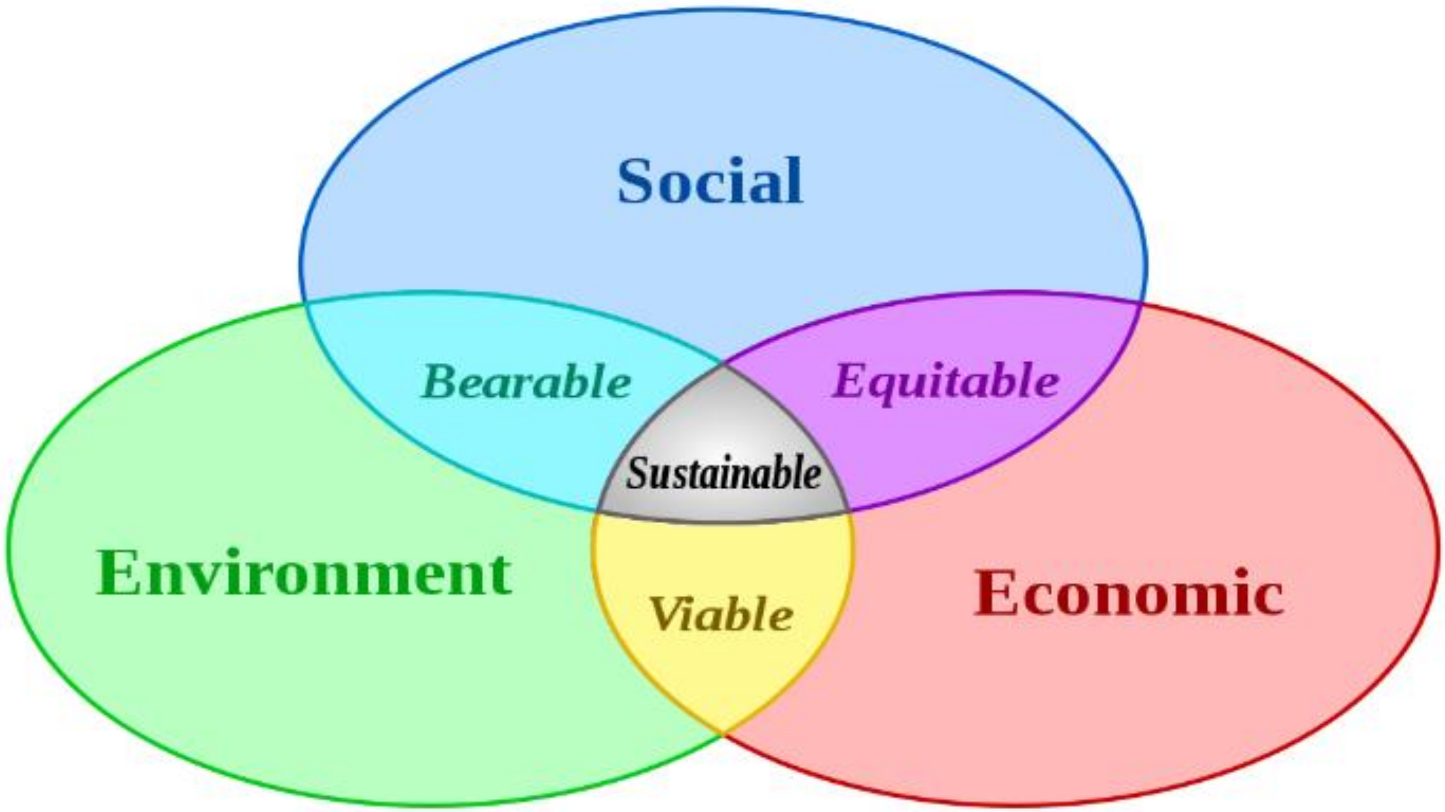
Joseph Fjelstad

Verdant
ELECTRONICS

Origins of Sustainability

- The Seventh Generation Philosophy – 1600s?
  - Centuries old Native American mandate that tribal decision makers consider the effects of their actions and decisions for descendants seven generations into the future. Acknowledgement that everything done today has consequences for something and someone else both now and in the future because of the interconnectedness of everything on the planet.
- *"The Fight for Conservation"* - Gifford Pinchot – 1910
  - "The right of the present generation to use what it needs and all it needs of the natural resources now available [recognizing] equally our obligation so to use what we need that our descendants shall not be deprived of what they need."
- United Nations' Brundtland Commission -1987
  - "Sustainable Development is development that meets needs of the present without compromising the ability of future generations to meet their own needs"
- World Summit on Social Development - 2004
  - Triple Bottom Line of Sustainable Development…
  - Economic development, social development, environmental protection

Making The Triple Bottom Line Work



Originator: Johann Dre'o

Importance of Industrial Ecology

Industrial ecology is the multidisciplinary study of industrial systems and economic activities, and their links to fundamental natural systems.

B. R. Allenby, *Industrial Ecology: Policy Framework and Implementation*, Prentice Hall, Englewood Cliffs, NJ (1999).

Sustainability Drivers

- **Top business drivers for sustainability**
  - Customer demand
  - Competitive advantage
  - Need to comply with legislation/standards
- **Social drivers for sustainability**
  - Public opinion
  - Corporate values and policies
  - Media spotlight (e.g. sustainability rankings)
  - Moral imperative to assure survival of species

Corporate Touchstones to Addressing Sustainability

- Management commitment
- Management Systems
- Stakeholder involvement
- Best practices identification
- Triple Bottom Line cornerstones
- Supply chain buy in and involvement
- Measurement and Analysis (e.g. LCA)
- “On the record” communications
- Inculcation of the workforce
- Innovation and acceptance of change

Principles of Sustainable Production

Products are safe and ecologically sound throughout life cycle

- designed to be durable, repairable, readily recycled, compostable, or easily biodegradable;
- produced and packaged using the minimal amount of material and energy possible.

Processes are designed and operated such that:

- wastes and ecologically incompatible byproducts are reduced, eliminated or recycled on-site;
- substances or physical agents and conditions that present hazards to human health or the environment are eliminated;
- energy and materials are conserved, and the forms of energy and materials used are most appropriate for the desired ends;
- work spaces are designed to minimize or eliminate chemical, ergonomic and physical hazard.

Source: Lowell Center for Sustainable Production

Sustainability/Reliability Nexus

- To hold to the ideals of sustainable manufacturing, the electronics industry must make products that are be robust enough that they can be passed along to future users with no concern about longer term reliability.
- In Japan and elsewhere, the manufacturing community has rallied around the idea that to build sustainable products one only need consider "Three Rs"… Reduce, (materials and energy), Reuse and Recycle.
- Reliability should be added to that list as reliability and sustainability are really intrinsically linked.

Reliability is Defined as:

… the measure of a product's ability to:

perform a specific function or service

in a specified use environment

for a specified amount of time without unscheduled interruption

Reliability is commonly reported in terms such as mean time to failure.

However it was suggested by one observer that reliability may perhaps be best measured not on the return of product but by the return of the customer…

Reliability is key to customer trust and retention

Changing Views on Reliability

- Reliability expectations vary for different types of products depending on application.
- However the importance of reliability has been fading, especially for consumer products due to faster products cycles
- The concept of application specific reliability should be a concern to manufacturer and consumer alike
- Electronic products are rapidly becoming much like seasonal fashion statements
- Is the electronics industry headed in the right direction?

Reliability and Economics

Origins of Planned Obsolescence

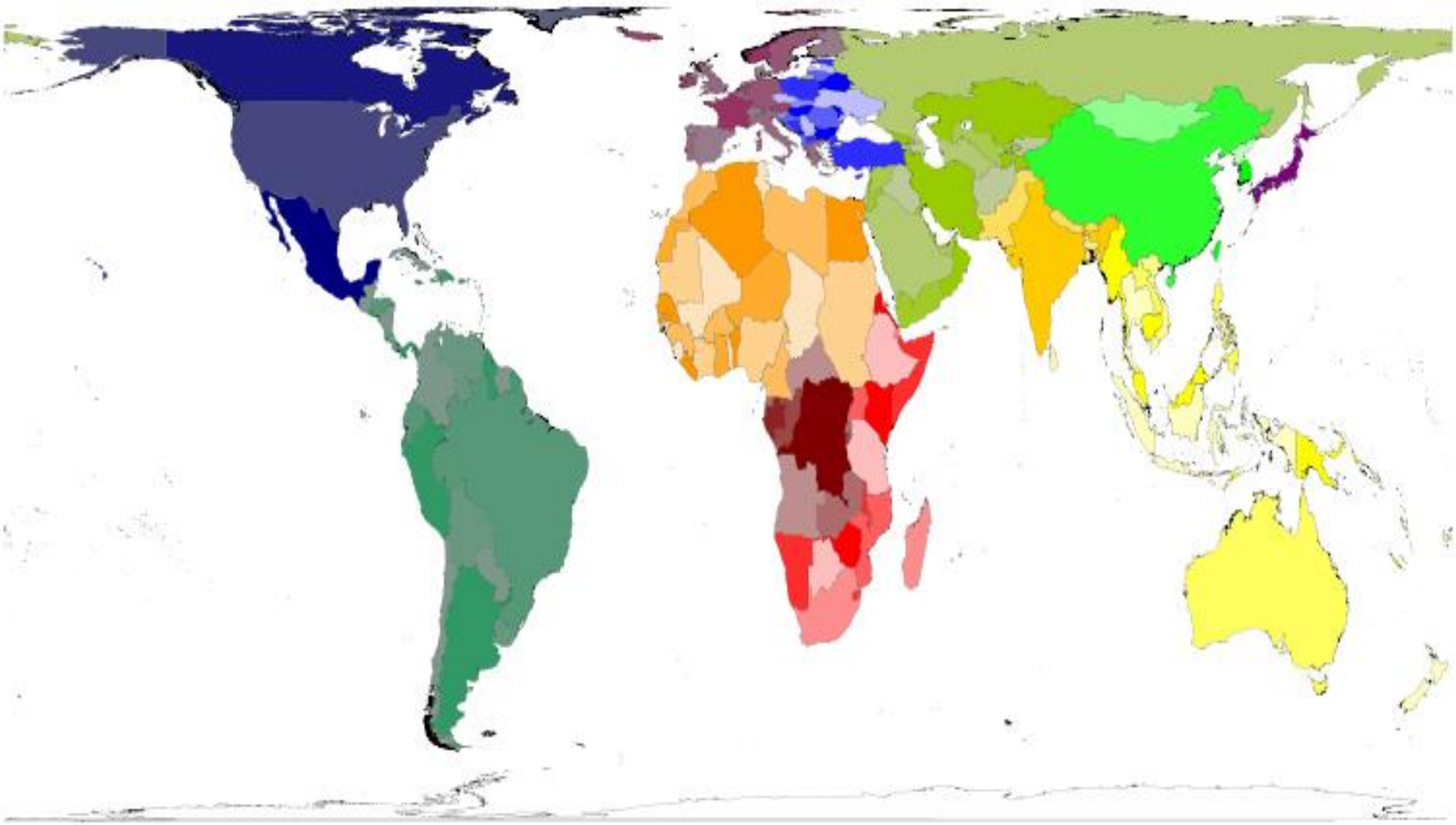
- Concept dated to 1932 with the publication of Bernard London's pamphlet titled *"Ending the Depression through Planned Obsolescence"*.
- The fundamental idea was to create products that became obsolete or ceased to function after a certain period of time or amount of use in a way that is planned or designed for by the manufacturer
- London extolled the importance to the economy of consumers not delaying purchases.
- The concept holds sway still today but there have been subtle changes…
- Advertising influences emotions and confuses wants and needs

Impact of Planning for Failure

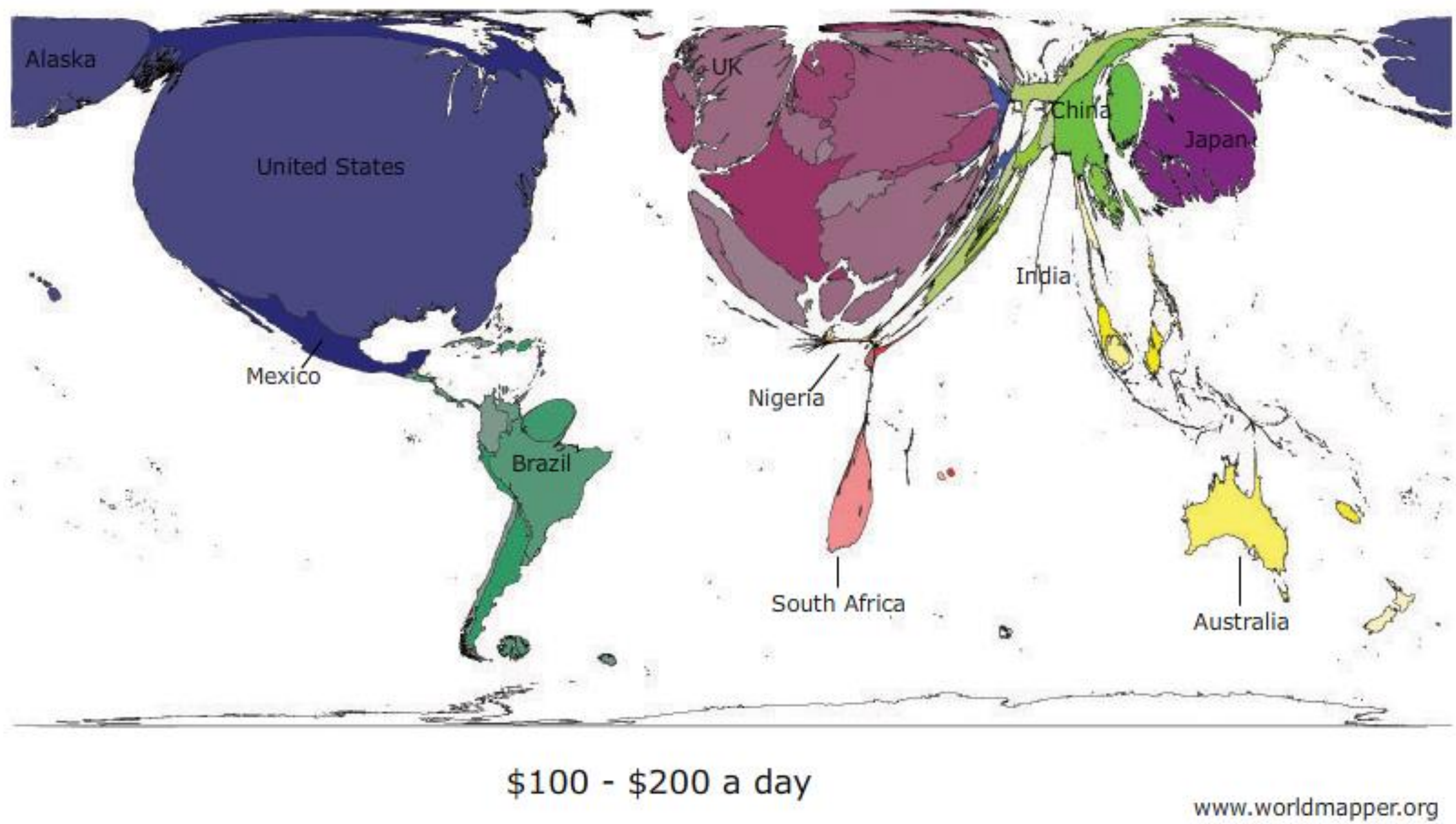
- For planned obsolescence to work, some self-destructive mechanisms must be integrated (implicitly if not explicitly) into the manufacturing systems. One is a reduced concern about reliability.
- "Brave New World" by Aldus Huxley -1932
- There is another negative aspect to accelerating the rate of change in product cycles…

  It is simply not sustainable if all of the world's peoples are to be served and benefit from electronic products nor it is morally or environmentally responsible with most present approaches. The world is bigger than just the developed nations

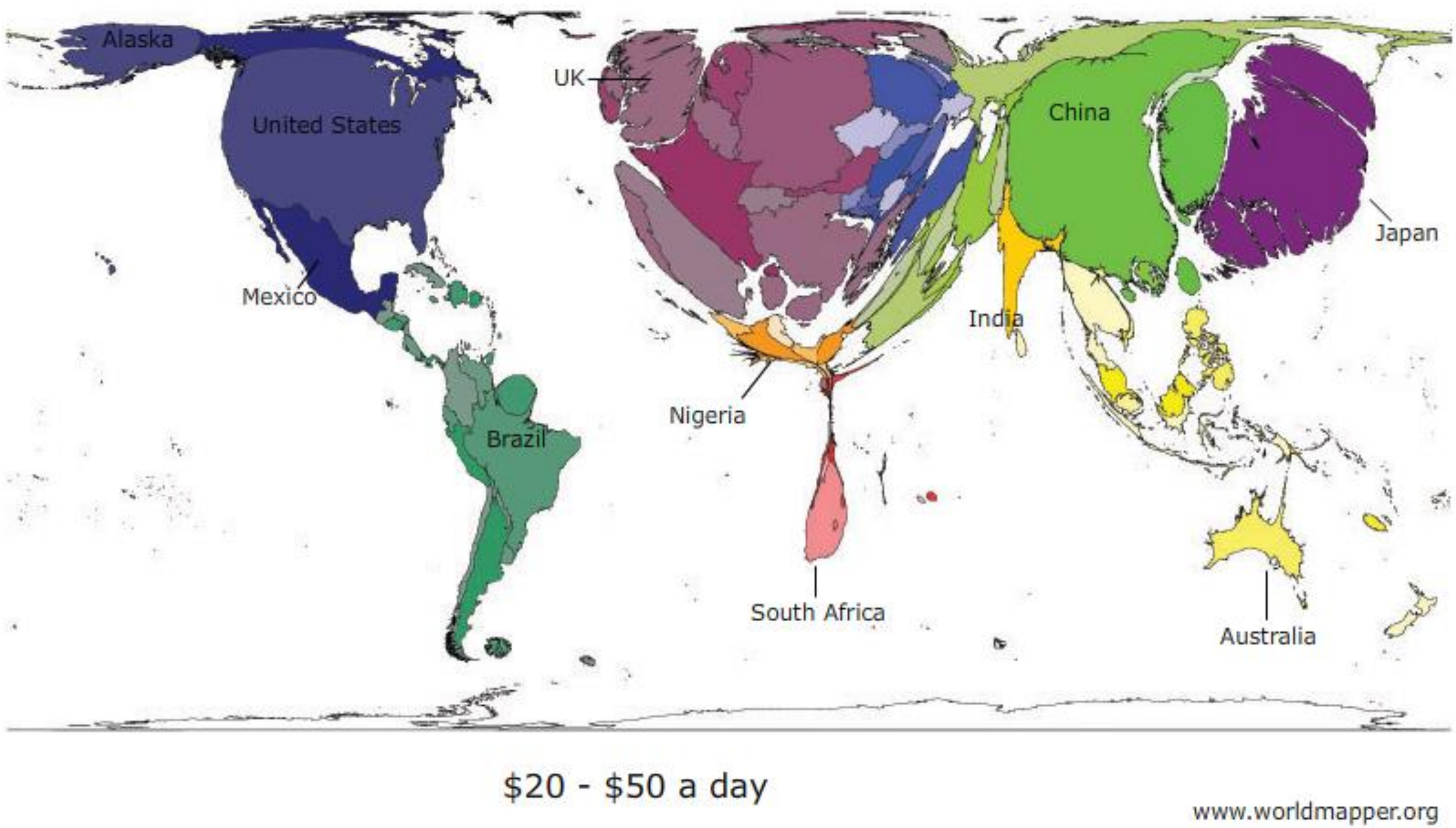
World Geo-Political Map



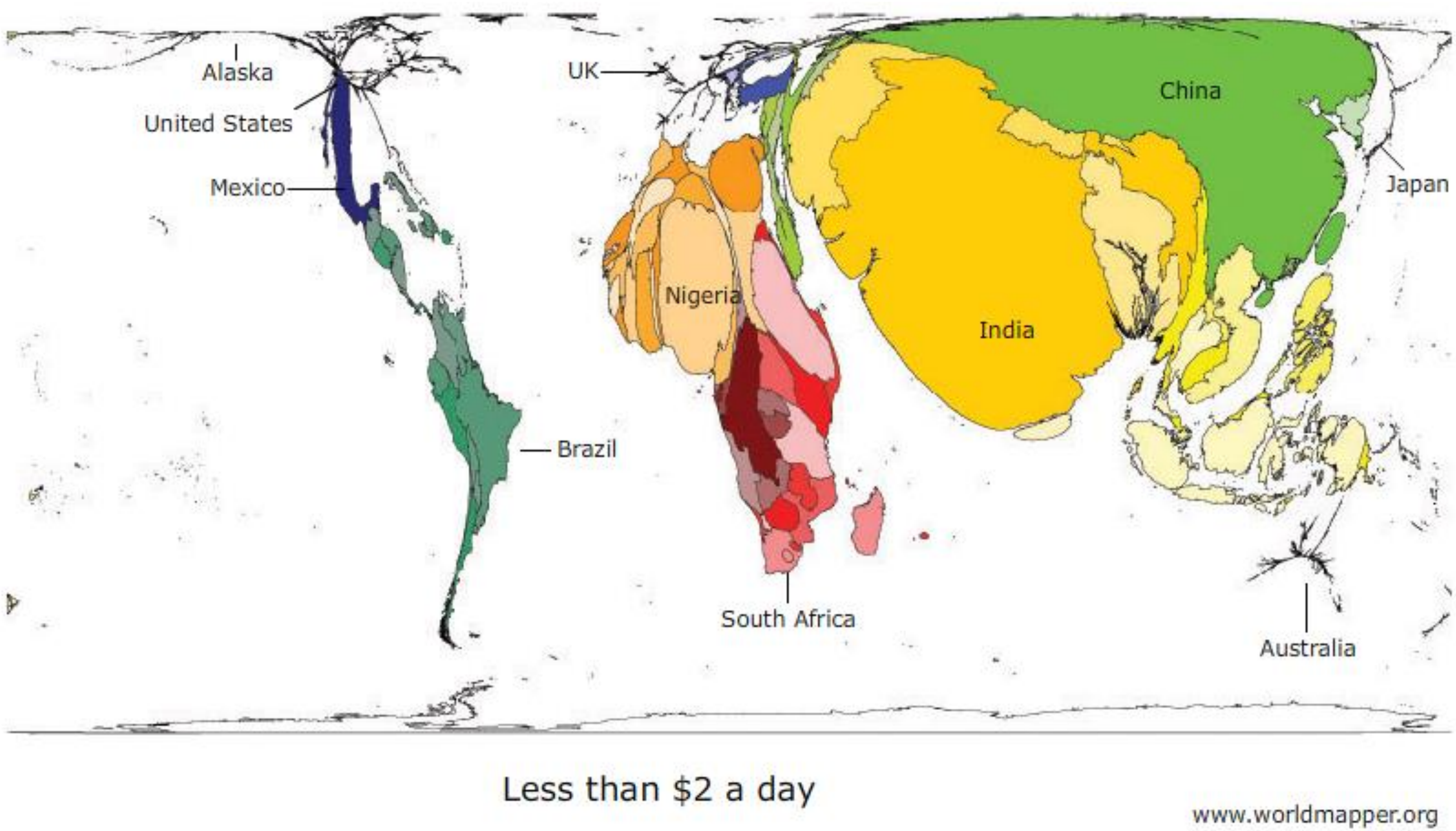
Individual Purchasing Power $100 to $200 per day



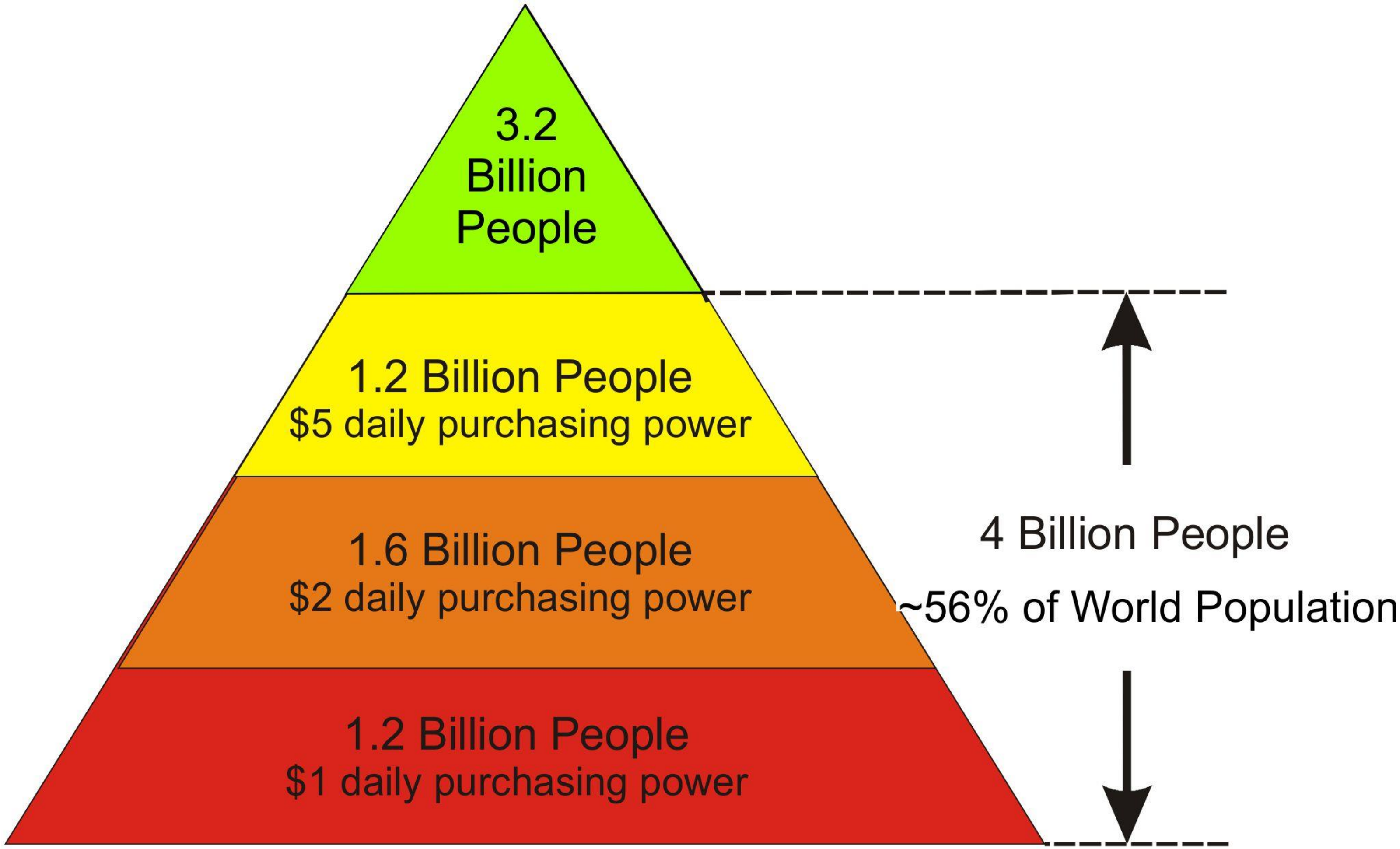
Individual Purchasing Power $20 to $50 per day



Individual Purchasing Power Less than $2 per day



More Reliable Products are Required to Meet the Needs of a Growing Population



Low income = Lower education = Fewer opportunities and a higher birthrate

Outline for a Sustainable Future… Utopian or Simply Necessary?

1. Human fertility limited to the replacement rate to stabilize population.
2. Natural resource use and pollution per unit of industrial output cut by at least 75 percent.
3. Industrial production stabilized at the level prevailing in the late twentieth century.
4. Goods and services redistributed from the rich to the poor to provide a high quality of life for all members of the global community

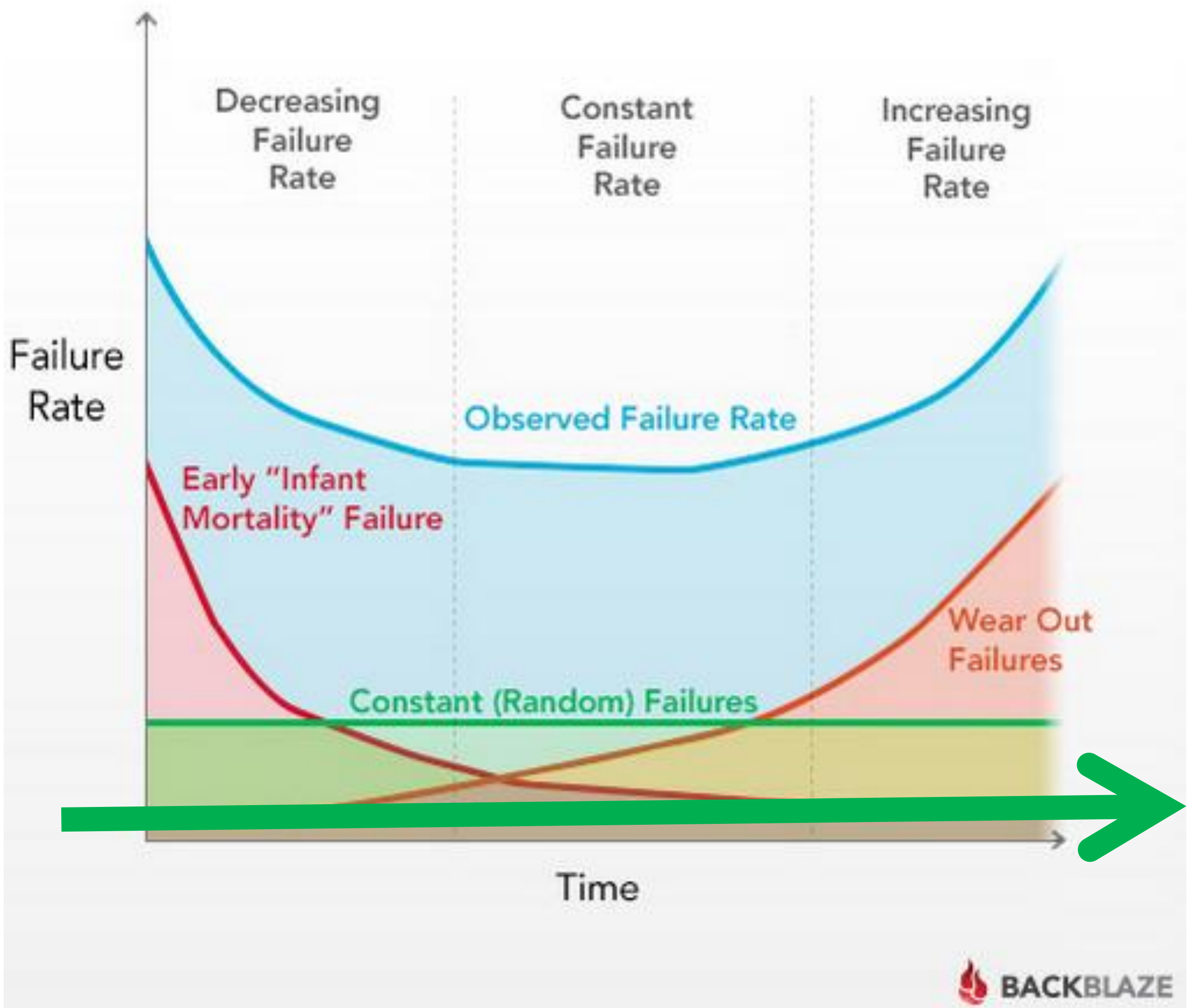
Source: D. Meadows, et. al. ***The Limits to Growth*** 1972

Electronics and Sustainability
Current Status

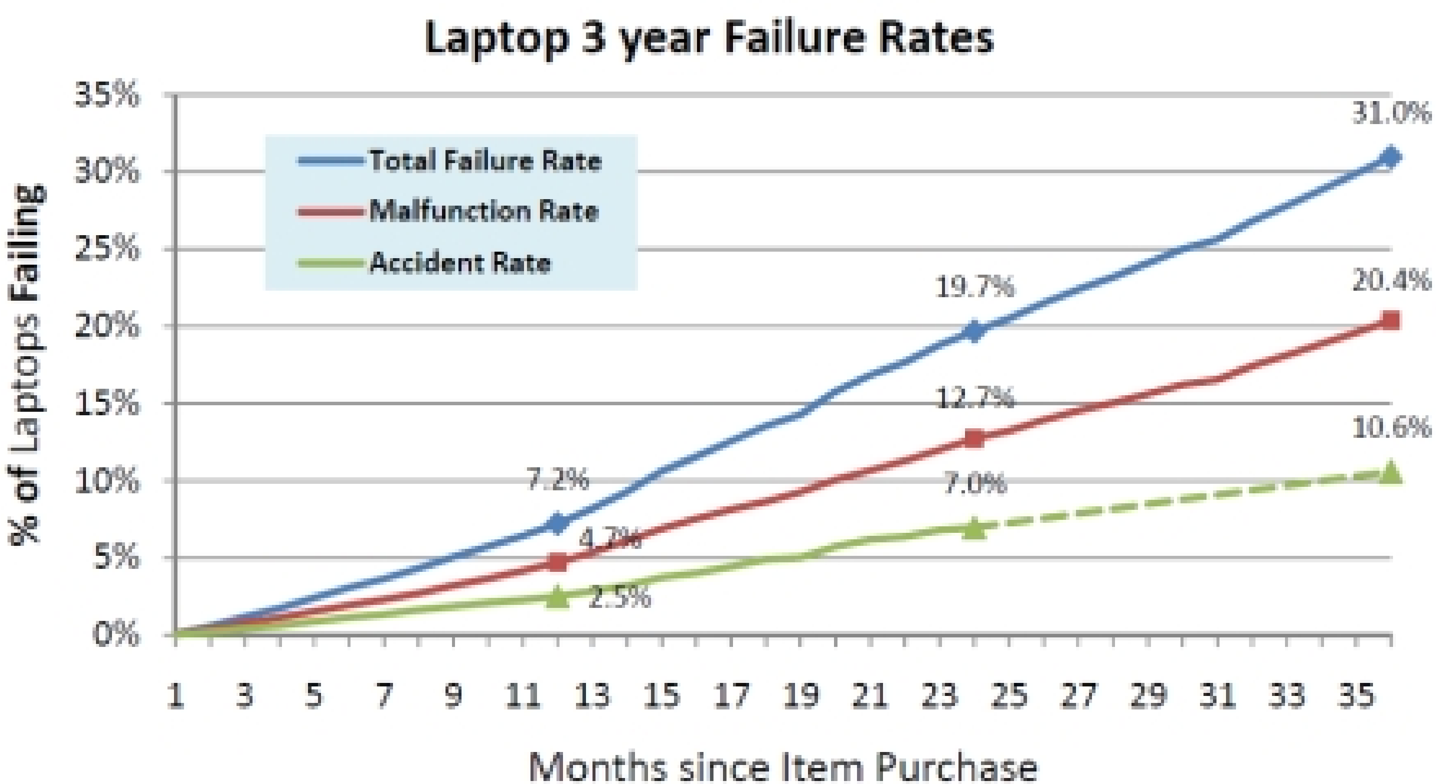
Electronics Slipping Reputation

- Warranty provider, Square Trade published a report titled: "*1 in 3 Laptops Fail Within 3 Years*"
- The report noted that a full two-thirds of these failures (20.4% of all product built) were the result of hardware malfunctions.
- The other third (10.6%) were from accidental damage
- The report also noted that the increasingly popular netbooks are projected to have a 20% higher failure rate from hardware malfunctions than more expensive laptop computers.
- This should be a wake up call to both electronic manufacturers and electronic consumers alike

General Failure Rates



Failure Rates…
Are They "Good Enough"?



Economics of Early Failure

- Early failures result in higher warranty costs to the manufacturer and the potential for product recalls, the cost of which can run into tens of millions of dollars
- Those millions in losses could potentially be multiplied many times over as every manufacturer faces the same risk when products do not perform to promised levels.
- In short, poor reliability is very costly to individual companies, the world's peoples & the environment

Reliability
and
The Environment

“Green” Legislation Impact

“The road to hell is paved with good intentions”
~ Proverb ~

- Lead free solder negatively to electronics reliability
  - Higher energy use
  - Moisture sensitivity increase
  - Thermal damage to components and boards
  - Shock and vibration
  - Tin whiskers return
- Net effect?
  - Reduced product reliability at increased cost
  - Overall negative impact on the environment

Lead Levels in US Population vs Lead in Gasoline Over Time

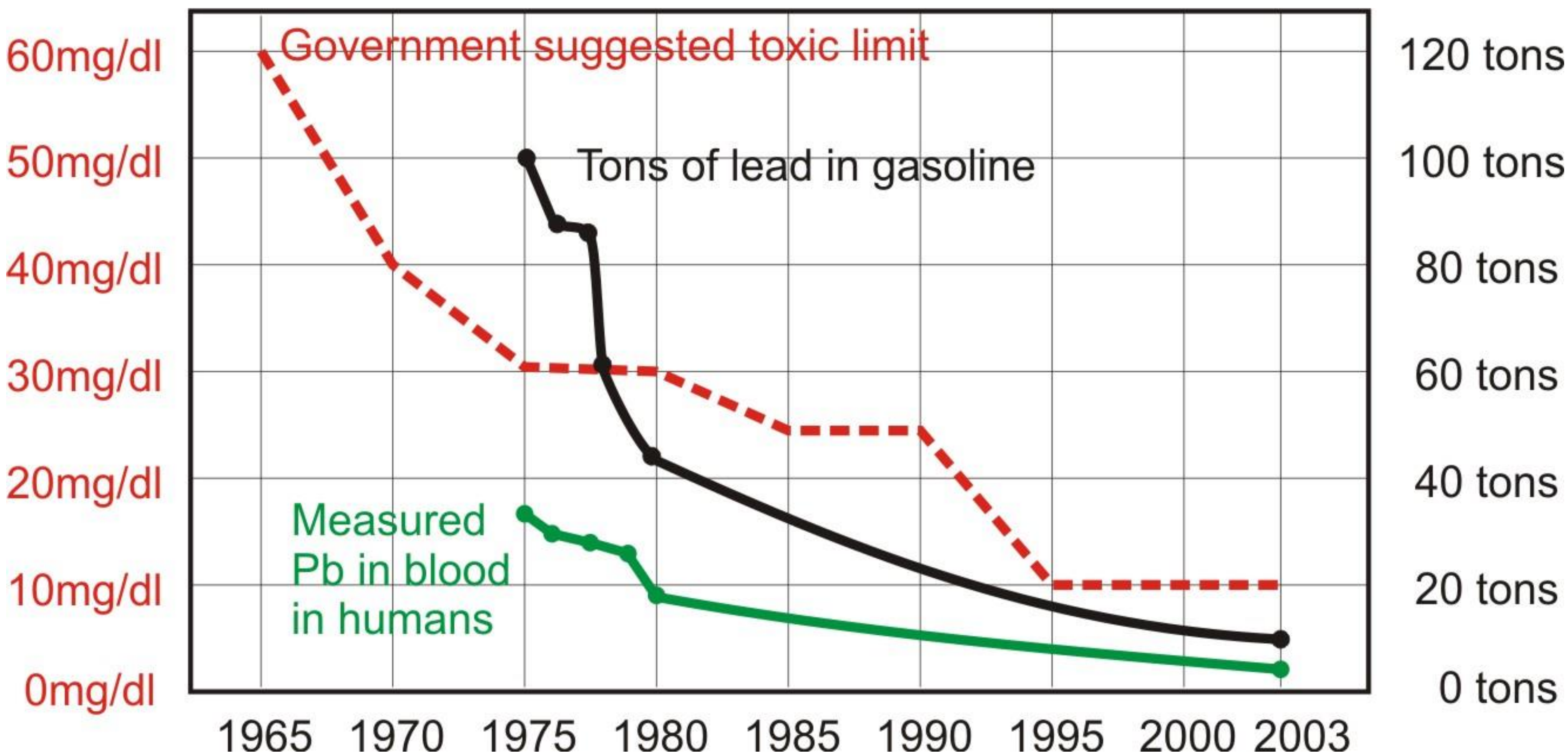


Chart created from data from "American Scientist" journal

Reliability of Electronic Elements

Some Known Weaknesses

Capacitors

Ceramic Capacitors (dielectric breakdown) are also fragile

Electrolytic Capacitors (electrolyte evap., dielectric dissolution)

Resistors

Must be properly de-rated for use in application to assure reliability

Integrated Circuits

Future generation designs with few nm features will be at risk

Relays (and other electromechanical components)

Limited ability to models wear out at present

Connectors

Must be properly matched to design, properly specified and placed

Solder Joints

Most electronic failures occur at interconnections

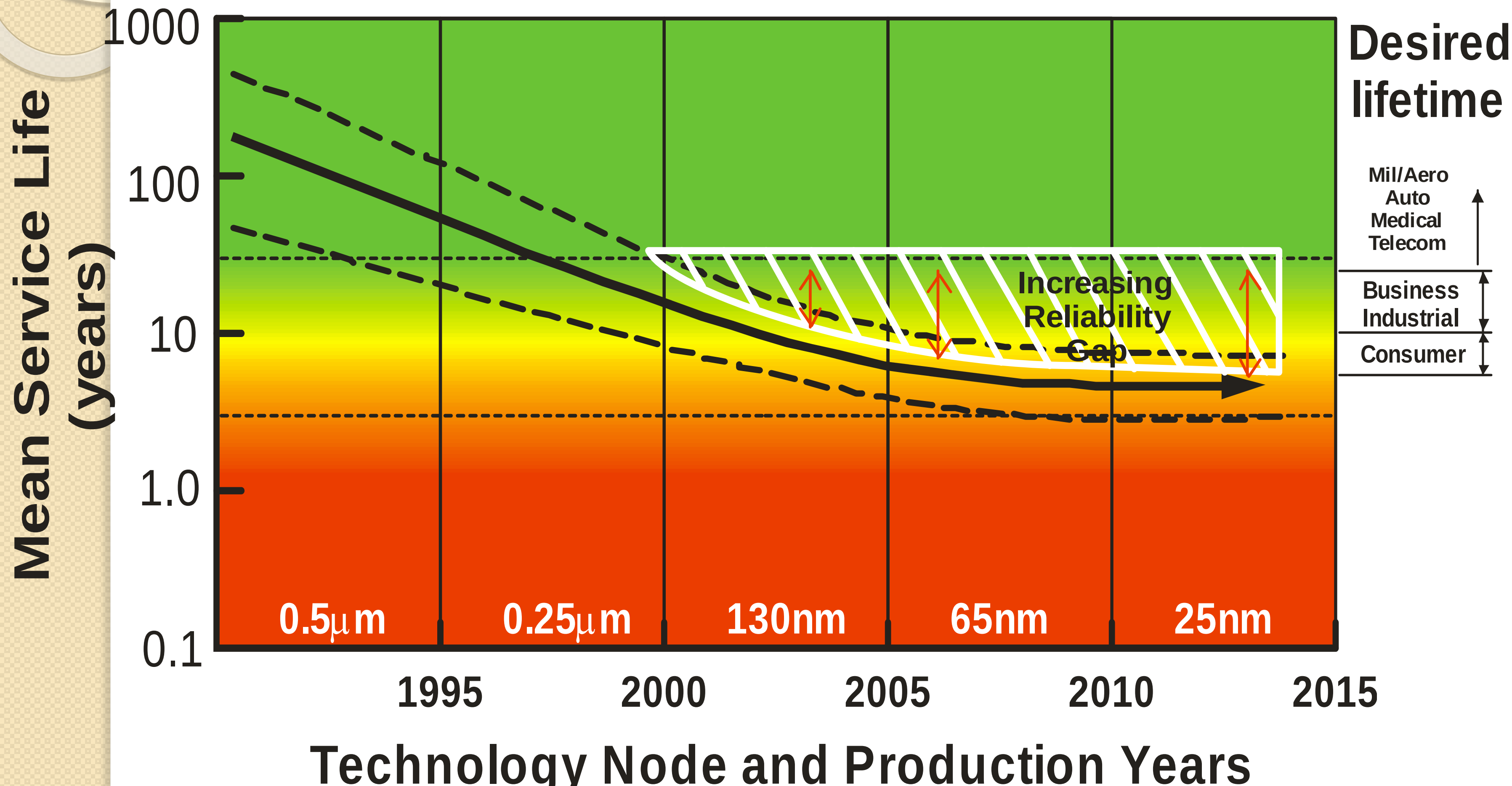
Solder creep, fatigue and shock resistance are concerns

Tin whiskers are a wild card

Looming Concerns About ICs

- **Solder is not the only concern in the increase being seen in early electronic failures**
- **It has pointed out that the semiconductor industry, which is driven largely by Moore's Law, continues to pursue new ever finer feature nodes, seemingly oblivious to the impact of such efforts on long term reliability**
- **We are facing a growing gap between customer desires for long life and performance reality**
- **Can sustainability objectives be better served by going back to earlier nodes?**

The Growing Reliability Gap



Modified after C.Hillman

Reliability and Design

Many if not Most Reliability Problems Begin at Design

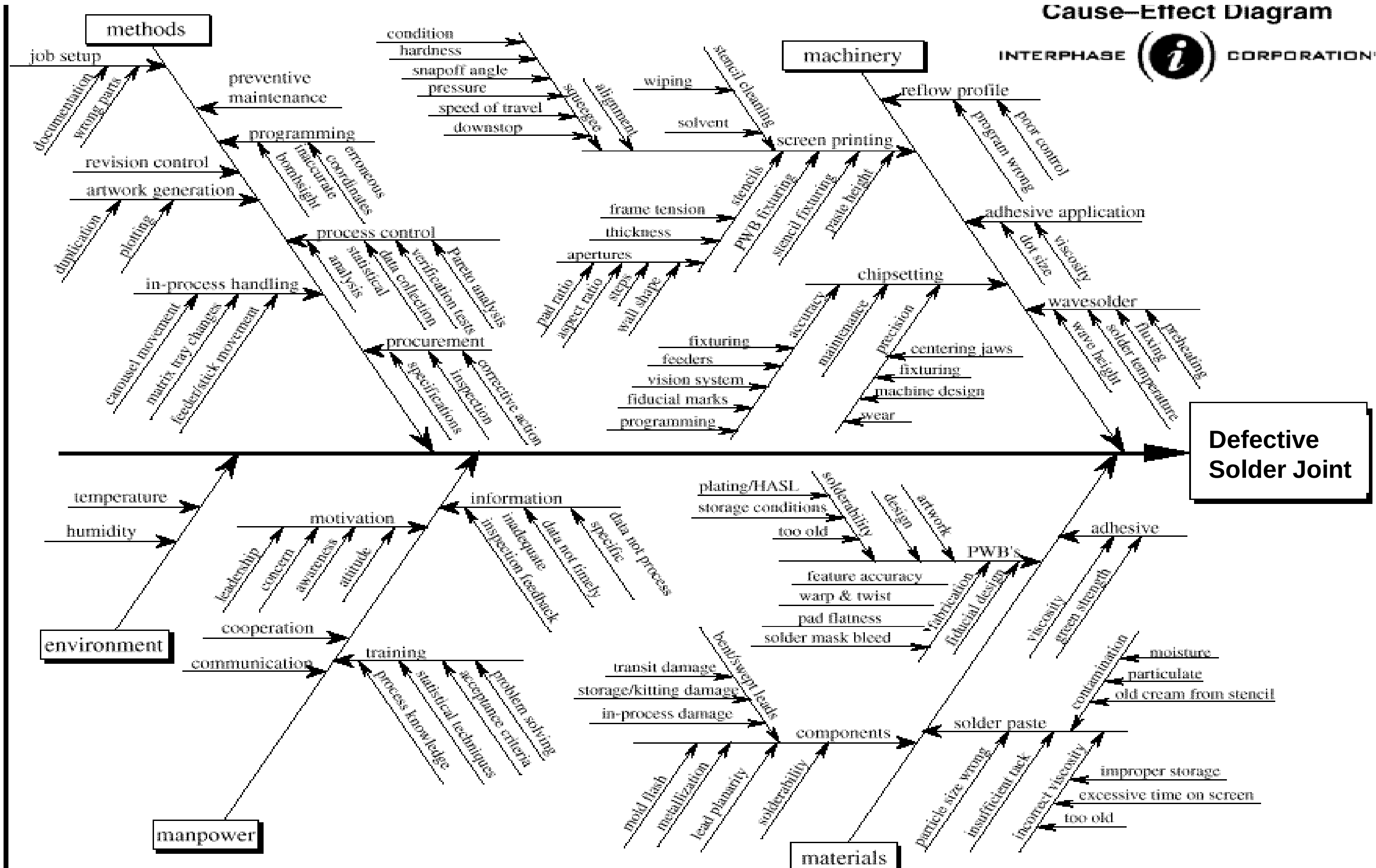
- **Many important questions must be asked upfront**
  - Does design match up with capabilities of the selected manufacturer?
  - Are trace and space within current standard manufacturing limits?
  - What laminate material will be used?
  - Is design symmetrical from side to side? How many layers?
  - What type of plated interconnections will be used?
  - How thick is board and what assembly methods are anticipated?
  - What assembly materials and equipment will be used?
  - What types of components will be used and what is their structure?
  - Is the component spacing appropriate?
  - What is the maximum size component?
  - Will stacking of components be employed?
  - Are components kept distant from prospective points of flexure?
  - What is/are the moisture sensitivity level (MSL) of the components?
  - Will second operation assembly be required?

Soldering -
An Assembly Technology with Mixed Blessings

Soldering: A timeless joining method

- Soldering is a centuries old method for joining metals originally used for simple metallurgical joining applications

Electronic Soldering However… Not so Simple



Source: Interphase Corporation

Solder - Lynchpin & Limiting Technology

- For decades solder has been used to perform mass assembly of electronic components
- Soldered interconnections are also commonly the limiting factor in product reliability
- Reasonably reliable electronic interconnections were possible in the past with tin-lead alloys, however lead-free solder is a wildcard with a thus far checkered reputation.
- The higher temperatures required and higher material and operating costs of lead free are impediments to improved relaibility

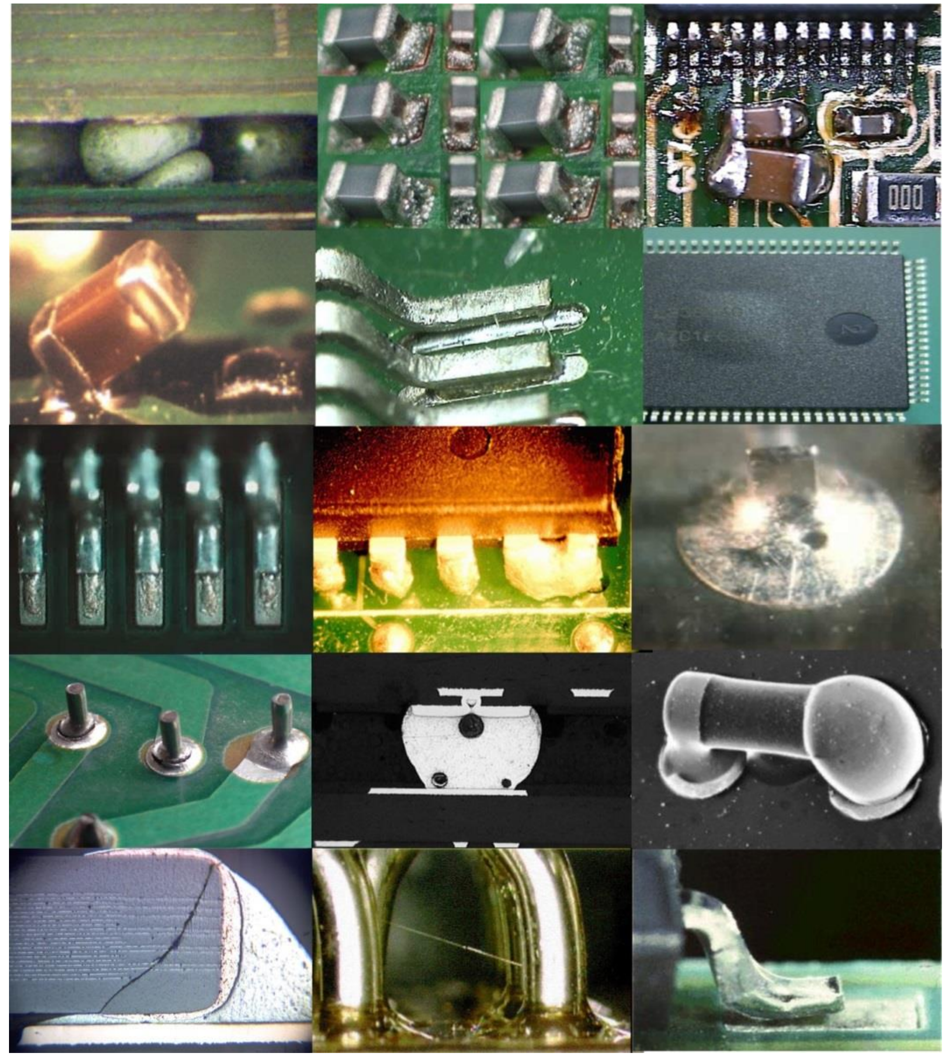
Solder - Lynchpin & Limiting (cont.)

- There are as well intrinsic problems with solder, especially lead-free and as device contact pitch drops the limitations of solder are becoming increasing apparent.
- Industry journals are filled with articles on the problems of solder and prospective solutions:
  - Opens, shorts, non wetting, voids insufficient solder, excess solder whiskers, popcorning, head in pillow, pad cratering, black pad, poor cleaning beneath low standoff components, etc…

Fact: Solder is the root cause of most failures

Solder Related Defect Types on the Rise

Opens and Shorts
Insufficient Solder
Excessive Solder
Solder Cracking.
Tin Whiskers
Poor Wetting/Dewetting
Voids
Blowholes
Cold Solder Joints
Brittle Solder Joints
Head on Pillow
Graping
Tomb Stoning
Solder Balling
Misregistration
Insufficient Cleaning

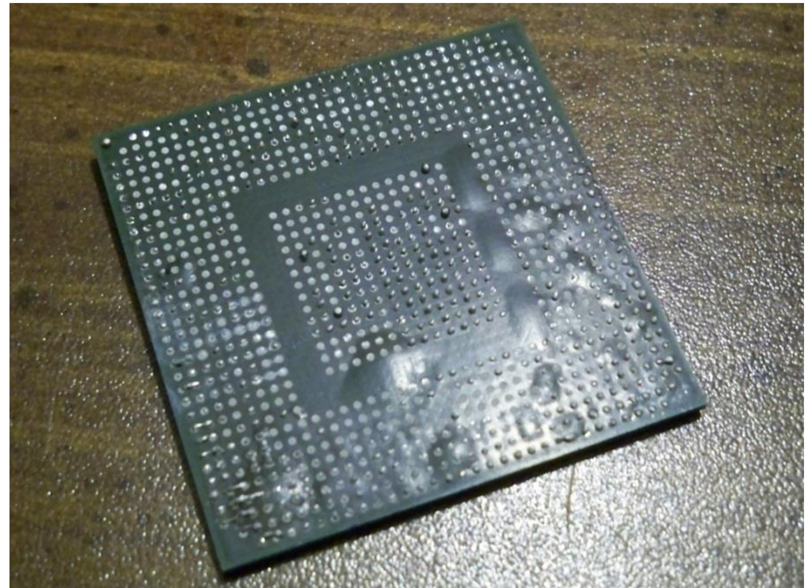


Collateral Damage to PCB Caused by Solder Process

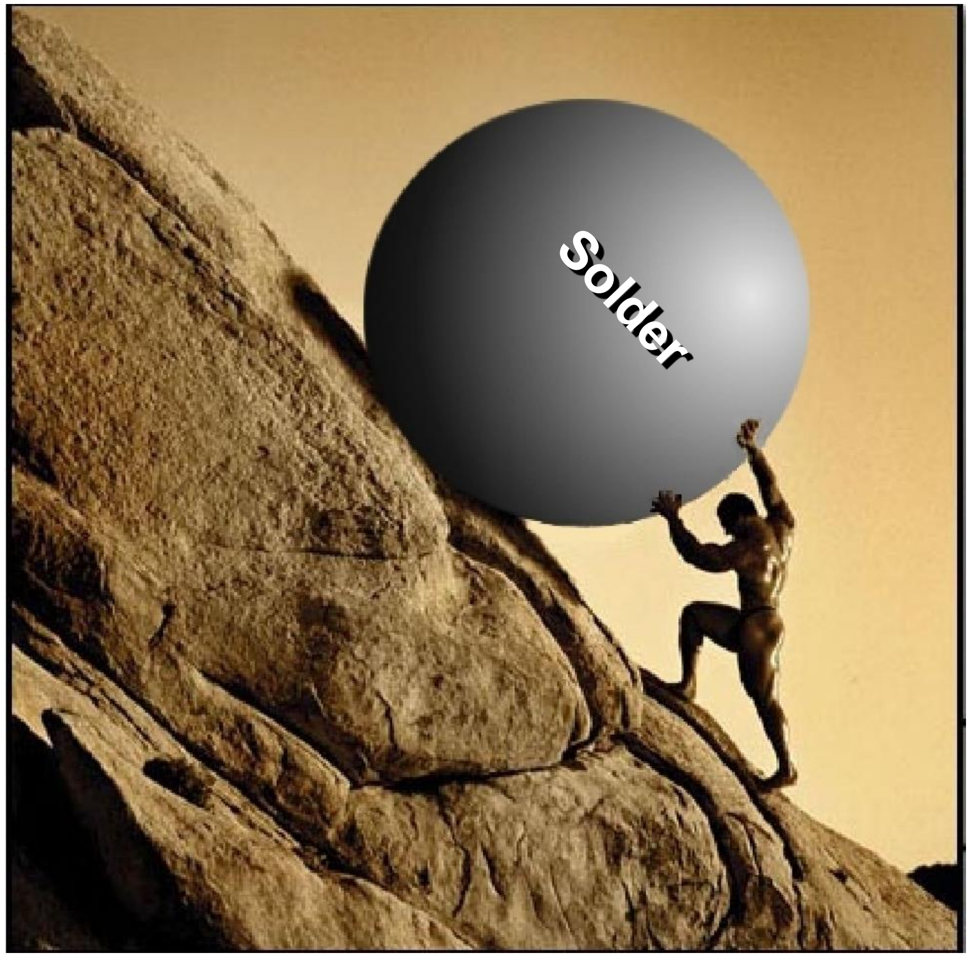
Corner Cracking
Barrel Cracking
Post Separation
Hole Wall Pull Away
Resin Recession
Delamination
Pad Cratering
Decomposition
CAF internal shorts

Collateral Damage to Components

Popcorning
Cracking of components
Cracking of package
Thermal damage to IC
Thermal degradation



Industrial Solder Effort… To what effect?

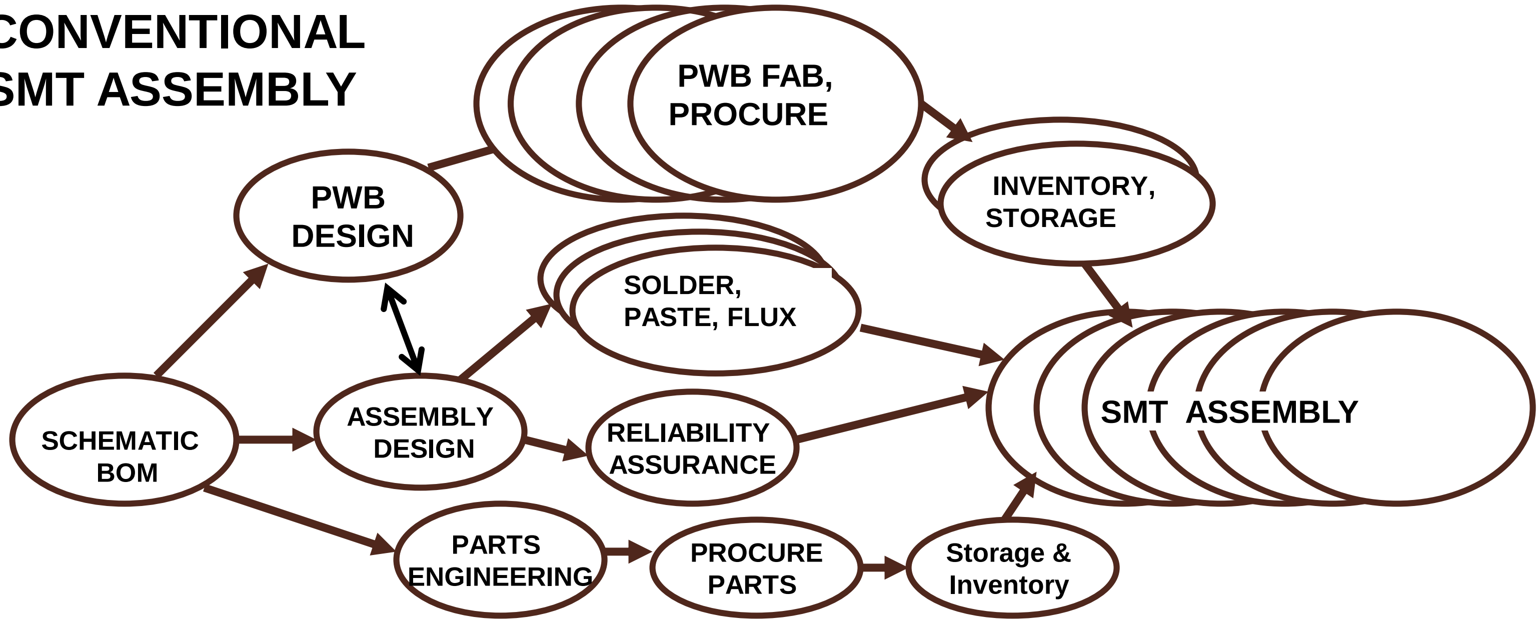


Prospective Sustainable Solutions for Electronics Manufacturing Based on Lower Material and Energy Use and Higher Reliability

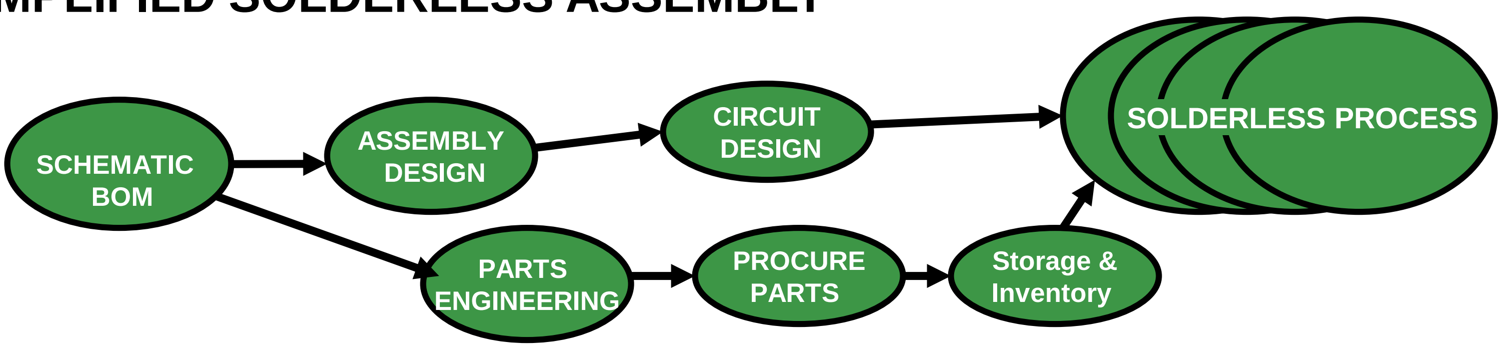
Reversing the Assembly Process to Eliminate Soldering

1. Position & bond various tested components on a temporary substrate or permanent metal or organic carrier in up or down position depending on base
2. Encapsulate/coat the tested components in place
3. Expose terminations (multiple options)
4. Interconnect terminations by additive or semi-additive board fab methods, combinations or alternative direct interconnection methods. Layers required will normally be less than for standard approaches do to the lack of need for solder connection lands

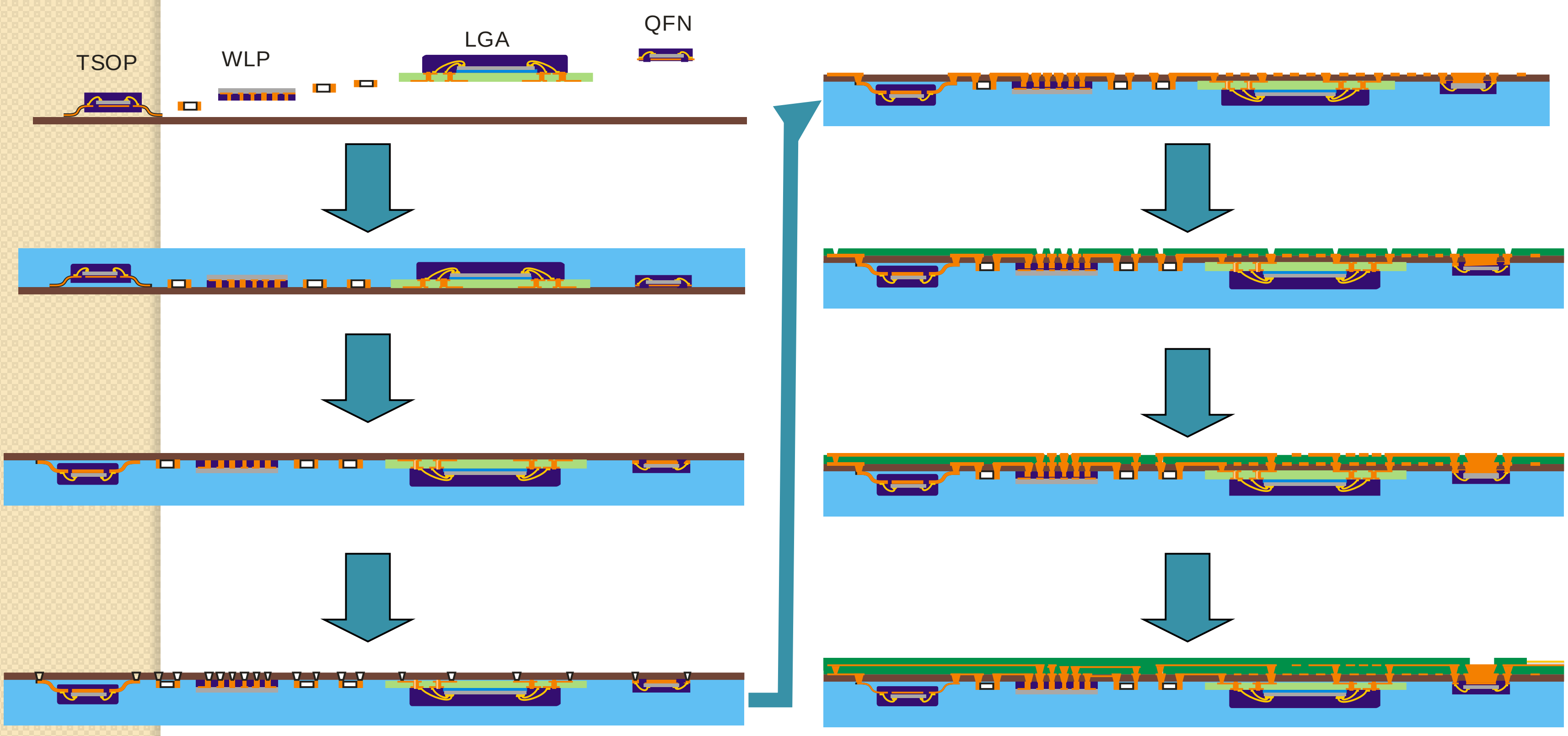
CONVENTIONAL SMT ASSEMBLY



SIMPLIFIED SOLDERLESS ASSEMBLY

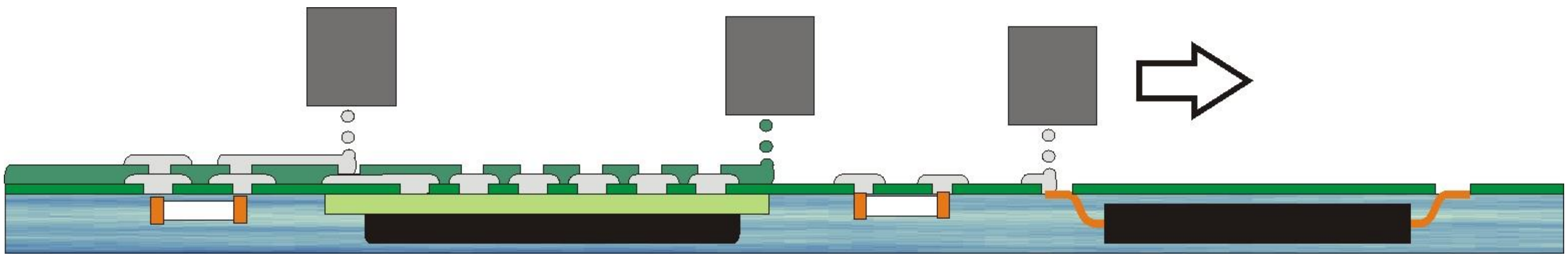


Sample Process Sequence



Patented

Direct Write Prototyping without Solder



Presently with parts in hand, first prototypes could possibly be completed in hours rather than days, weeks or months.
Future developments will allow printing of base material substrate, components and circuits

Patents Pending

Why Eliminate Solder?

- **No PCB required**
  - No procurement, shelf life, testing, environmental related issues
- **No soldering required**
  - Multiple steps obviated, weak link eliminated, no high temp exposure
- **Reduced component concerns**
  - Leadless devices, MSL-1, all copper, no high temp damage, low profile
- **Increased product design security**
  - Component detail hidden
- **Enhanced reliability**
  - Simpler, low temperature process, no solder joints, ESD & EMI mgmt, no CAF
- **Multiple novel structure options possible**
  - Stacked assemblies, rigid flex assemblies, optical pathways
- **Facilitates use of aluminum as a substrate**
  - Aluminum has many benefits
- **Integral thermal management**
  - Aluminum substrates – high conductivity and close CTE match to Cu

Electronics Manufacturing Steps

Design PCB Assembly	Fabricate PCB (multilayer)	Assemble PCB
1. Create schematic	1. Verify RoHS compliance	1. Procure components
2. Indentify components	2. Cut core laminas to size & tool	2. Verify RoHS compliance
3. Layout circuits	3. Clean and coat with resist	3. Verify component solderability
4. Validate signal integrity	4. Image and develop resist	4. Verify component MSL number
5. Validate design DfM	5. Etch and strip resist	5. Kit components
6. Validate design DfR	6. Treat exposed copper	6. Procure PCBs
7. Validate design DfE	7. AOI or visual inspect layers	7. Verify RoHS compliance
	8. Cut B-stage to size and tool	8. Verify PCB solderability
	9. Lay up core and B-stage	9. Verify PCB High Temp capability
	10. Laminate	10. Design solder stencil & purchase
	11. X-ray inspect (optional)	11. Develop suitable reflow profile
	12. Drill (stack height varies)	12. Track component exposure (MSL)
	13. Desmear or etchback	13. (Rebake components as required)
	14. Sensitize holes	14. Position PCB & stencil solder paste
	15. Plate electroless copper	15. (monitor solder paste)
	16. Clean and coat with resist	16. Inspect solder paste results
	17. Image an develop resist	17. (height and skips)
	18. Pattern plate copper	18. Dispense glue dots (optional)
	19. Pattern plate metal resist	19. Place components
	20. Strip plating resist	20. Inspect for missing parts
	21. Etch base copper	21. Reflow solder
	22. Clean and coat with soldermask	22. Repeat Steps 13-18 if two sided assy
	23. Image and develop	23. (second set of fixtures required)
	24. Treat exposed metal (options)	24. Perform hand assembly as required
	25. Solder, NiAu, Sn, Ag, OSP, etc.	25. (odd sized or temperature sensitive)
	26. Electrical test	26. Clean flux from surface and under
	27. Route to shape	27. Verify low standoff devices
	28. Package	28. Test cleanliness
	29. Ship	29. Underfill critical components
		30. X-ray inspect soldered assembly
		31. Identify shorts, opens, voids, missing
		32. Electrically test
		33. Rework and repair as needed
		34. Package
		35. Ship

Electronics Manufacturing Alternative

Design PCB Assembly	Fabricate PCB (multilayer)	Assemble PCB
1. Create schematic	1. [redacted]	1. Procure components
2. Indentify components	2.	2. [redacted]
3. Layout circuits	3.	3.
4. Validate signal integrity	4.	4.
5. Validate design DfM	5.	5. Kit components
6. Validate design DfR	6.	6. [redacted]
7. Validate design DfE	7.	7.
	8.	8.
	9.	9.
	10.	10.
	11.	11.
	12. Drill (stack height varies)	12.
	13. Desmear or etchback	13.
	14. Sensitize holes	14.
	15. Plate electroless copper	15.
	16. Clean and coat with resist	16.
	17. Image an develop resist	17.
	18. Pattern plate copper	18.
	19. Pattern plate metal resist	19. Place components
	20. Strip plating resist	20. Inspect for missing parts
	21. Etch base copper	21. [redacted]
	22. Clean and coat with soldermask	22.
	23. Image and develop	23.
	24. Treat exposed metal (options)	24. Perform hand assembly as required
	25. [redacted]	25. [redacted]
	26.	26.
	27. Route to shape	27.
	28. Package	28.
	29. Ship	29.
		30.
		31.
		32. Electrically test
		33. Rework and repair as needed
		34. Package
		35. Ship

Capital Equipment Requirements Traditional vs SAFE Manufacturing

Capital Equipment List for Traditional Electronics Manufacture (Abbreviated list)

PCB Fabrication
Shearing Equipment
Drilling Equipment (mechanical and laser)
Surface Preparation Equipment (chemical and mechanical)
Metallization and Plating Equipment
Photoresist Application Equipment (includes solder mask)
Photoimaging Equipment (contact and laser direct print)
Image Development Equipment
Lamination Equipment
Routing Equipment
Cleaning Equipment
Testing Equipment (electrical and X-ray)
Packaging Equipment

PCB Assembly
Baking Ovens
Solder Paste Application Equipment (stencil printer)
Solder Paste Inspection Equipment (optical or x-ray)
Pick and Place Equipment
Component Placement Inspection (optical)
Reflow System (convection ovens, vapor phase, others)
Specialty Cleaning Equipment
Inspection and Test Equipment (optical x-ray and electrical)
Solder Rework and Repair Equipment
Depanelization Equipment
Packaging Equipment

Capital Equipment List for SAFE Assembly (Abbreviated list)

Pick and Place Equipment
Component Placement Inspection (optical)
Shearing and Punching Equipment
Encapsulation Equipment
Via Formation Technology (Laser or photoimage)
Surface Preparation Equipment (chemical and mechanical)
Metallization and Plating Equipment
Coating Equipment (for photoimage materials)
Image Development Equipment
Routing / Depanelizing Equipment
Cleaning Equipment
Packaging Equipment

Aluminum: A Feature Rich and More Sustainable Alternative Substrate

Aluminum has **many attractive attributes** which make it an appealing circuit substrate alternative…

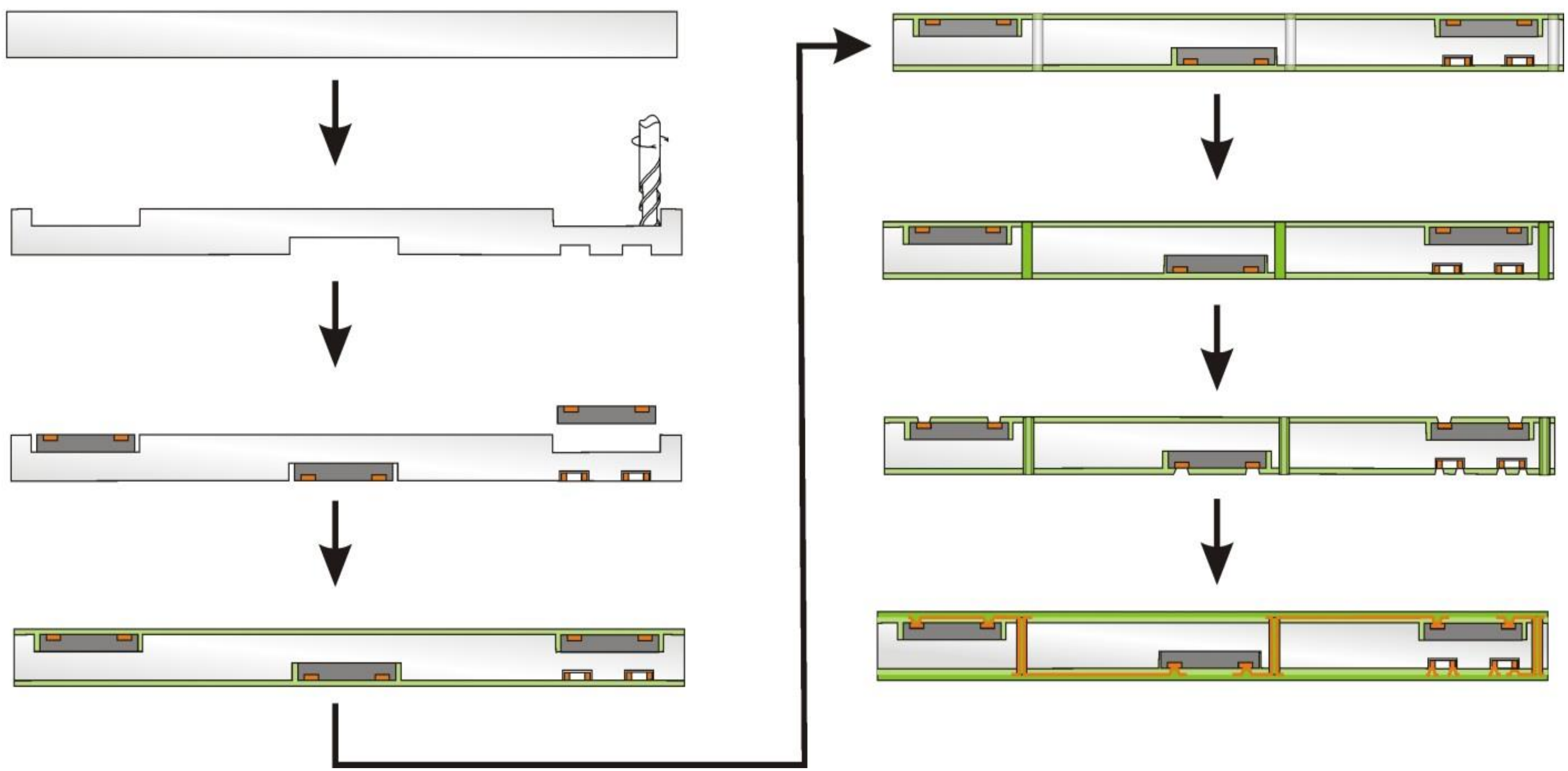
Aluminum is:

- **Abundant**: 3rd most common element (8.3 % of Earth's crust)
- **Nontoxic**/Environmentally friendly
- **Low cost**: $2.00/kg, $0.98/lb, $.015/mil/sq.ft.
- **Good thermal conductor** (~200 W/mK)
- **Relatively light we**ight (2.8g/cc vs 1.85 for FR4)
- **Dimensionally stable**
- **Good CTE** that approximates copper (22 vs 18 ppm/C)
- **Easily processed** (machined, punched, chemically milled)
- **Can be Anodized** to form an alumina (Al_2O_3) surface layer
- **Electrophoretically coatable** with epoxies or enamels
- **And it is a readily recyclable metal**

Why The Delay?

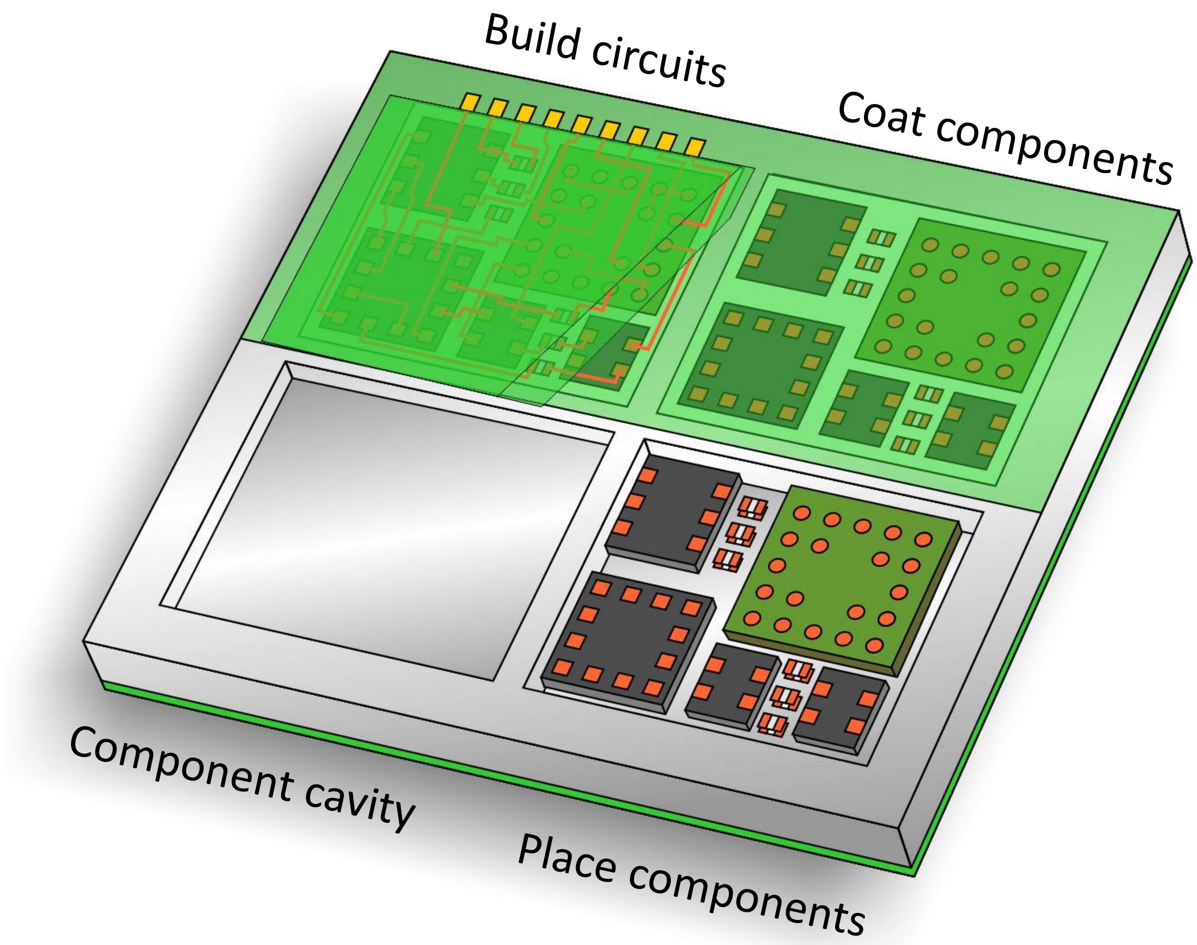
- **Aluminum has be used in only a relatively few applications for a few compelling reasons, most notably is its high thermal conductivity which makes soldering difficult in the best of cases and nearly impossible in others.**
- **Good thermal conductivity increases the risk of the assembler forming cold joints on the one extreme and thermally damaging components at the other if dwells are excessive.**
- **Thus with some notable exceptions, such as for LEDs most designers have determined it is easier to use traditional laminates and then solve the thermal management issues associated with the assembly upon completion.**
- **There is however a way to employ aluminum if one is willing to think differently about the process of assembly, specifically by reversing the process and instead of placing components on circuit boards, building circuits on component boards…**

Aluminum Process Example

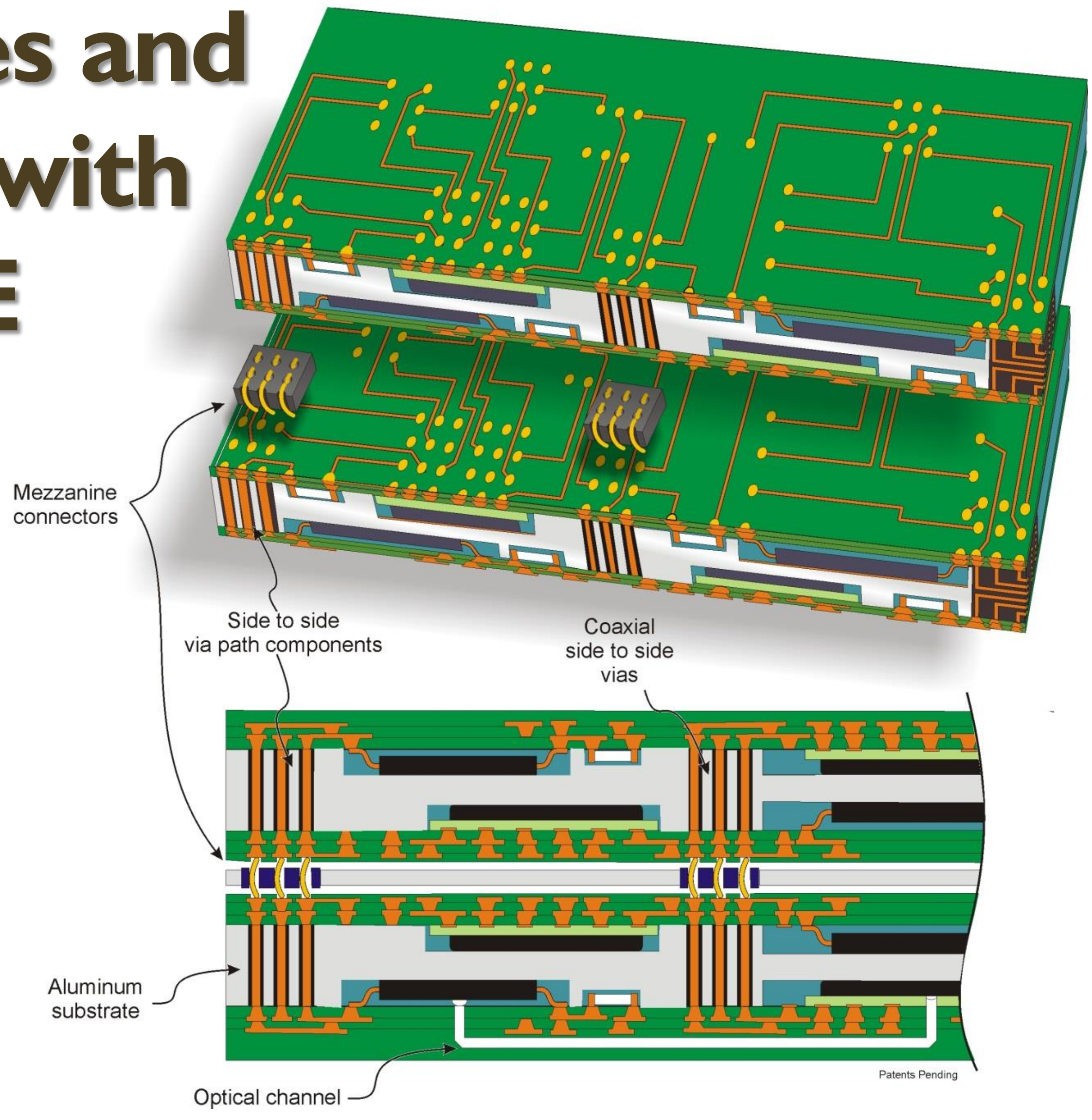


Patented

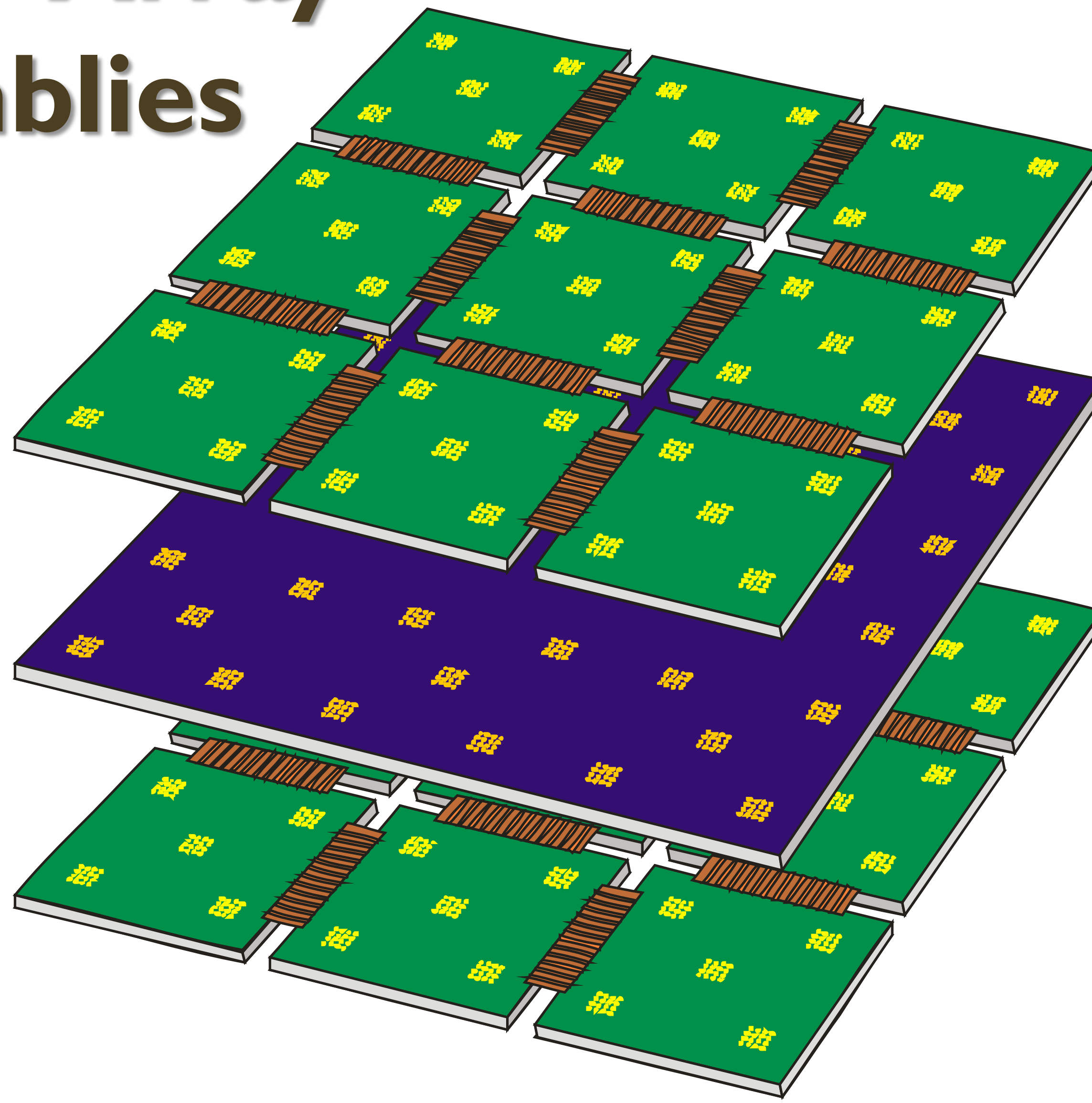
Aluminum Substrate Structure



Novel Possibilities and Benefits with SAFE

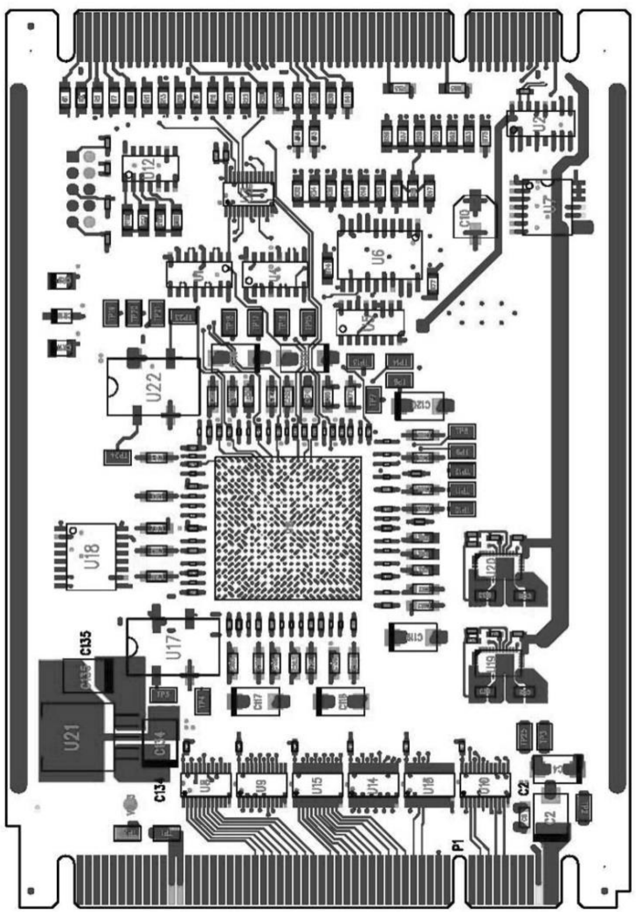


Modular Array Assemblies



Solderless Redesign Exercise

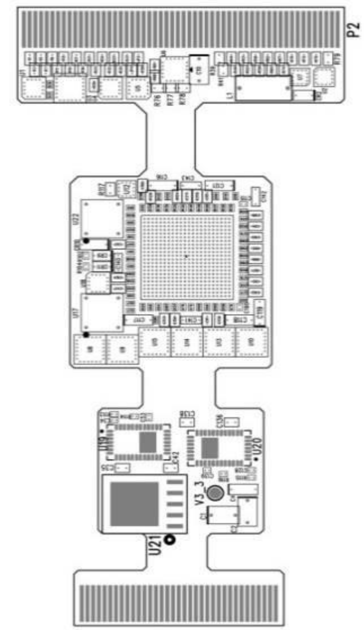
Original soldered based design



12 layer FR4 Multilayer PCB

- **140mm x 100mm**
- 442 FPGA 0.8mm pitch

Solderless Redesign



6 layer Aluminum Rigid-flex Assembly

- **~30mm X 40mm** (when folded)
- All component leads on 0.5mm pitch
- Used same design rules as original design (50µm line/space with 50µm vias)
- Design is ~70% smaller in terms of total area
- Folds into an assembly with footprint ~15% of original design with minimal increase in height.

Necessary Industry Conditions for Advancement of Solderless Assembly

- Agreement on the merits of solderless asembly
  - Economic, Environmental, Performance, Reliability
- Acceptance of the need for change to improve
  - Solder continues to show its weaknesses
- Willingness to participate in change
  - Includes sharing of knowledge and technology
- Infrastructural adaptations to new approaches
  - Reconsideration of electronic packaging, design tools, manufacturing flow with greater emphasis on getting manufacturing right rather than inspection.

Summary

- Solder has been a useful technology and will likely continue to be used for decades to come due to “The Flywheel Effect
- Solderless assembly mitigates significant and fundamentally intractable problems associated with traditional materials and processes most of them related to solder
- Elimination of solder from the manufacturing process could, at once: increase design efficiency by opening up space for circuit routing while reducing the size and volume of the resulting assembly compared to standard methods
- Elimination of solder also obviates one to the major causes for failure of electronic products both in process and in use… Failed solder joints
- Simplicity is at the center of the concepts discussed, but ironically, to achieve simplicity requires greater design and manufacturing discipline.

Conclusion

- Buckminster Fuller observed that "We are all astronauts" and that we are riding on "Spaceship Earth" It is an important reminder
- Everyone here today is blessed and those blessings should be shared with others who will never see the inside of a building like this.
- Waste is the enemy, not the friend of progress. Sustainable manufacturing and systems must defeat wastefulness.
- Making more reliable products should result in significant cost and energy savings and equally important, more sustainable and more environmentally responsible products to help address the needs of the four billion people at the bottom of the world's economic pyramid.

One final thought from the past…

"If the earth must lose that great portion of its pleasantness which it owes to things that the unlimited increase of wealth and population would extirpate from it, for the mere purpose of enabling it to support a larger, but not a better or a happier population, I sincerely hope, for the sake of posterity, that they will be content to be stationary, long before necessity compels them to it."

John Stuart Mill,
Principles of Political Economy, 1848

"A mind, once stretched by a new idea, never returns to its original dimensions."

~ Oliver Wendell Holmes ~

American Philosopher and Jurist