Constraints - I

- Goals of this class
- Launch discussion of constraints
- Introduce modularity
- Discuss constraints on modularity based on system power level
- Essentially the difference between power and information

Constraints

- One of our recurring themes
- The structure of systems is not random
- We see a variety of patterns, and these patterns are important to the behavior and other characteristics of systems
- What kinds of constraints do we see?
- What causes them?
- What system patterns or characteristics do they create or prevent?
- What is the role of constraints in enabling or preventing modularity?

A Few Obvious Patterns

- Density of connections varies
  – Clusters, “modules”
- Number of connections varies
  – <k> and variation in <k>
  – “cost of connection”
- Capacity of links varies
- Structural patterns vary, leading to discussion of modules and modularity

“Cost of Connection”

- Examples

Modularity

- A characteristic of system structure
- Sometimes considered "good"
- Numerous definitions
- ?

Modularity or Module in Different Fields

- Engineering
  - Physical elements with identifiable function
  - Products with platforms and subassemblies
- Economics
  - Firms, supply chains and vertical disintegration
  - Economic actors, arrangements determined by market forces, transaction costs, property and property rights, specific resources
- Biology
  - Species, genes, cell clusters, molecular reactions
- Social science
  - Social groups, cliques, association mutuality
- Ecology
  - Niches, ecological hierarchies, elements in food chains

Better Definition(s) of Modularity

- Modularity 1:
  - The system can be decomposed into subunits (to arbitrary depth)
  - These subunits can be dealt with separately (to some degree)
    - In different domains, such as design, manufacturing, use, recycling
- Modularity 2:
  - The functions of the system can be associated with clusters of distinct elements
    - in the limit one function:one module
  - These elements operate somewhat independently
  - They do not have to be physically contiguous
- Common to both definitions
  - Independence of some kind
  - Identifiable interfaces (perhaps standardized)
  - More interactions inside a module, fewer interactions between modules

Other Uses of "Modularity"

- In biology:
  - Modules are repeating patterns
  - Modularity 2 also is used
- Also:
  - Members of a decomposition tree or hierarchy are sometimes called modules

VOLUME 92, NUMBER 18 PHYSICAL REVIEW LETTERS week ending 7 MAY 2004

Networks, Dynamics, and Modularity

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This paper creates random dynamic system coefficient matrices, measures the stability, and then seeks to improve the stability by rearranging the network. The resulting networks are usually cascades of dynamic elements rather than complex interconnections.

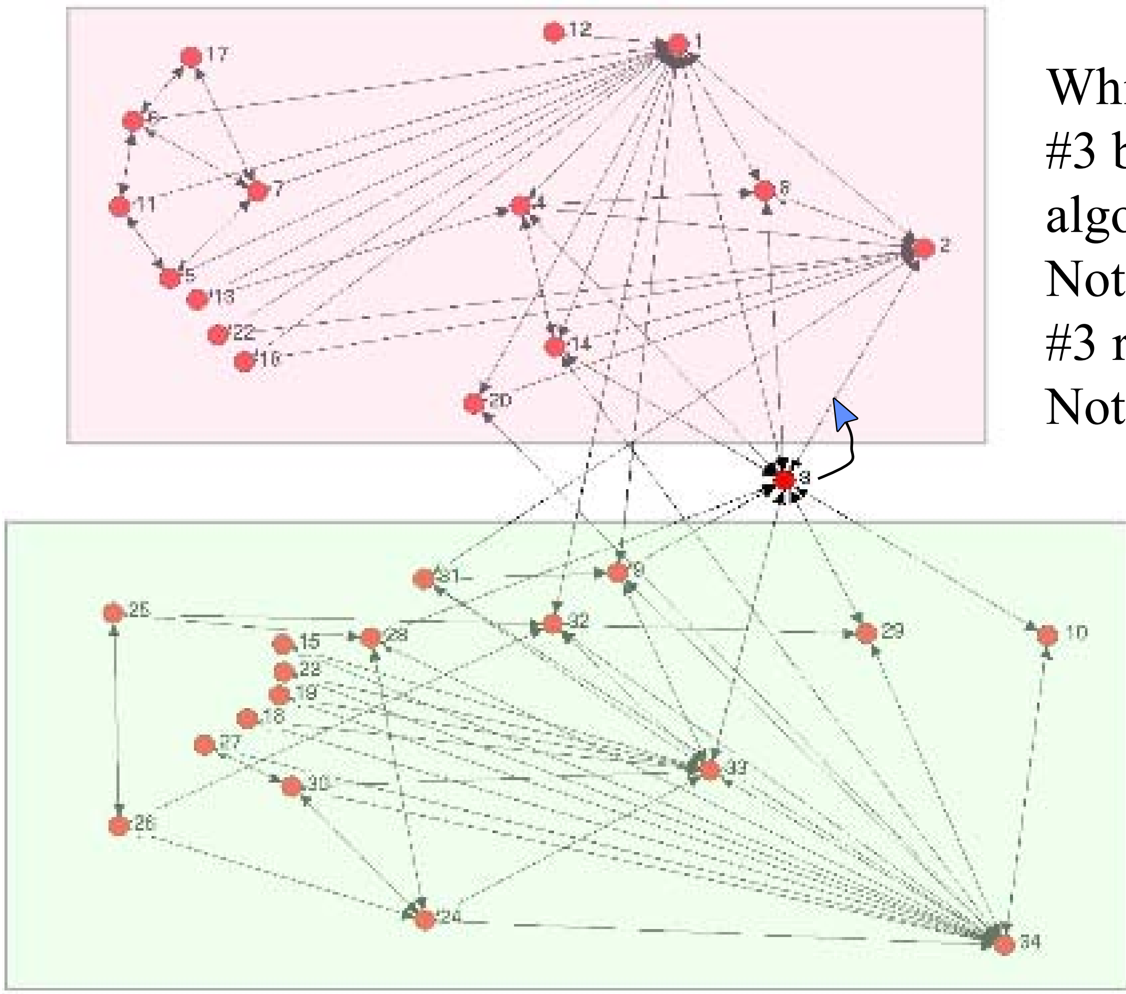
Calculating Modularity (1)

- Social science methods seek to find clusters
- Clusters have many links among each other and few with members of other clusters
- Many algorithms exist, differing in
  - What technique they use
  - How fast they run as a function of number of nodes or edges
  - Their "accuracy"

Newman-Girvan Algorithm

- Seeks edges along which a lot of traffic flows between nodes, revealed by high edge betweenness
  - Edge betweenness rises with number of shortest paths between all node pairs that pass along that edge
- Removing this edge and repeating the process reveals clusters that roughly conform to Modularity 1 (?)

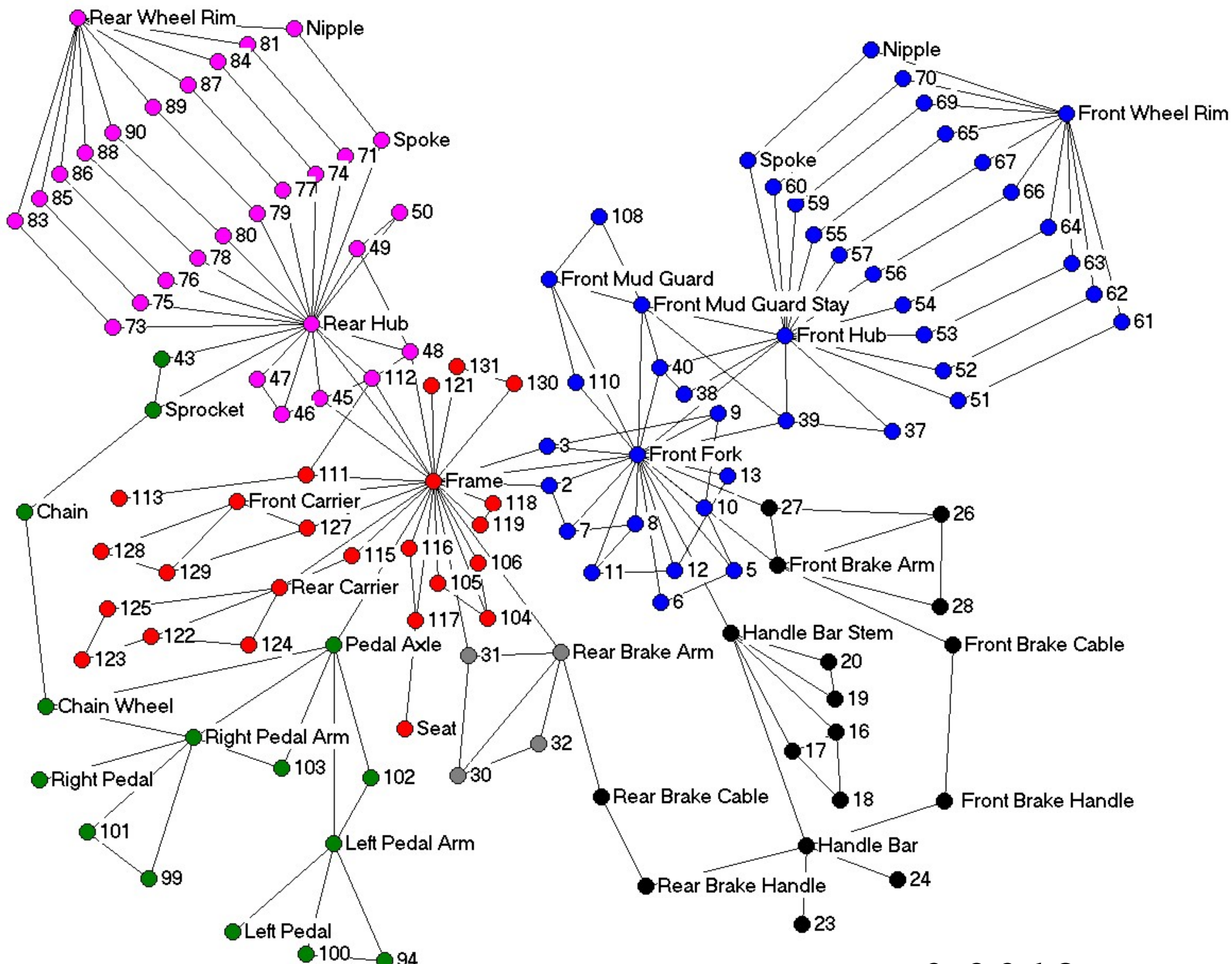
Zachary's Karate Club Dataset



Which group does #3 belong to? Different algorithms disagree.
Note: Zachary got #3 right.
Note 2: #9 joined #1's group.

Links denote politically-based communication between club members outside of class. Zachary included strength of relationship but later researchers do not.

Sometimes It Works Pretty Well



bike newman girvan 2.jpg

r = - 0.2018

Integrality and Modularity (2) in Engineered Systems

- Modular (2) systems are, ideally, those in which
  - Functions and behaviors can be associated simply and directly with modules more or less one-to-one
  - Only predefined interactions occur between modules
  - Interactions occur at, and only at, predefined interfaces
  - Modules don't need to know what is on the other side of the interface
- Integral systems differ as follows:
  - Functions are shared among modules
  - It matters what is on the other side of the interface
  - Interactions that were not defined can occur, and they can occur at undeclared interfaces
  - Behaviors can arise that are not easily traceable to modules one-to-one
  - In many cases you can't stop this from happening
  - To the extent that this occurs, all systems are more or less integral
- "Integral" and "modular" represent extremes and all real systems lie in between

Ulrich's Nail Clippers

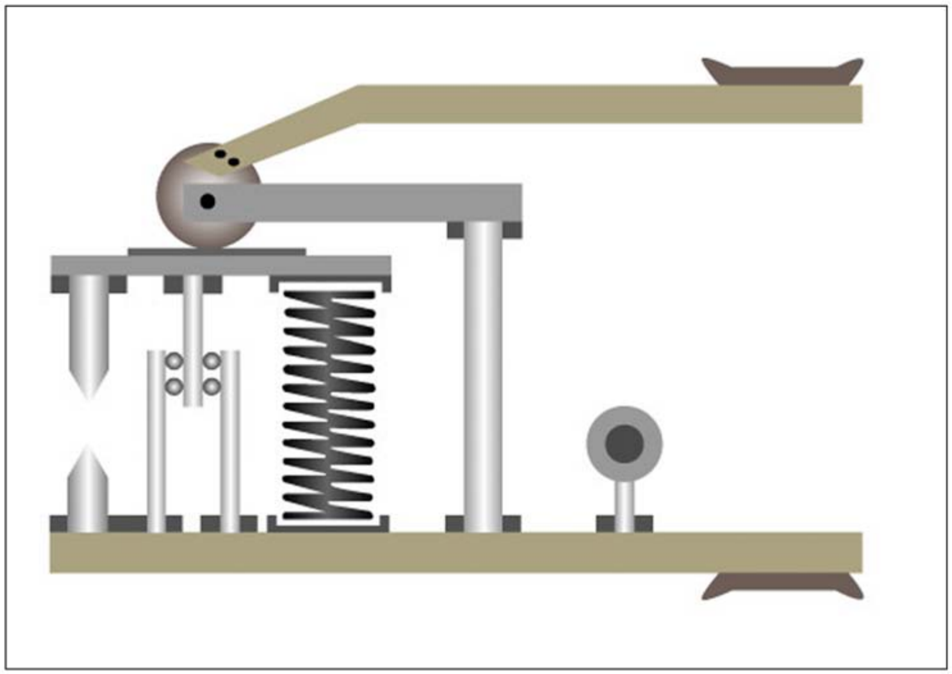


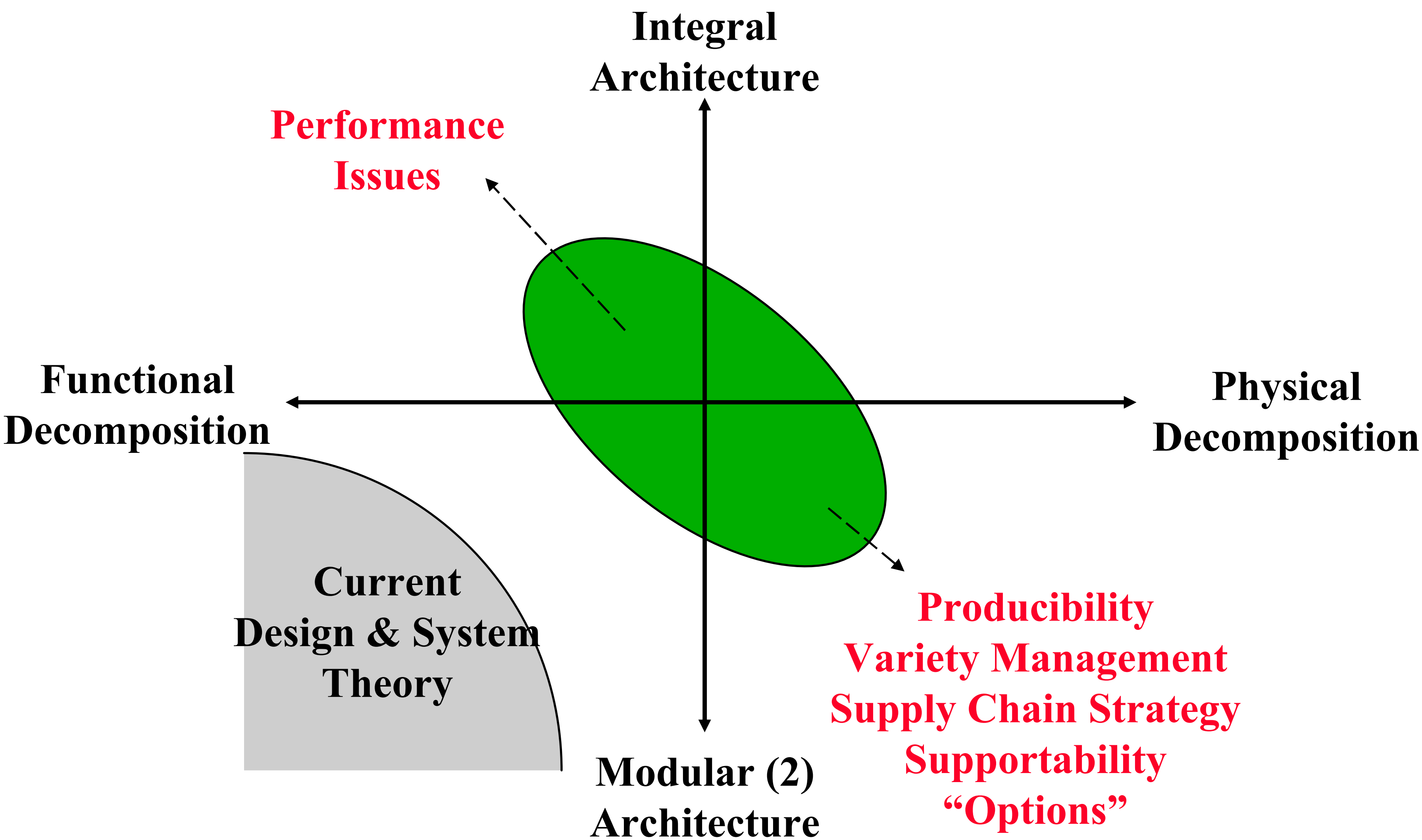
Image by MIT OpenCourseWare.

A modular (2) design

Image by MIT OpenCourseWare.

An integral design

Modularity in Theory and Practice



Integral/Modular (2) Situations*

(read down!)	Each function is realized by	Many functions are realized or shared by
One part	VLSI Modular Architecture◊	Cast or molded parts Transaxle case Integral architecture and/or function sharing◊
Many parts	Typical simple assembly Integral "chain*" or "holistic#" architecture	Most assemblies Car door Integral - coupled Architecture*

Ulrich-Eppinger View

Mixed architectures are the most common, in which some functions are realized by some options and others by other options

*Tim Cunningham, PhD thesis; #Ulrich and Ellison; ◊Ulrich & Eppinger

“Modularity (2) is Good”

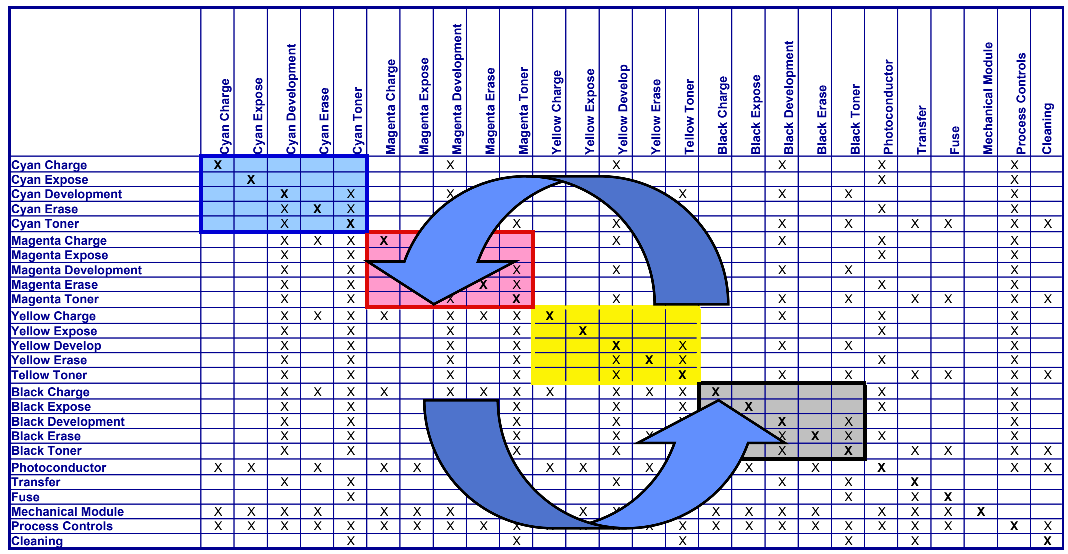
- It allows parallel activities
- It reduces the size of individual problems
- It emphasizes identifying the (hopefully small amount of) information that must be shared
- It allows substitutions, enabling flexibility
- According to Baldwin and Clark, it enables exploration, generating economic growth
- It enables robustness: resistance to attack, ability to evolve locally, compartmentalization
- Modularity is claimed to characterize systems that evolve “naturally” (sometimes used as a value judgement) (Simon)

“Modularity is Bad”

- It hides problems or suppresses events that could reveal problems
  – Just in Time “lowers the water so you can see the rocks”
- It adds inefficiencies in terms of extra interfaces that may contribute little or no functional value
- These interfaces have to be managed explicitly, adding overhead
- Modules may have to be over-designed to compensate for invisible information or possible substitutions
  – The least common denominator problem
  – Unpredictable combinations create unpredictable potential failure modes

Modularity May Be An Illusion

- Company hoped to sell a family of color and B/W copiers but the color method did not work
- Color copier design included complex color process that made black and white copies expensive
- Company had to try selling expensive B/W copies



SDM Thesis by David Craig

Physical Limits to Modularity (2)

- When do designers have freedom to define modules and assign functions to them?
- What limits this freedom?
- Will some kinds of systems always be harder to make modular than others for reasons we cannot change?
- Can the Baldwin-Clark theory of modularity be extended to other industries besides the computer industry?

Background

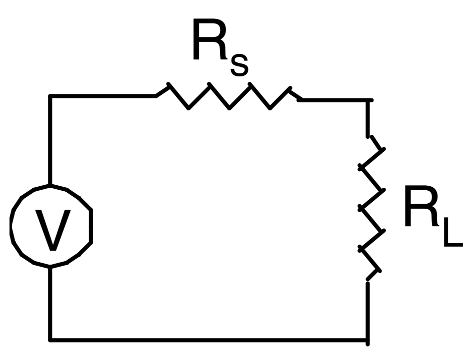
- Draper proposal to DARPA in 1989 to study complex electro-mechanical-optical (CEMO) systems
  - Missile seeker heads
  - Polaroid cameras
- DARPA's reply: get smart, do mechanical design the way VLSI design is done
- It's not that easy, but how to counter this argument?

Background - 2

- Whitney builds a computer (1980) with his son
- Actually a small calculator
- Based on two half adders
- Parts from Radio Shack
- Biggest problem was mechanical: plugging DIPs into the protoboard without bending their legs
- How come a mechanical engineer could build a computer?

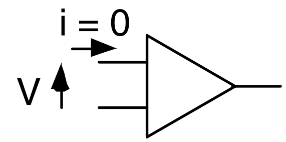
Backloading and Impedance Matching

- Without a load, a power source can generate a voltage or force at some level
- When a load is applied, current flows and losses inside the source reduce the voltage or force available to run the load
- This is called backloading
- Maximum power delivery to the load occurs when the internal losses in the source equal the internal losses in the load, so that only half the power created by the system is delivered to the load
- Equalizing source and load impedance is called impedance matching



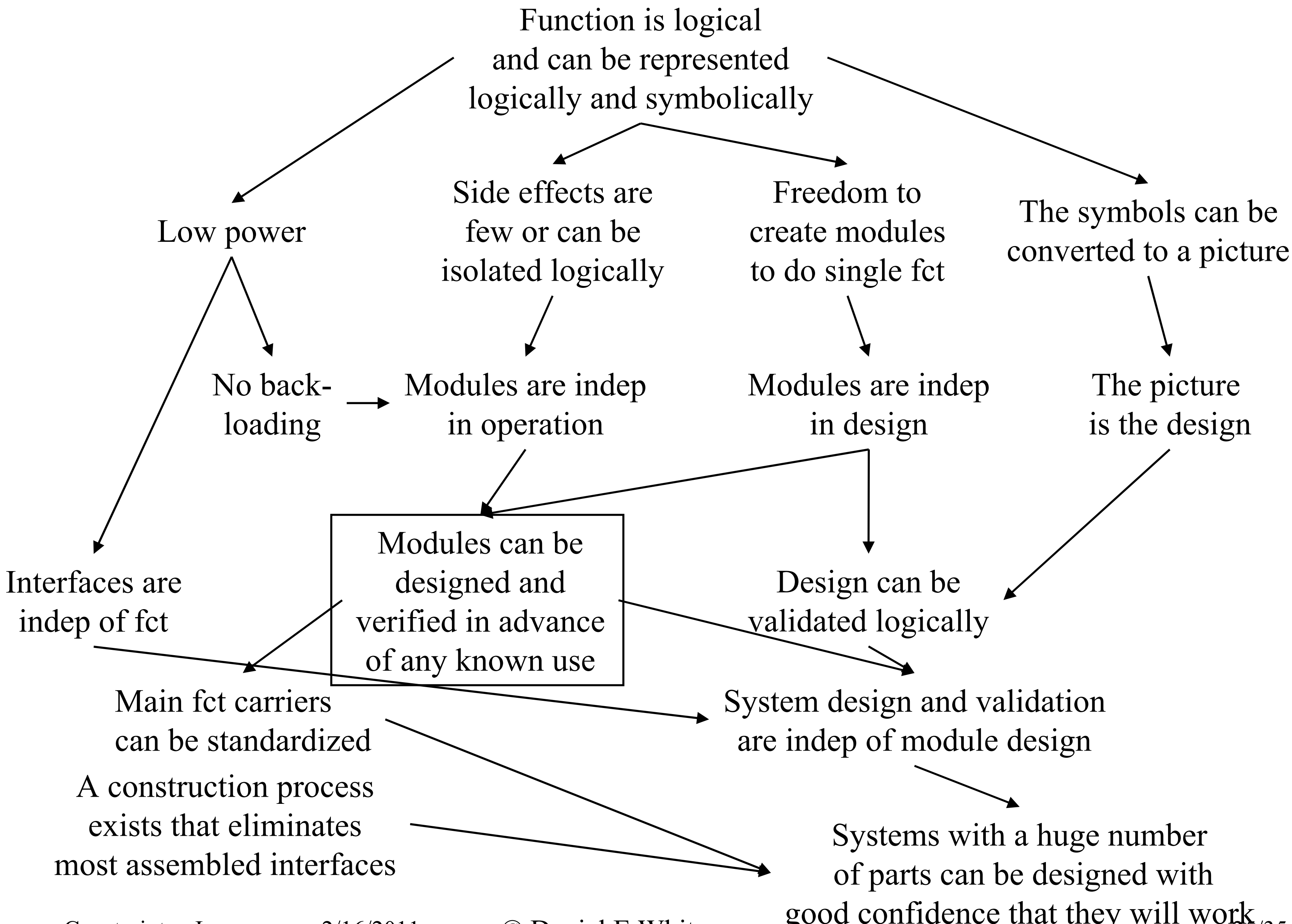
Physical Limits to Modularity

- Distinction based on power level in the system
- Information processing systems are easier to modularize
- Elements do not back-load each other due to huge impedance mismatch - $R_L >> R_S$

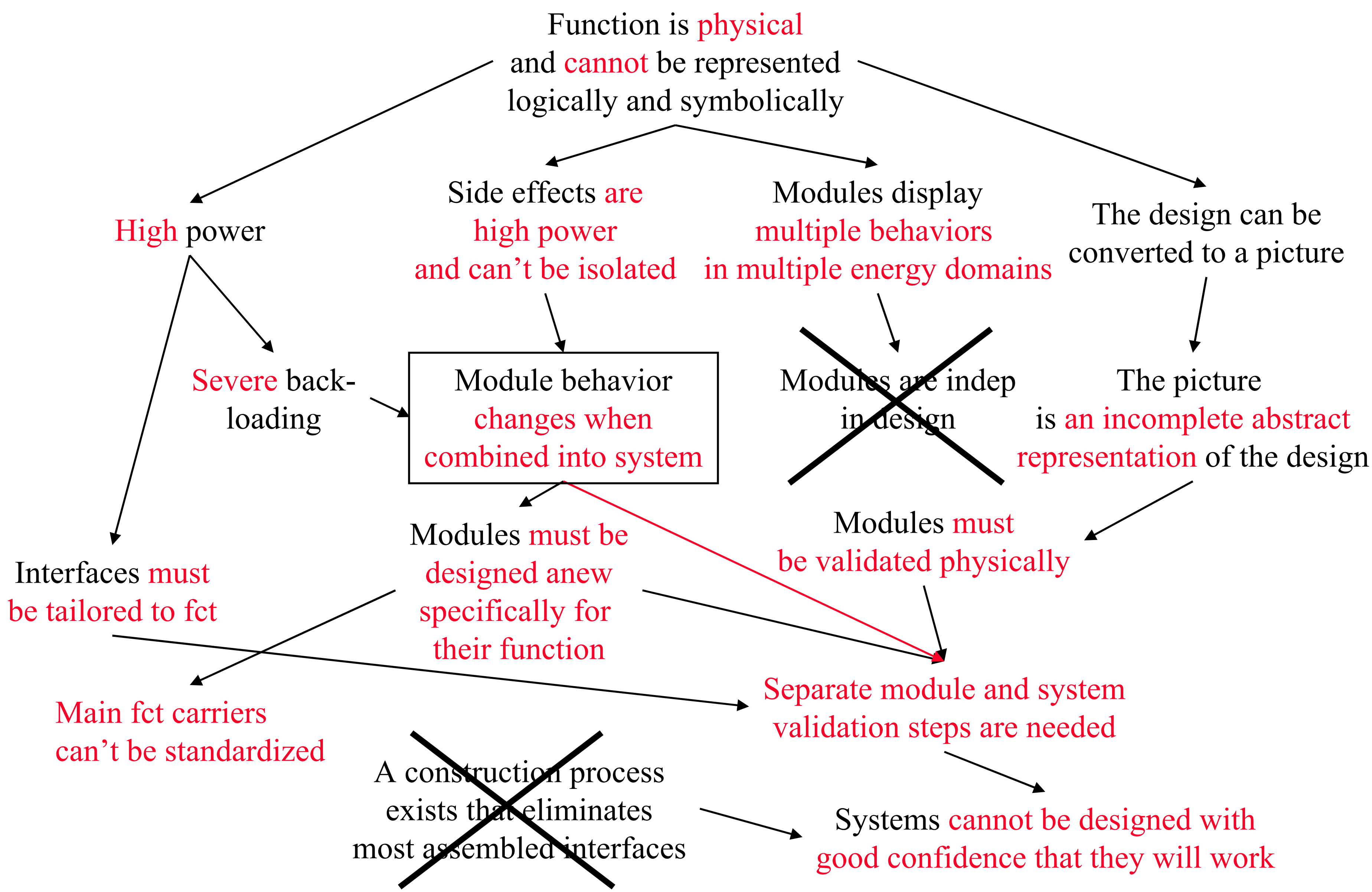


- No worry about wasting power (until recently)
- Side-effects are also low power and can be dealt with logically
- Power processing systems contain unavoidable interactions at undeclared interfaces
- Side effects in high power systems occur at the same power level as main effects: vibration, heat dissipation, crack growth
- These side effects either constitute or generate integrality

Low Power Items - VLSI



High Power Items - Jet Engine



Counter-Example Proves the Rule?

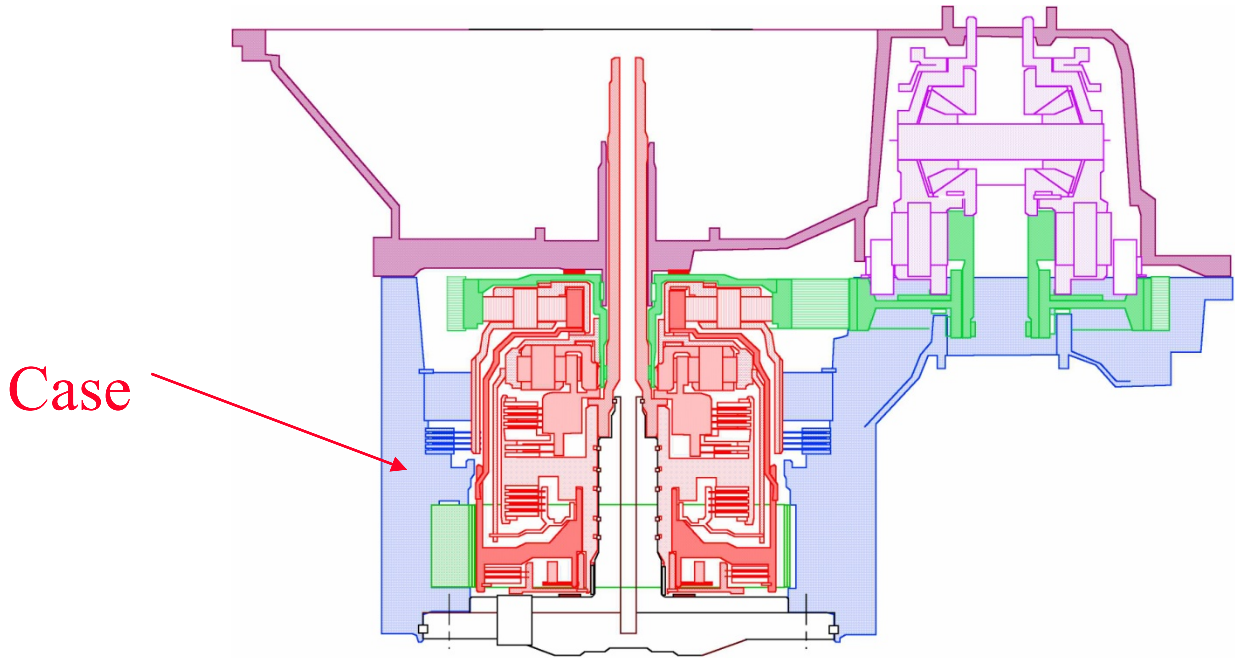
- Microprocessors increasingly give off huge amounts of heat - frying pans with computing power
- Inability to get rid of this heat is THE blockage to following Moore's Law, not lithography or other traditional barriers - processors self-destruct
- Thermal management costs a lot
- Heat dissipation equates to short battery life and hot laps, threatening the laptop computer market
- The campaign to mitigate heat has tied together electrical and mechanical designers, microprocessor designers and computer makers and software designers
- These are symptoms of integrality
- Conclusion: high power drives traditional modular item into integrality

Evidence at Intel

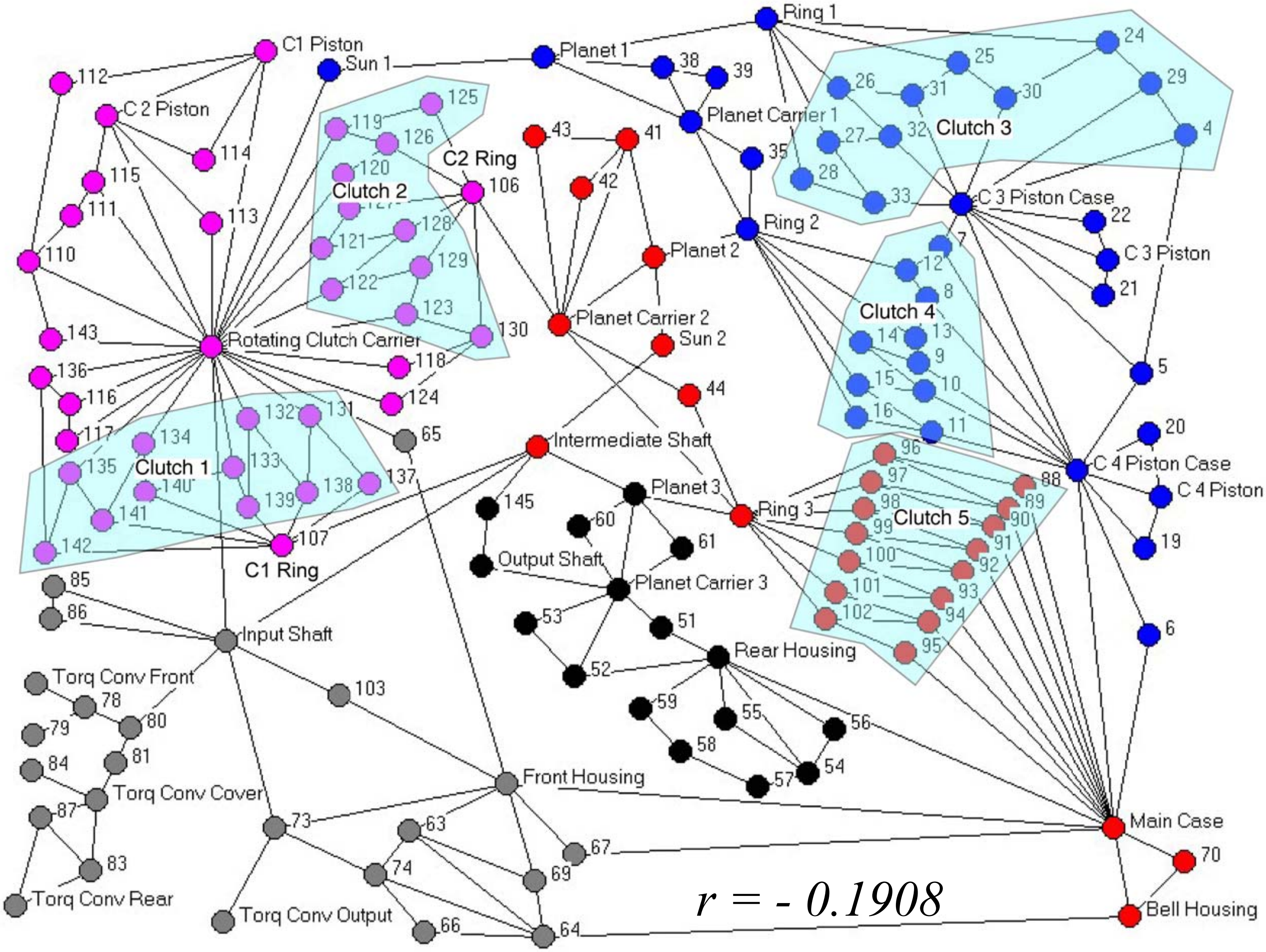
- Patents on fans
- Investments in software and heat transfer solutions
- Close cooperation with PC designers
- Major shift in marketing strategy to de-emphasize processor speed
- Ref: SDM Thesis by Sam Weinstein, March 2004, LFM thesis by Tom Evans, June 2003
- Shift by Apple to Intel processors

Car Transaxle Case

- Single part does many things: it is integral
- Designers would not switch to modular design
- This is a possible reason why some parts have high nodal degree, like the V-8 engine block



Network Model of Automatic Transmission



$r = -0.1908$

Car Transaxle Case: Integral vs Modular

Function	Modular Design	Integral Design
Align shafts, gears, clutches	Space frame	Thin wall casting
Retain fluid	Plastic membrane	Thin wall casting plus impregnation*
Contain noise	Foam or other insulation	Thin wall casting
Carry driveline loads	Space frame	Thin wall casting

* Modular: each pore is plugged separately

Low and High Power Domains

- VLSI designers want modularity because it permits them to conquer complexity
  - System design with standard tested modules is fast
  - Integrality would smother them in testing costs
- High power system designers exploit integrality and function sharing to achieve efficiency and elegance
  - Modularity would saddle them with unreliable Rube Goldberg things
  - Extra interfaces take up space and weight and are sources of failures

What Makes Something "Inherently Integral?"

- It has multiple performance attributes (a measure of complexity?)
- Attribute delivery is distributed within the product, and shared by many parts
- The attributes are coupled and may conflict
  - car door leaks helped by tight seals
  - car door closing effort hurt by tight seals
- Inter-module couplings are very strong
  - load paths in aircraft structure
  - data exchanges in time-critical computing tasks
- As a result, the product may appear modular but it is not

Some Educational Implications

- EEs are given their components
  - Linear, independent, pre-tested, single function
  - They can start designing systems as sophomores
  - Separate component experts exist (chemists, solid state physicists)
- MEs must learn to design components first
  - Non-linear, coupled, designed to suit, multifunctional
  - They don’t see system design until they are seniors
    - This happens in basic servo theory
    - Mechanical assembly is not taught

Some “Principles”

- Power levels can be determinative in limiting modularity (2) choices - a constraint on system structure
- “Business issues” further limit or shape modularity (1) choices: customization, reuse, common architecture
- Business and physical domains are coupled, sometimes by confusion between M-1 and M-2
- Hidden integrality in one domain (business or physical) can scramble sought-after modularity in the other domain

Backups

What Design and System Theory Say

- Design theory and system engineering strive for independence of relationships between functional requirements and physical embodiments (M-2)
- Design theory seeks to attain this by means of decomposition in the functional domain
  - Each functional element is then given its physical counterpart
  - This hopefully leads to a modular design but not always
- System engineering seeks to attain this by decomposing carefully and managing interfaces
  - This, too, hopefully leads to a modular design

Main Function Carriers and Not

- Electronics main function carriers
  - Circuit elements like VLSI, resistors, capacitors
- Non-main function carriers
  - Terminal strips, labels
- Both main and non-main function carriers can be standardized

- Mechanical system main function carriers
  - Engine block, crankshaft, camshaft
- Non-main function carriers
  - Screws, washers
- Only the non-main function carriers can be standardized

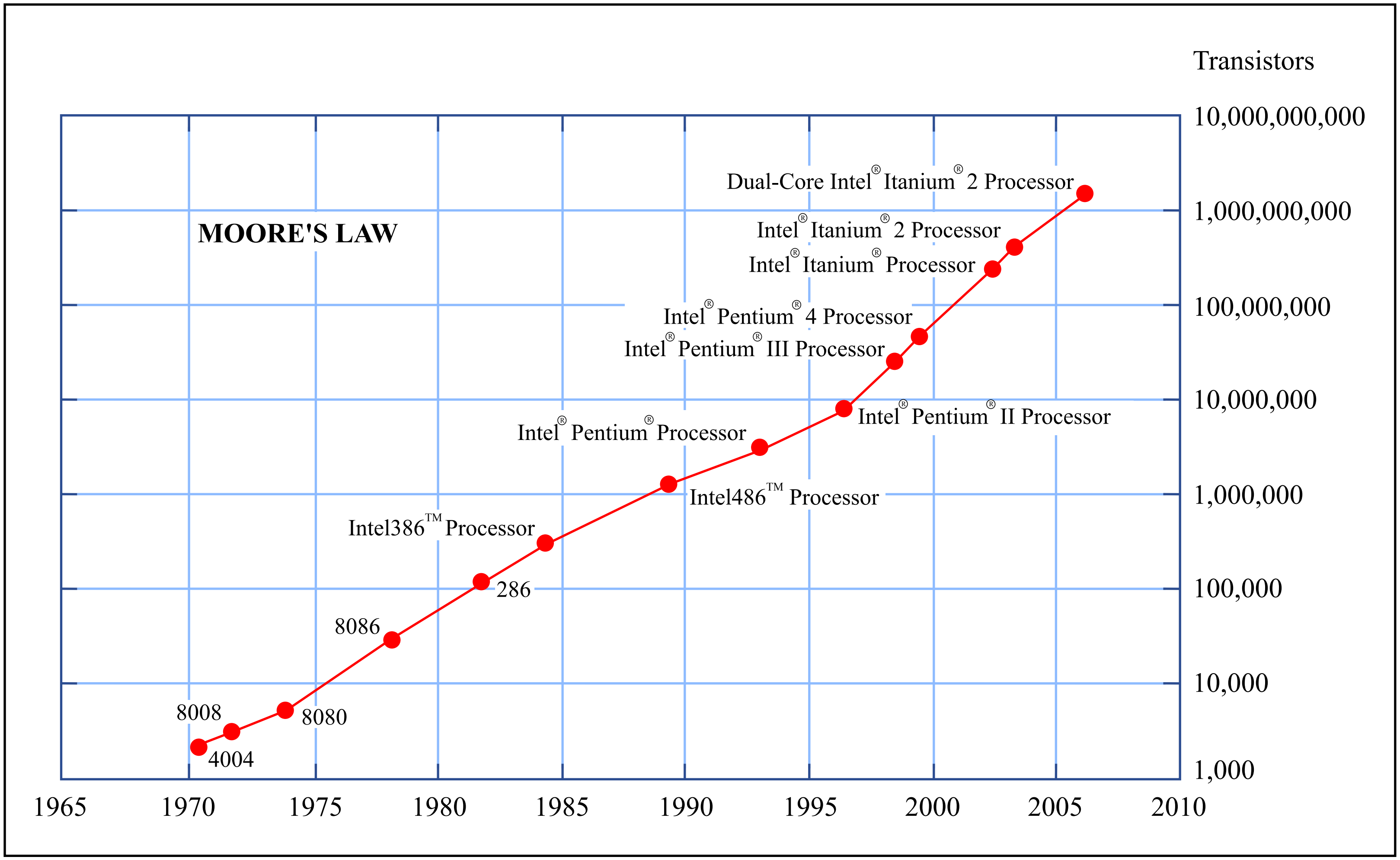
More "Modularity is Good"

- When individual performance is most important, specialization is rewarded
  - Baseball hitters
  - Fighter pilots
- But real excellence is very rare
  - Plenty of evidence that a few % of participants account for a huge % of total achievement

More “Modularity is Bad”

- When group performance or interaction with others is paramount, extreme specialization may be counter-productive, and broad capability may be better even if people are not excellent in any one domain
  - N E Patriots players who can play more than one position
  - Michael Jordan-Scotty Pippin
  - Switch hitters in baseball
  - Toyota managers trained and selected for “connection knowledge” (Sobek)
  - RAF: medals for bravery
  - Luftwaffe: medals for kills
- Note generic broad-deep tradeoff

Moore's Law



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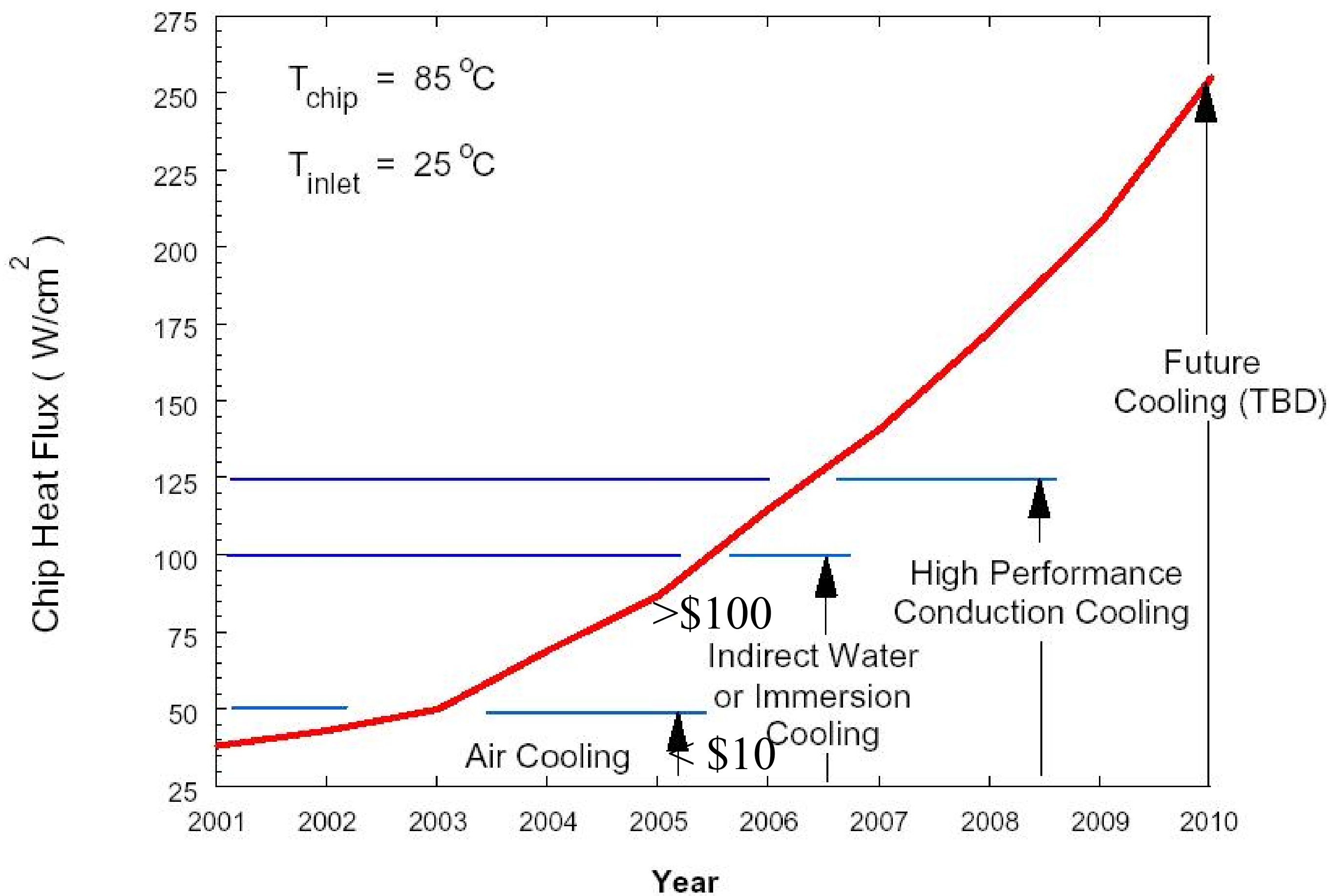
Cost of Thermal Management



ESD.342 Network Representations of Complex Engineering Systems
Spring 2010