Reconfigurable Electronics and Advanced Packaging

a selected eclectic topical introduction

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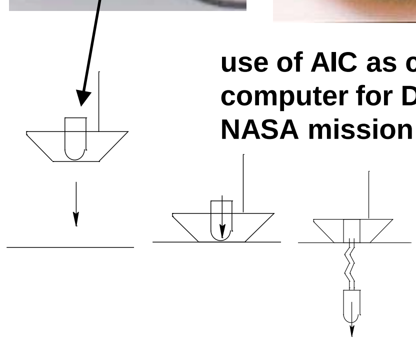
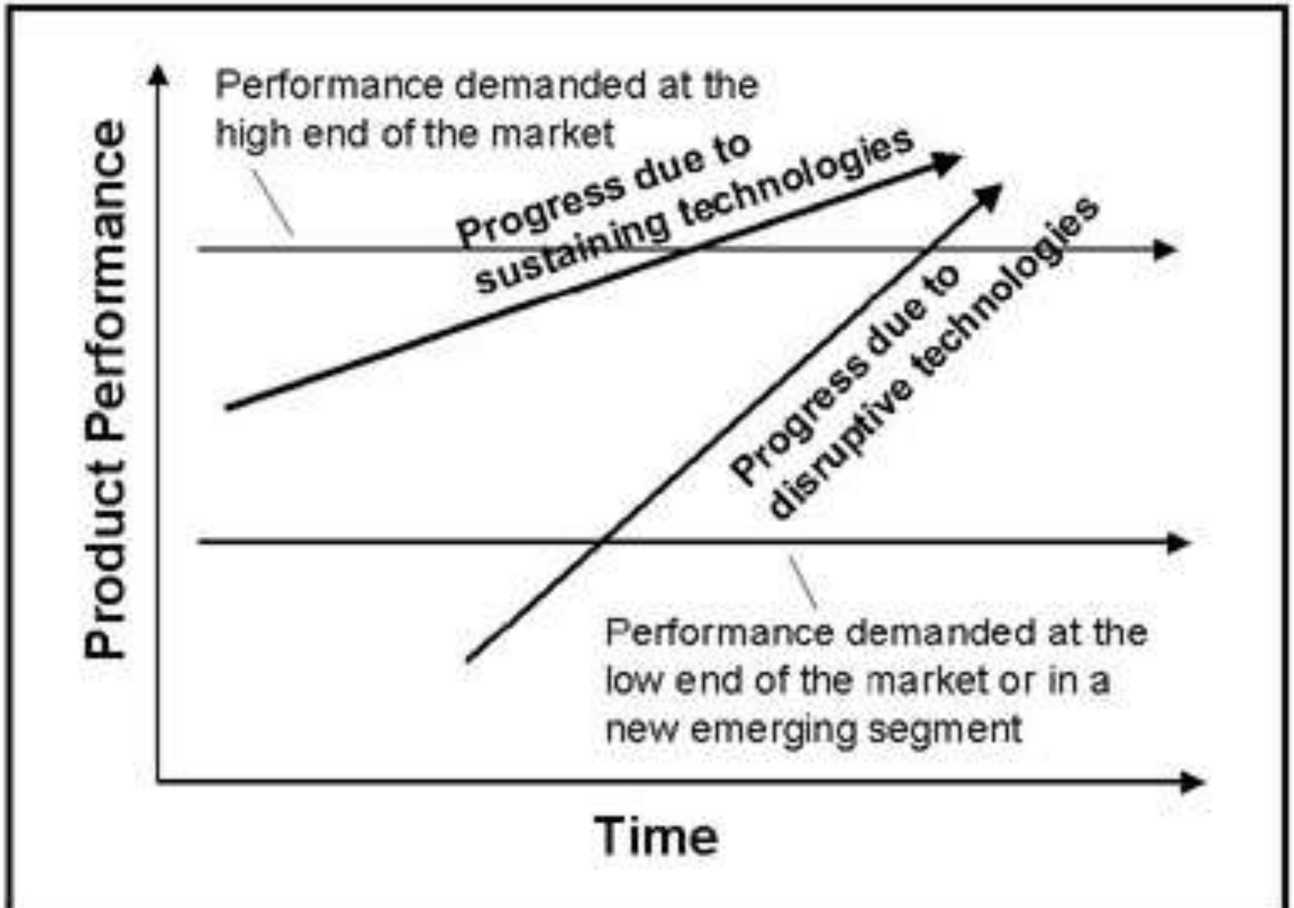
Advanced Instrument Controller (AIC) (1997-2000)

use of AIC as control computer for Deep Space 2 NASA mission



- Uniquely forumulated to address needs for Mars penetrators operating in Southern polar region
  - 30,000 G, -130 deg C, 50 mW power, frequent interruptions
  - USAF investment preserved flexibility in AIC design features for general-purpose use

Two Technology Trends

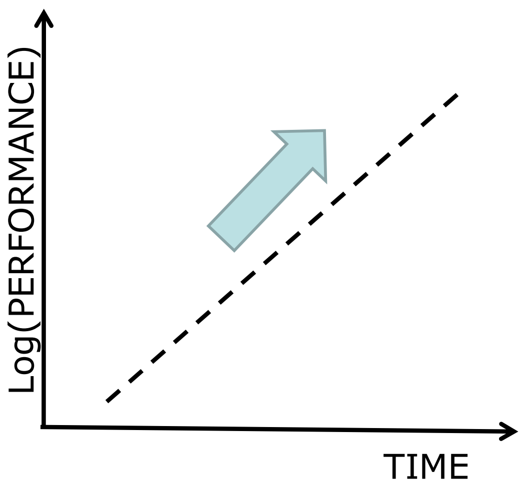


Source: **Christensen, Clayton M. *The Innovator's Dilemma: When New Technologies Cause Great Firms to Fail*. Boston, Mass.: Harvard Business School Press, 1997.**

Preliminary – About Disruption

- If we see it coming, it may not be disruptive
- Random “scary” technologies may not be disruptive (just “scary”)
- Speculations about disruption are only meaning in context of application-connected goals (performance, energy, accelerated creation, dynamic morphability, evolution/autonomy)

Moore's Law vs. ?

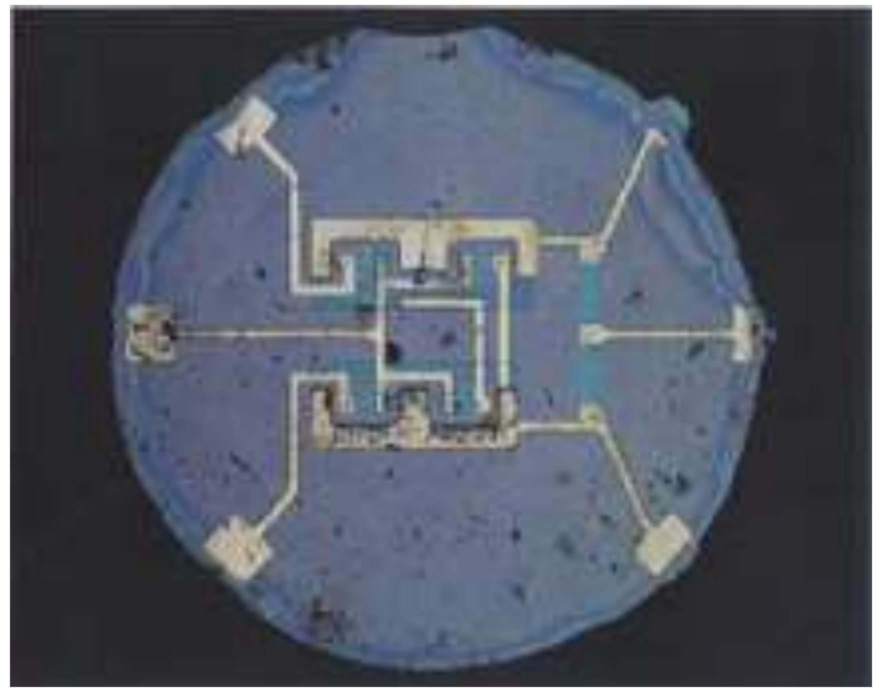


- Predictable trend
- Performance-focused
- Challenging goals
- Rallying points for an industry

"Terminator 2"

- Disruptive concepts
- Non-traditional metrics (e.g.,time-focused)
- "Good enough" Performance
- Challenging goals
- Not clear how to rally industry

What Became of Moore's Law?



Kilby's first integrated circuit

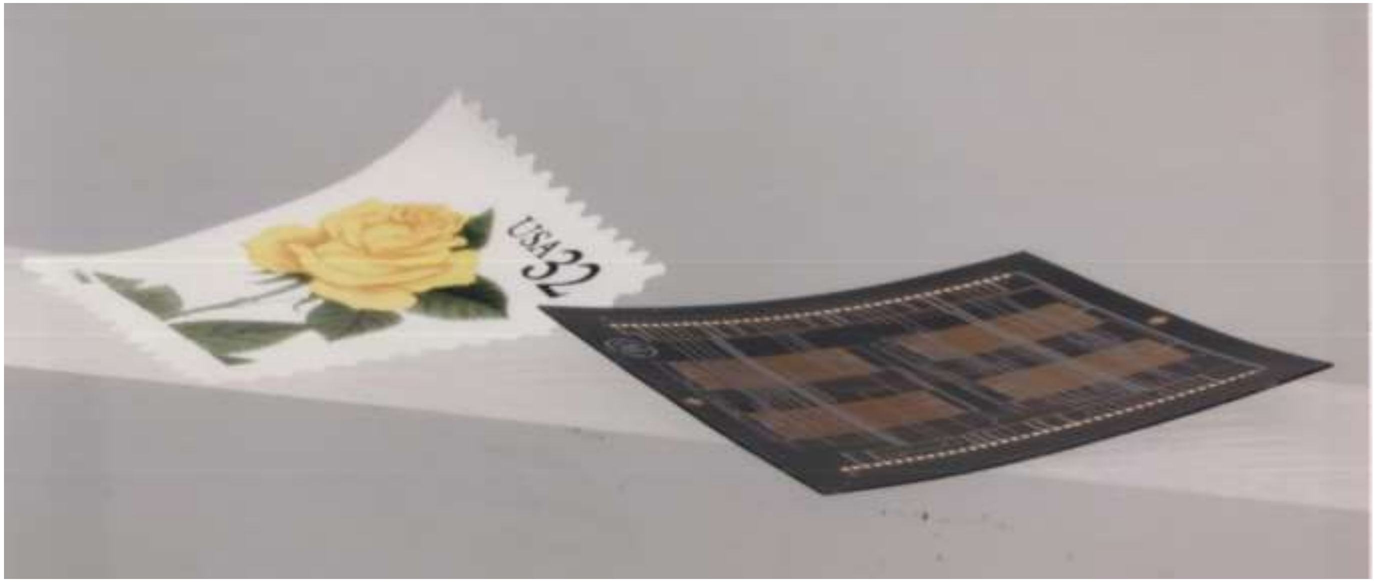
Noyce: the first planar integrated circuit

Moore’s Law Past and Future

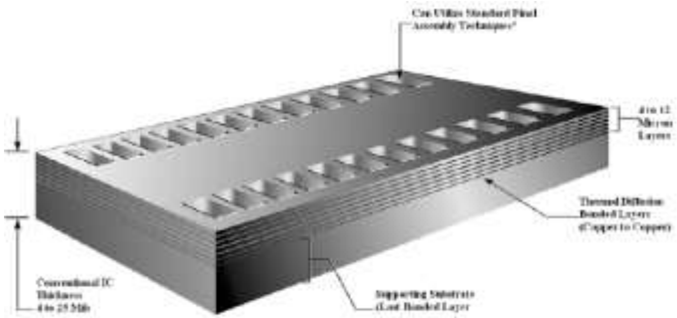
- Moore’s Law was the disruptive idea
  - You can count on a doubling of transistor density every 18-24 months
- Moore’s Law drove new disruptions
  - PC, FPGA, smart phones
- Some say it is starting to end…
- But we could extract six more orders of magnitude (i.e., Moore’s Law to 2060) by going (1) 3-D and (2) molecular electronics

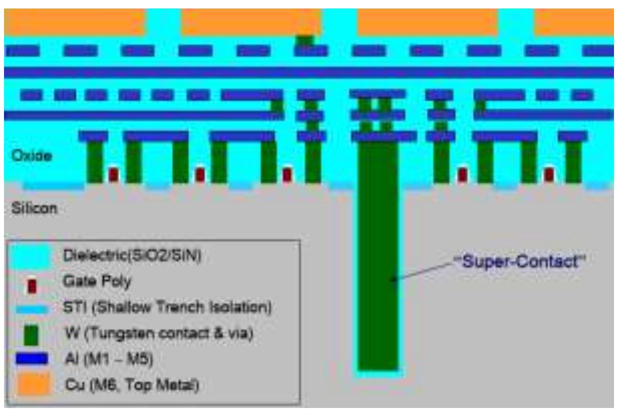
Ultra-thin High Density Interconnect

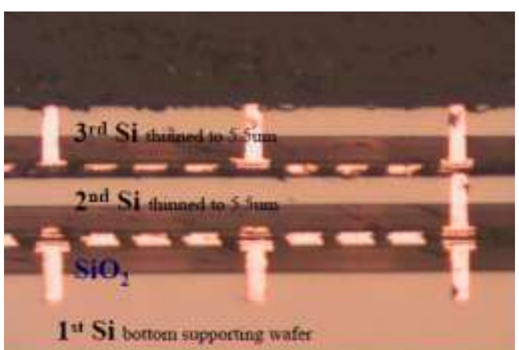
- Recently demonstrated capability to thin entire MCMs below paper thickness and retain functionality
- Silicon bends when thinned below 50um



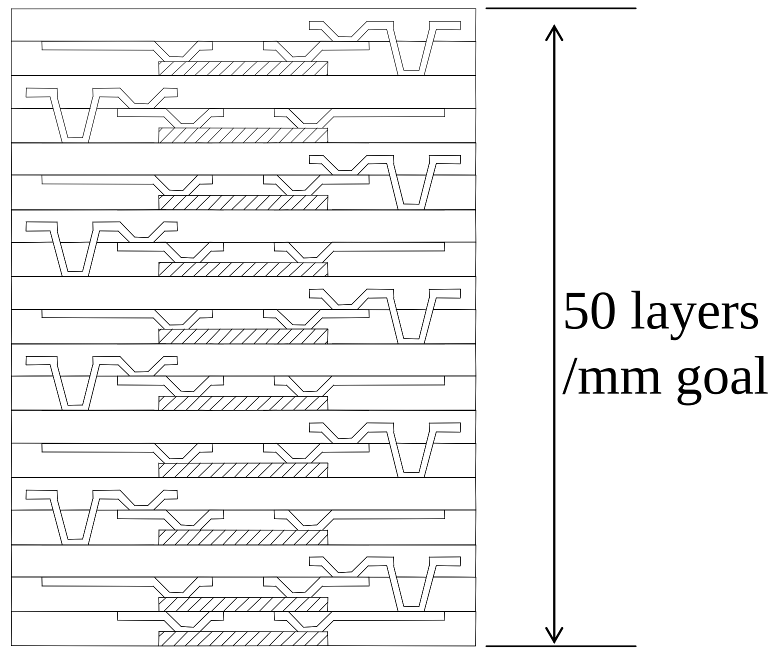
Three-dimensional integrated circuits (hierarchical 3-D IC/3-D overlay packaging)

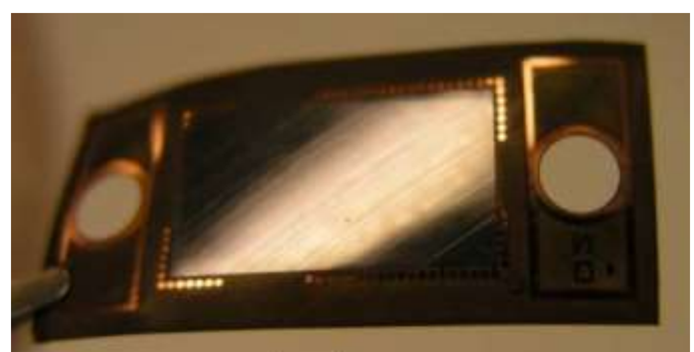






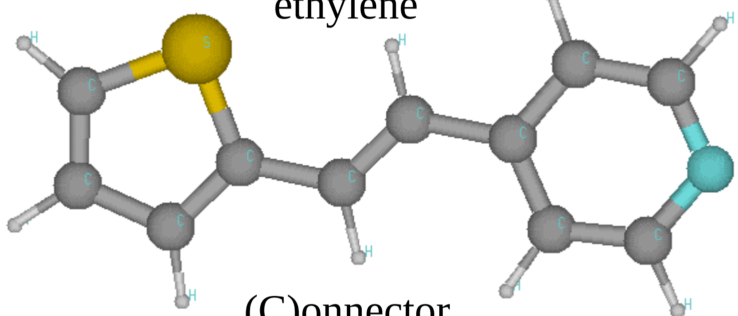
3-D IC





3-D stacked decal packaging

Molecular electronics



Molecular pn junction[1]

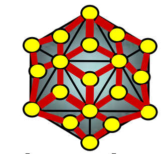
- Molecular electronics approaches may extend Moore’s law to 2050
- Building devices themselves is difficult
- Forming devices into effective aggregates involves fundamental challenges
  - Interconnections
  - Lithography alternatives
  - Yield

Concept: Exploit viral structures as basis for molecular circuit architecture

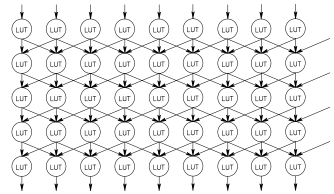
- Form virus mutations
  - Different connection opportunities on the virus
  - With various chemical and physical properties
- Attach “things” to the virii/viruses/virions??
  - The “things” are circuits
- Harness naturally tendency

  of viral structures to self-assemble
  - Form scalable computational architecture
- Establish bridge to dense VLSI architecture
  - VLSI architecture could be smart substrate

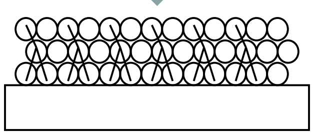
  for the virus-based circuit layers



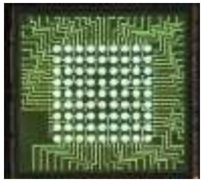
Molecular level



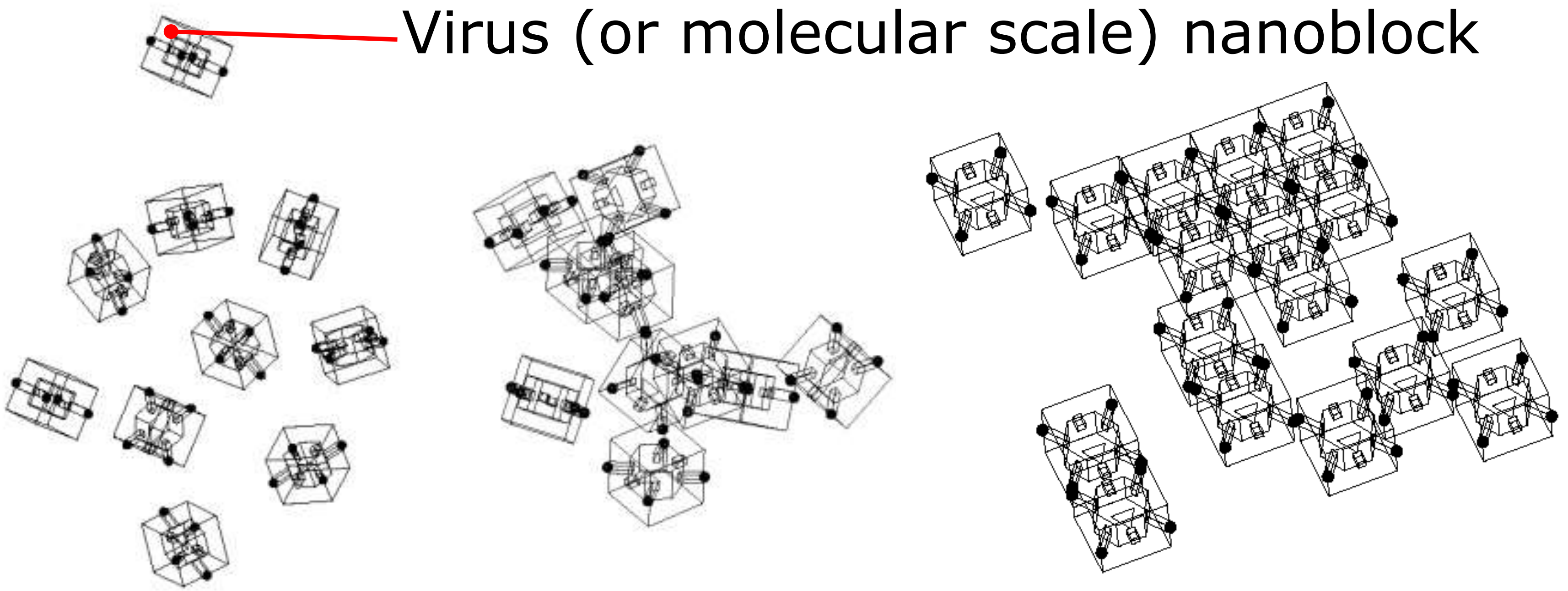
Viral nano block level (VSA)



Viral nano interconnect level



Ultra-dense (~10^4)
micro BGAmolecular package



Traits of a "good" molecularly scalable approach

- Lithographic alternatives
- Defect tolerance
- Exploit what nature gives us (periodicity, randomness)
- Simplest building blocks capable of universal expression (e.g., Turing-complete)

Additive Manufacturing as an Enabler for Future Electronics Systems

- Single/multimaterial
- Creative Exploitation
- Pick-and-print-and-place

How AM may improve electronics for space missions

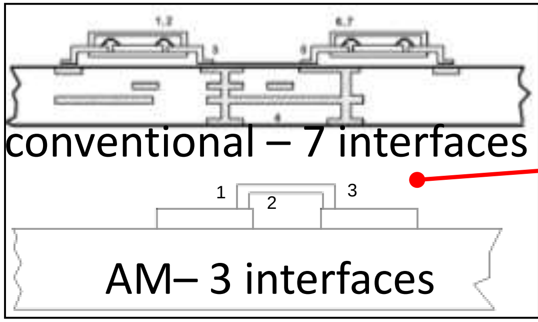
Feature	Potential AM attribute / benefit	Timescale for useful benefit
Comp dens	Dense / efficient packaging	Mid-to-far (requires high-density)
Mem dens	Dense / efficient packaging	Mid-to-far (requires high-density)
Inter dens	Dense/efficiency packaging	Mid-to-far (requires high-density)
Bandwidth	Less direct benefit	N/A
Acquisition	Reduction in parasitics and signal degradation	Near-term (other improvements in mid-far term[1])
Signal integrity	Ability to manage signal coupling and EMI	Near term (other improvements in mid-far term[1])
Efficiency (p)	Reduction in parasitics can yield improvement	Mid-to-far (requires greater geometric control, also [1])
Efficiency (fn)	Reduction in parasitics can yield improvement	Mid-to-far (requires greater geometric control, also [1])
Time precision	Ability to define/adjust pathlengths	Near-term
Geometry	Tightly-coupled / tunable geometries	Near-term
Reliability	Lifetime (systematic reduction in the number and extent of interfaces)	Near-term

1. Improvements in material properties (especially electrical conductivity) will significantly enhance benefits.

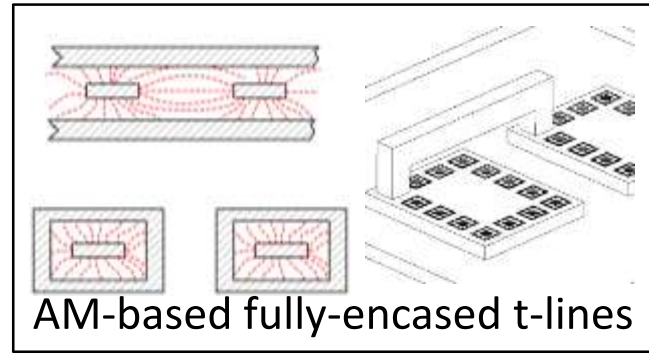
Red box: Emphasis of proposed work (experiments)

Blue box: Improved understanding of materials will lead to benefits here

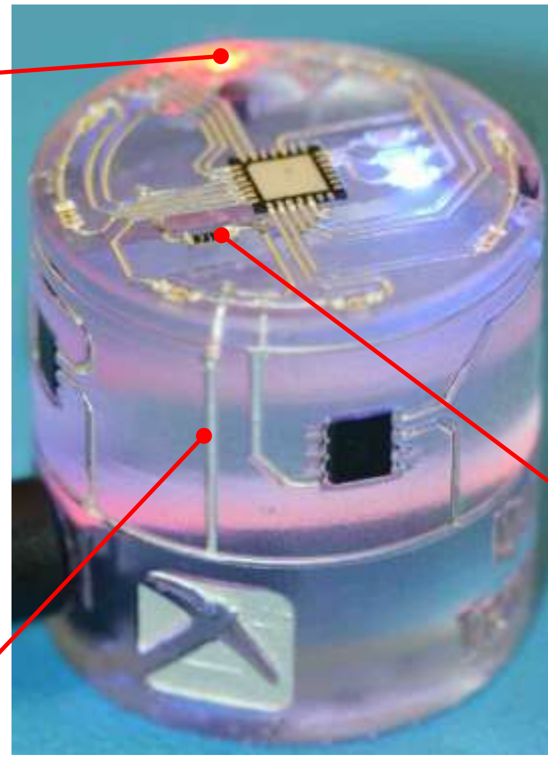
AM – Opportunities for Superior Performance in Electronics

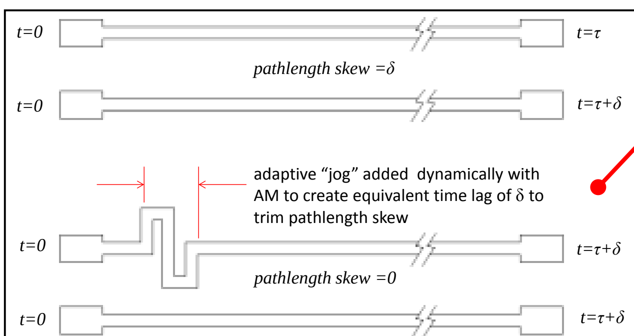


Improved reliability *through systematic reduction of interfaces, connectors in tightly-coupled design*

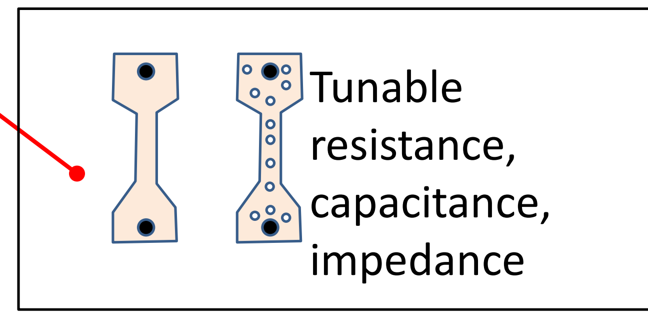


Reduced noise/crosstalk*: point-to-point customized micro-coaxial interconnections*





Improved timing precision*: sub-picosecond (adaptive) signal control*



Improved analog / microwave circuits*: Ability to vary / tune composition of dielectrics and conductors, eliminate manual tuning in custom-microwave modules*

Reconfigurable Systems as a Disruptive technology

- Science and engineering based on embracing change
- **Elements**
  - Developing new degrees of freedom within electrical, mechanical systems at varying levels of scale
  - Developing new understandings of the meaning of software-defined flexibility tightly coupled to the physical world
  - Developing strategies to exploit adaptation of degrees of freedom (self-organization, self-assembly)

The three benefits of reconfigurable systems

- Tele-alteration (ability to change and specify change remotely) (malleability focused)
- Resilience / Robustness (reliability focused)
- X-on-demand (time focused)

None of these benefits are performance-focused (as in Moore's Law)

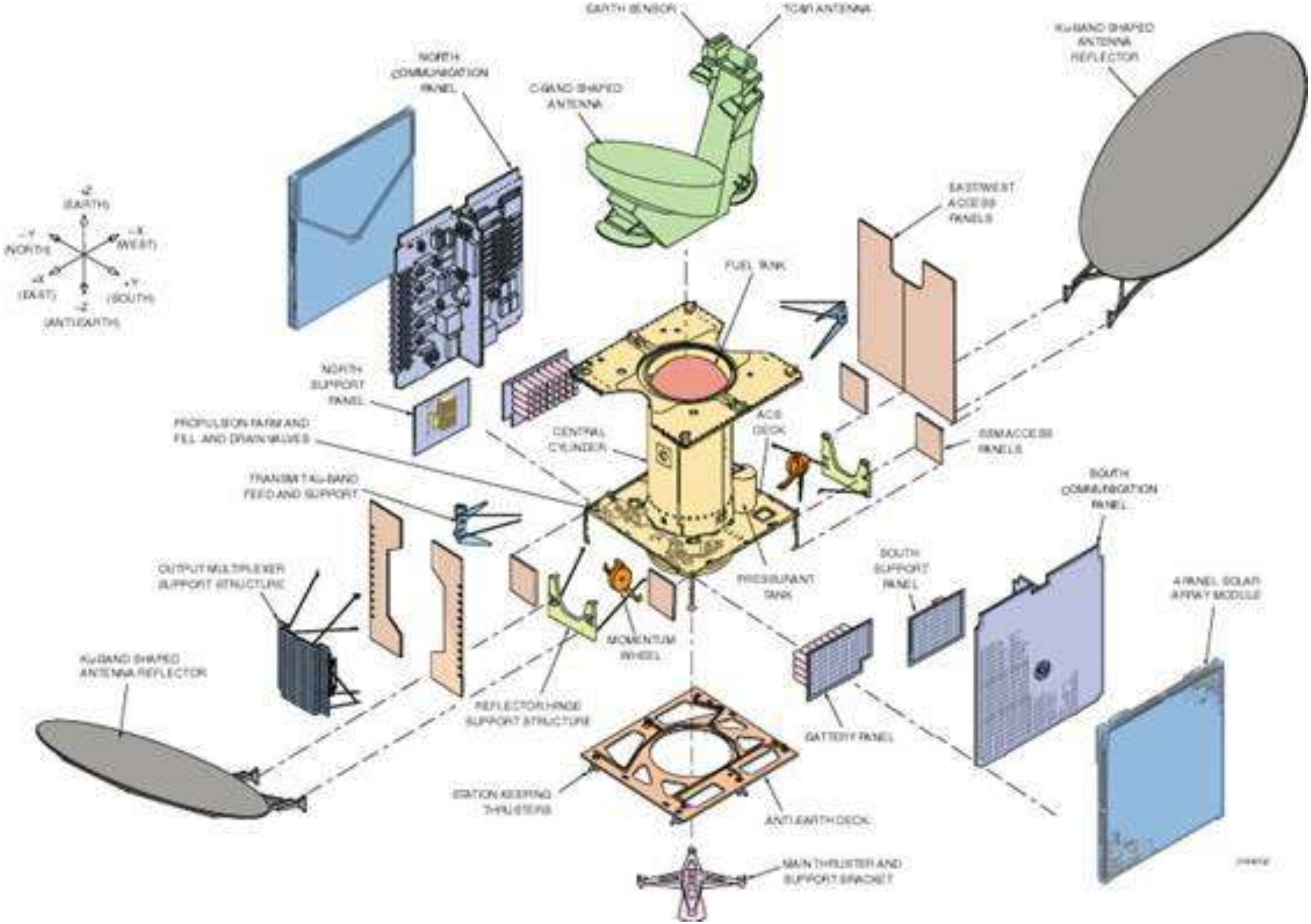
The Problem

- Multi-year schedule slips, multi-billion dollar overruns has become typical….

"Whether or not cost overruns are inherent in U.S. military satellites under development, we cannot say for sure. We can say that these overruns seem to be endemic. There are about 10 major satellite systems under development by the DOD, including the Advanced Extremely High Frequency (AEHF) satellites, the Future Imagery Architecture (FIA) satellites, the GPS IIR-M/IIF, the GPS III, the Mobile User Objective System (MUOS), the National Polar-orbiting Operational Environmental Satellite System (N-POESS), the Space Based Infrared System-High (SBIRS-High), the Space Radar (SR), the Space Tracking and Surveillance System (STSS), and the Wideband Gapfiller Satellites (WGS).
All of these programs are over budget (way over, in some cases) and behind schedule or delayed." [1]

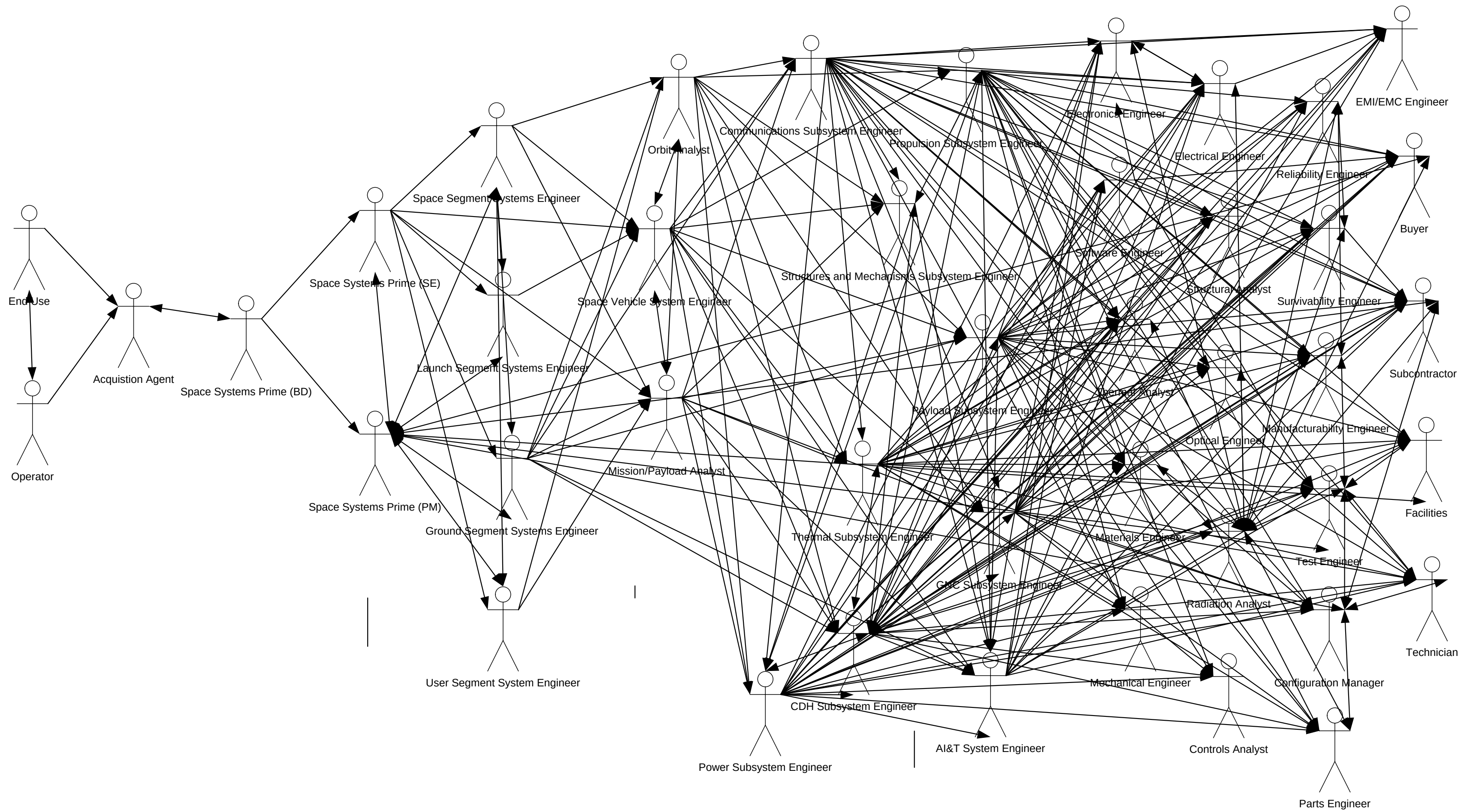
"What are the things that these programs share in common that make it seem as though cost overruns are part of their nature?"

1. **Marco Cáceres , "Cost overruns plague military satellite programs", Aerospace America (publication of AIAA), January 2006, pp 18-20, 23. Specific URL (working as of 2 Jan 08): http://www.aiaa.org/aerospace/images/articleimages/pdf/AA_Jan06_II.pdf .**



Source: http://www.ssloral.com/html/products/satint.html

The "Marching Army"



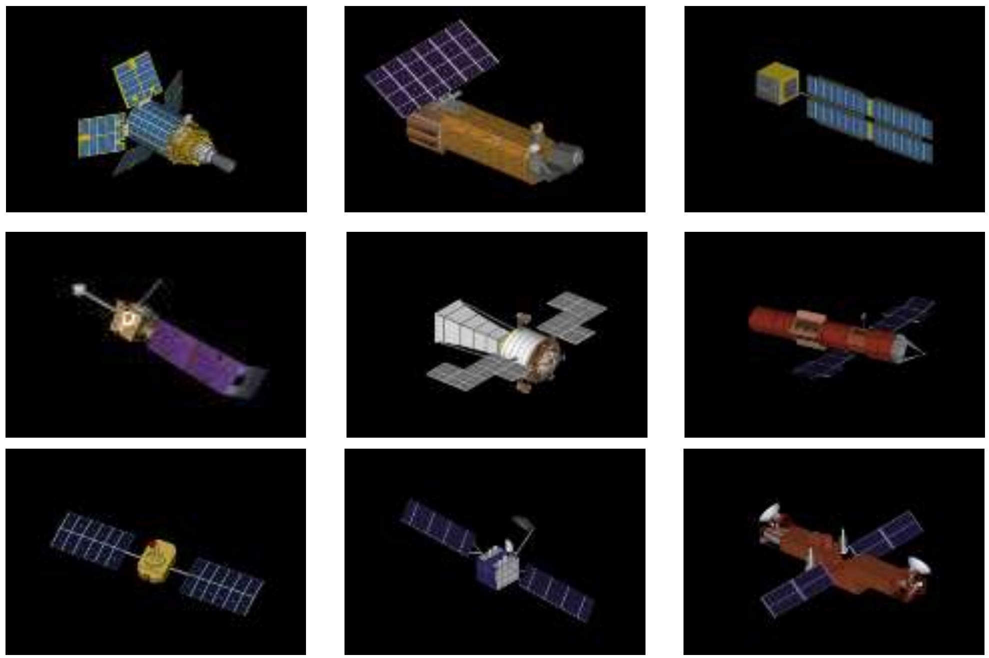
Courtesy of Michael Enoch, LM

What does this mean?

- Time is our enemy
- Complexity is our enemy
- Performance is important but not in isolation from mission
  - Major aerospace platforms take decades to create
  - We like that to be < 1week
- This frames a new perspective on basic research challenges

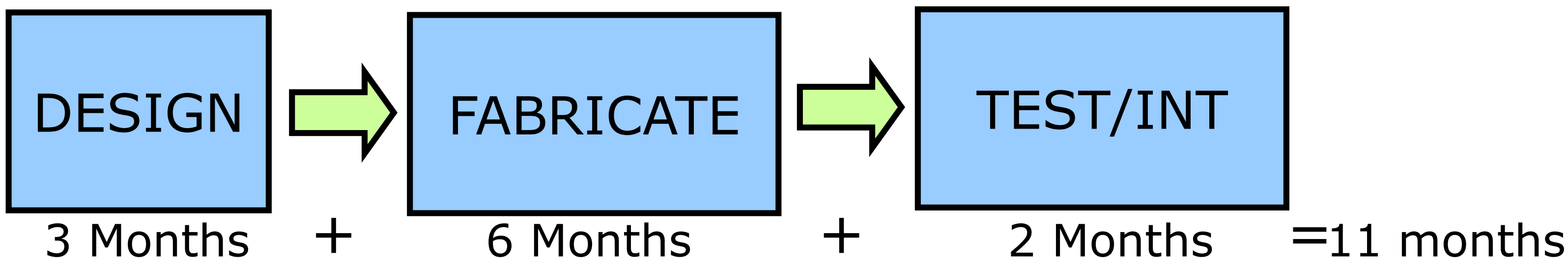
Problem Formulation

Create a spacecraft in less than one week

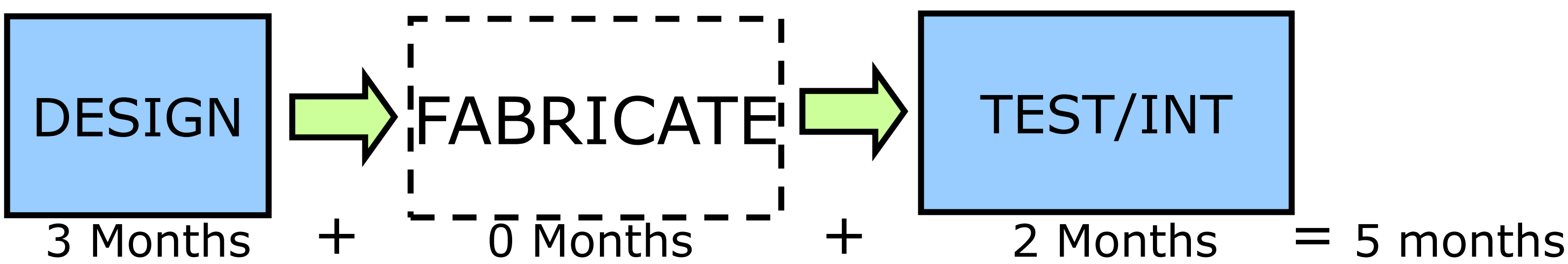


Beating time delay – an example

Integrated Circuit (IC)



Field Programmable Gate Array (FPGA)



Convert one type of time delay into another kind you can deal with!

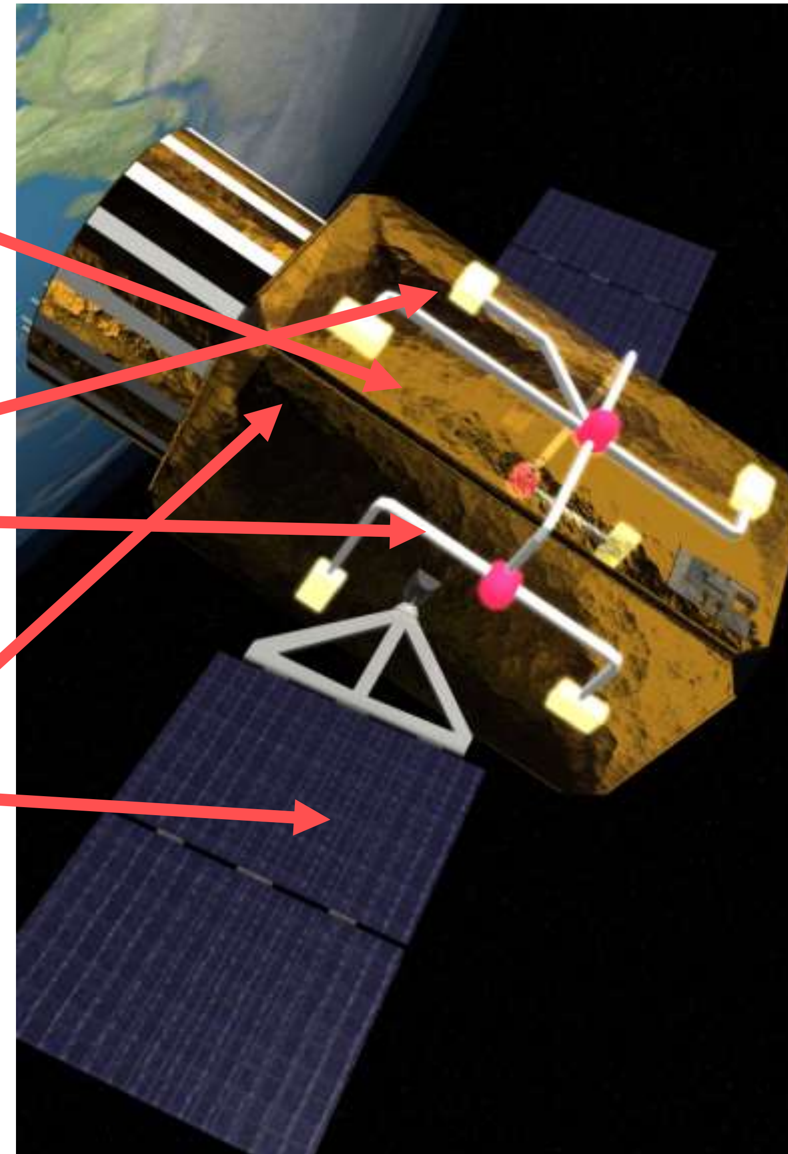
Field-Programmable Satellite Made with Field-Programmable Parts?

Eliminate wiring harnesses with pre-built programmable wiring

Integrate plug-and-play components into sockets of pre-built panels

Modularize power system components, add “smart combiners”

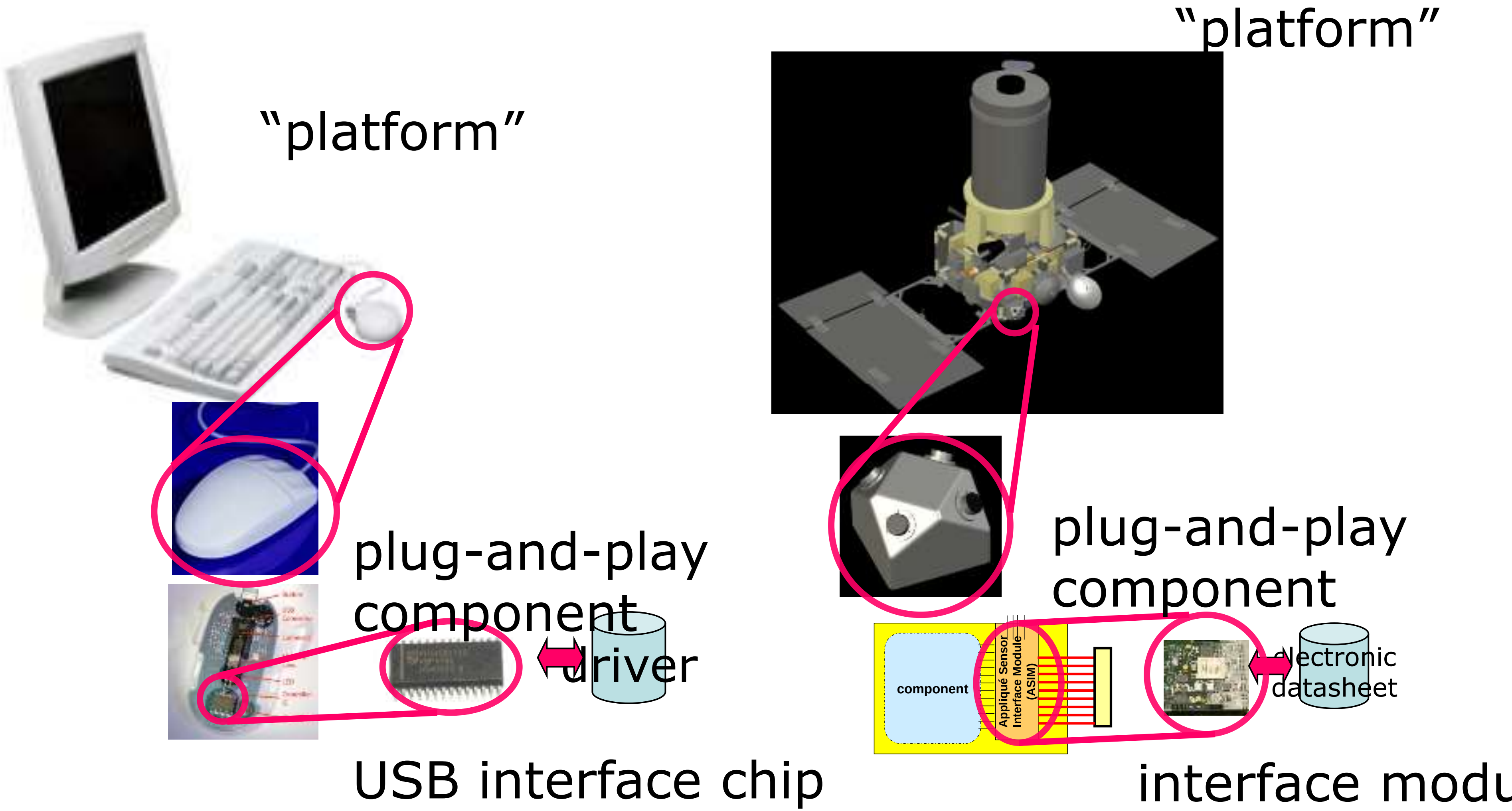
Programmable communications with software radio technology



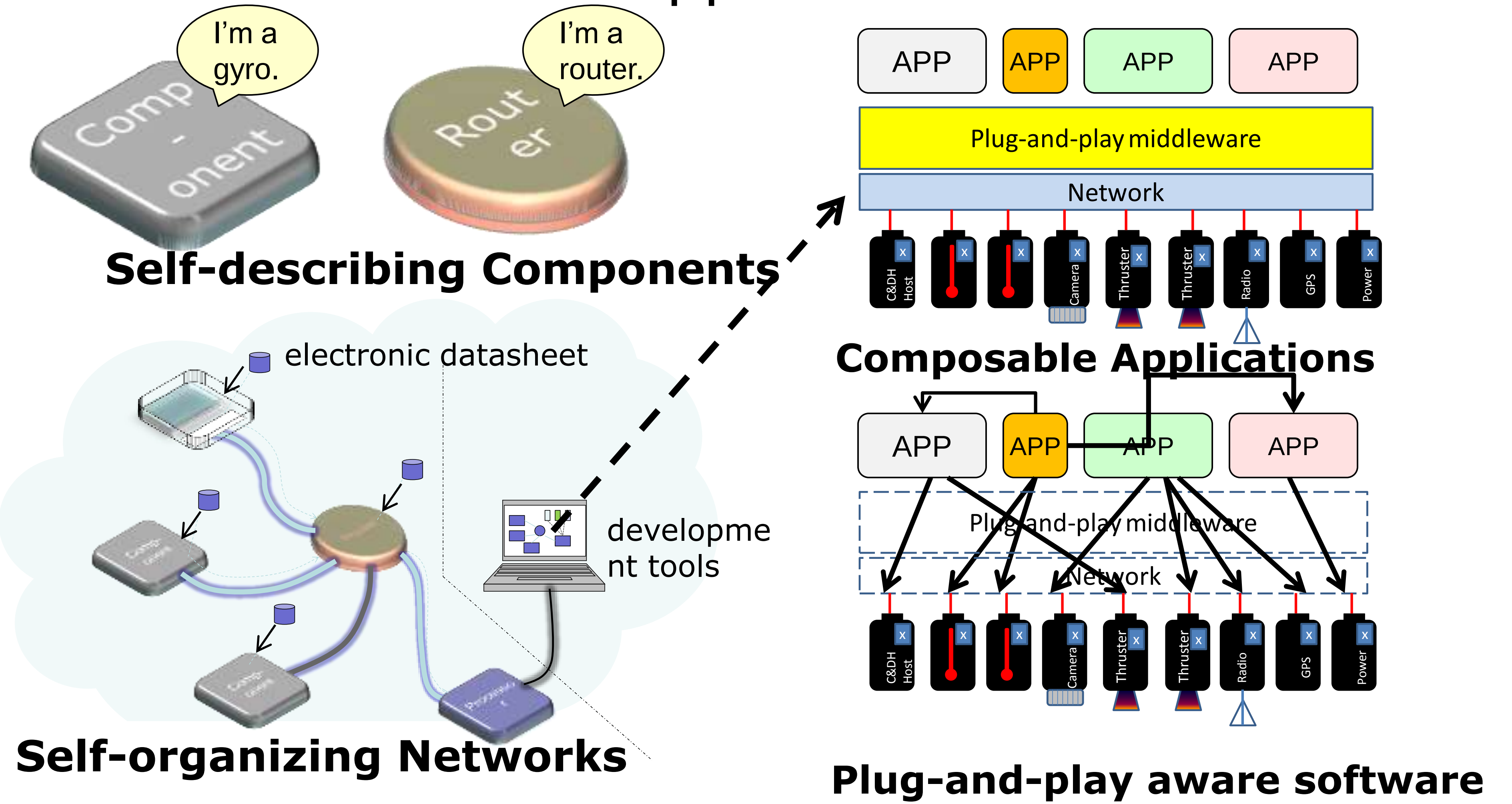
An Architecture for Reconfigurable Systems

- System are reconfigurable
- They are made of pieces
- The pieces are also reconfigurable systems
- The system elements have a unified structure for specifying configuration
- The system is “aware” of its pieces, their dependencies, and the configuration of all of them
- We have called this “space plug-and-play avionics (SPA)”

Intelligent Modularity By Design: “plug-and-play” components/technologies

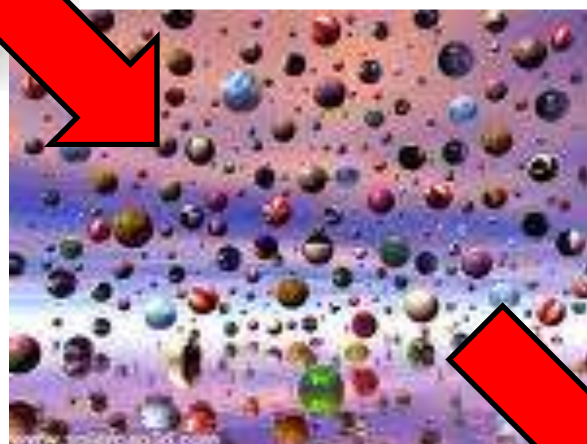


What is SPA? *Data-centric* plug-and-play approach



SPA promotes composable systems (hardware *and* software)

Towards a Programmable Matter



A Centennial Roadmap for reconfigurable systems

1950 1990 2000 2010 2020 ...2050

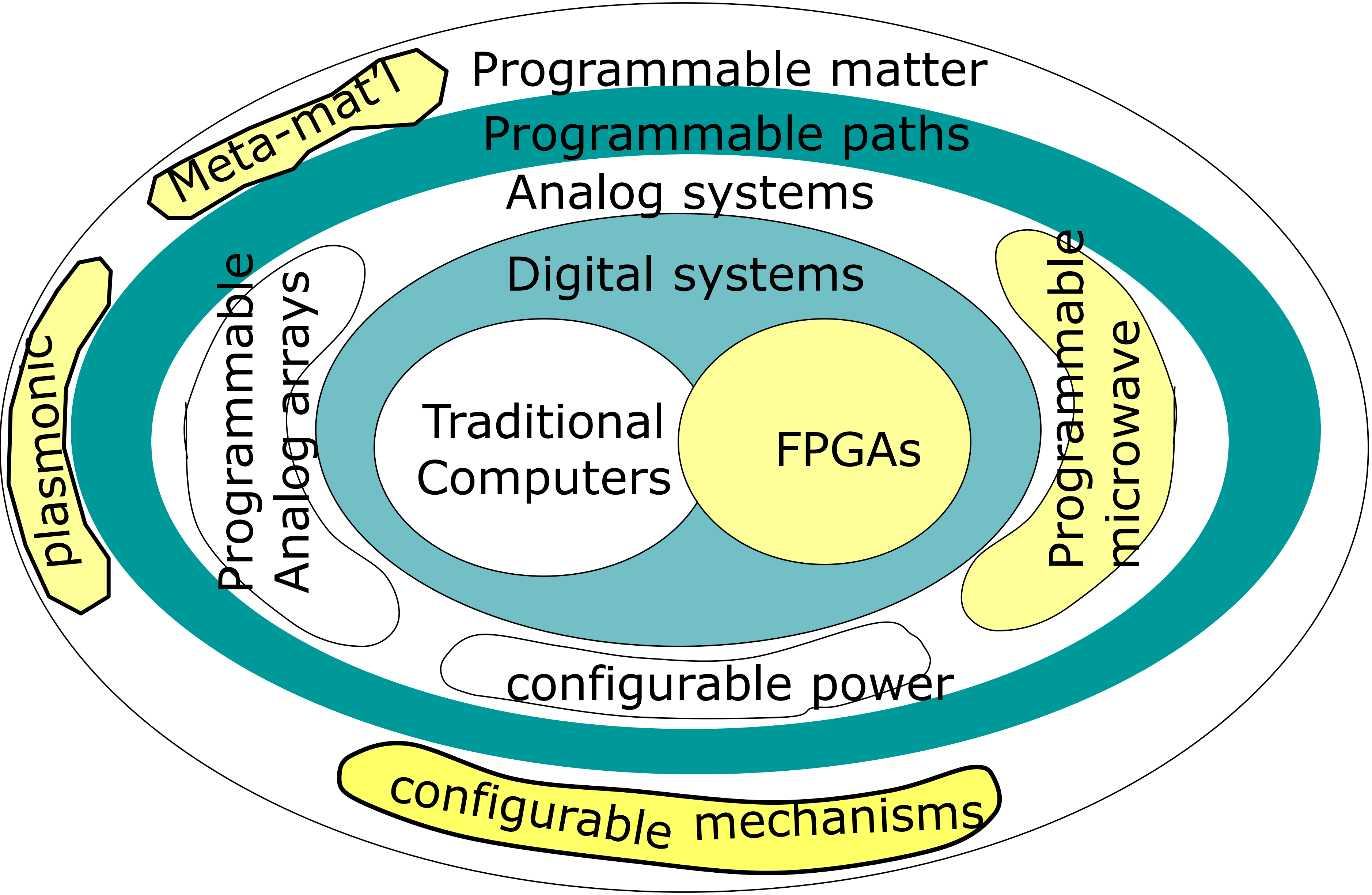
Von-Neumann computers → **reconfigurable processors** → **reconfigurable systems**

- **stored program computer**
- **flexibility by altering contents of <u>instruction registers</u> under user (software) control**
- **hardware structure largely fixed**
- **requires custom sensor adaptation**
- **requires custom pre-processing digital electronics**

- "morphing" computers
- flexibility by altering <u>logic and interconnections</u> under user (software) control
- requires custom sensor adaptation
- pre-processing digital electronics can be redefined at will and altered during mission

- morphing systems
- flexibility by altering contents of <u>logic, analog, rf, power, and wiring</u> under user control
- system block diagram itself can be redefined at will, even during mission
- Programmable matter?

Reconfigurable Systems Taxonomy

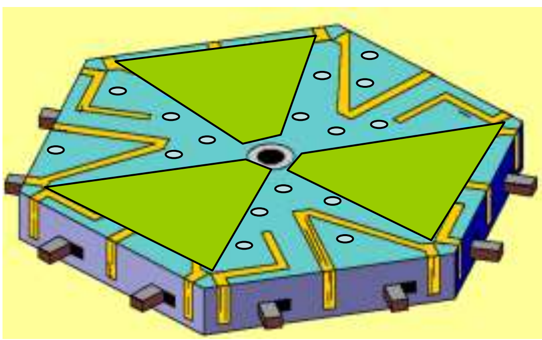


Cellular Approaches: Nature's self-assembly

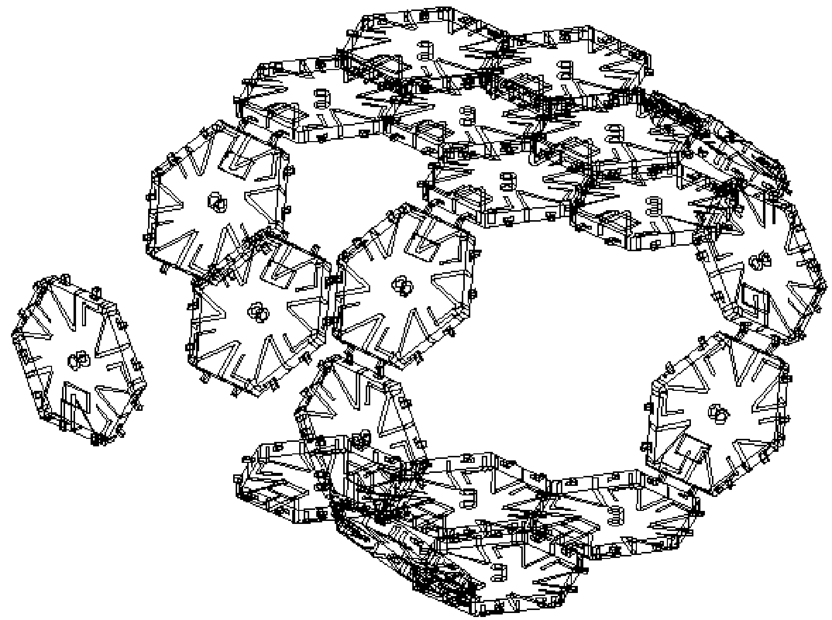
Before RNA-trigger

Spontaneous Assembly
After Trigger

Can we create a self-organizing system based on cellular elements?

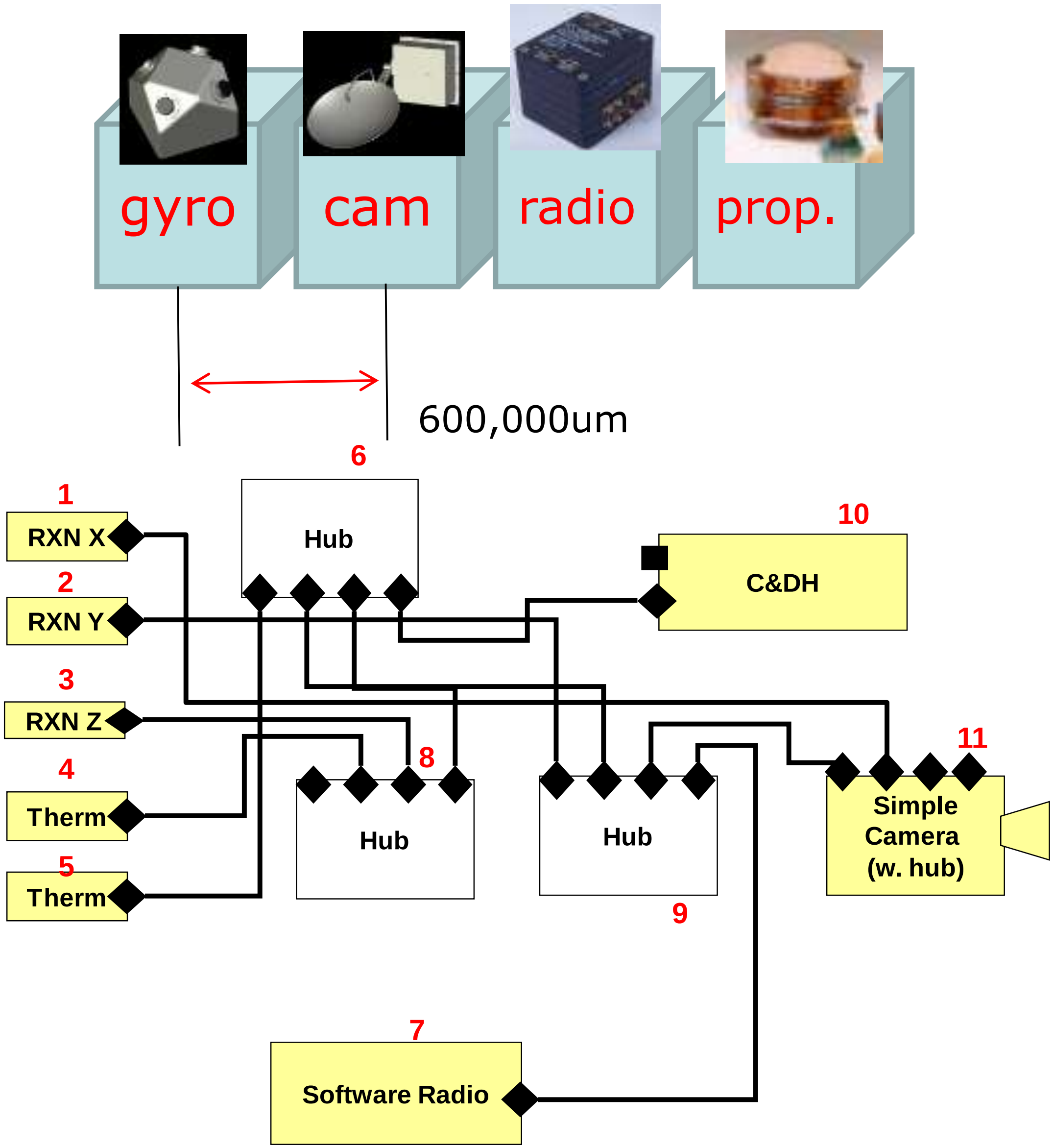


Protosat



Macrosat

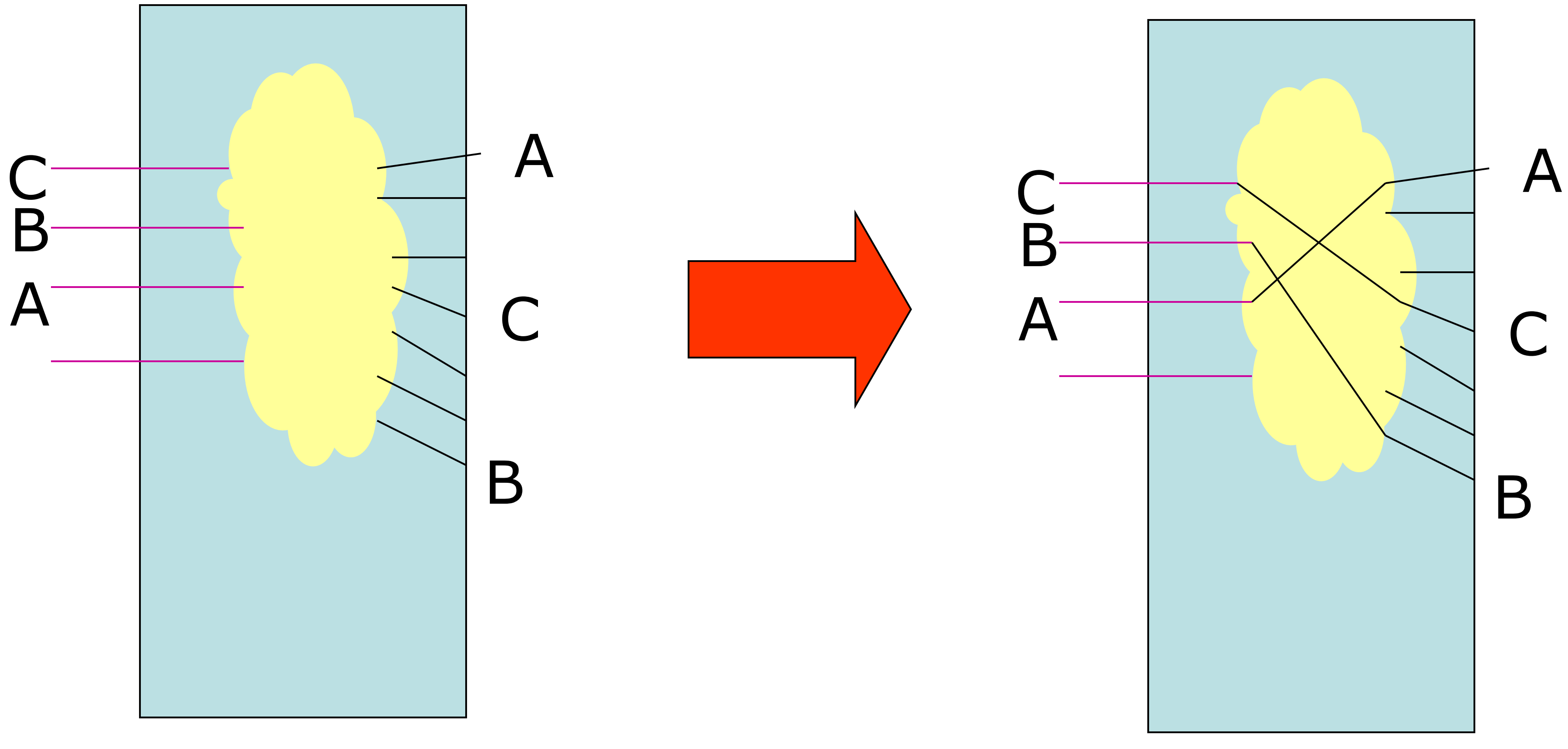
Cellular Interpretation of Plug-and-play Satellite – "Macroscopic Cellularity"



pnpsat

Concept bus

Adaptive wiring allows terminal connections to be set under software control



bla
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program
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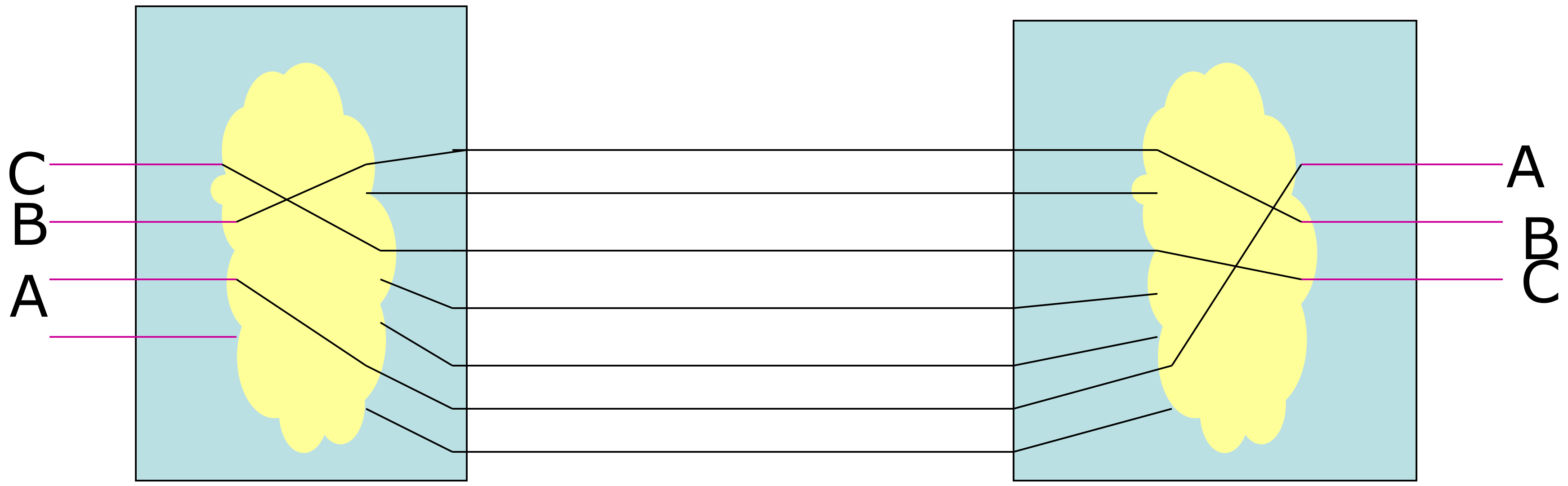
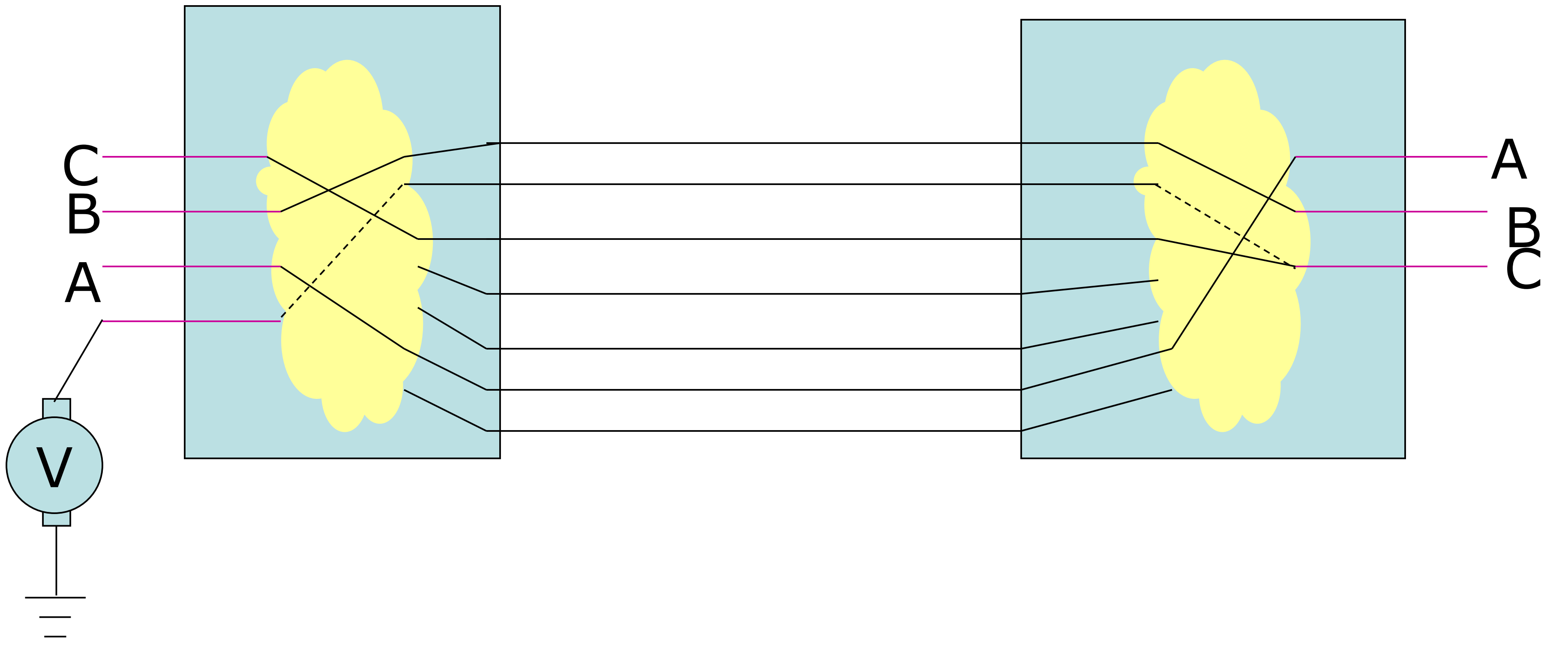
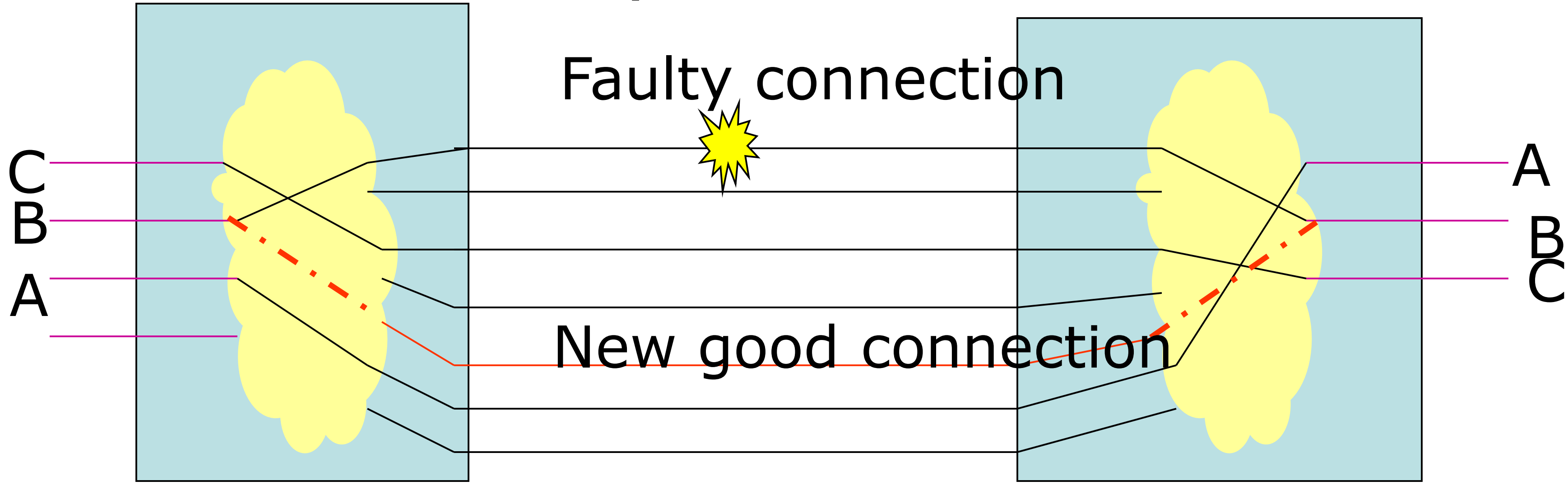
Adaptive manifolds can be built into panels or boards, which can flexibly assembled in different ways and programmed in ensemble to yield the desired connection patterns



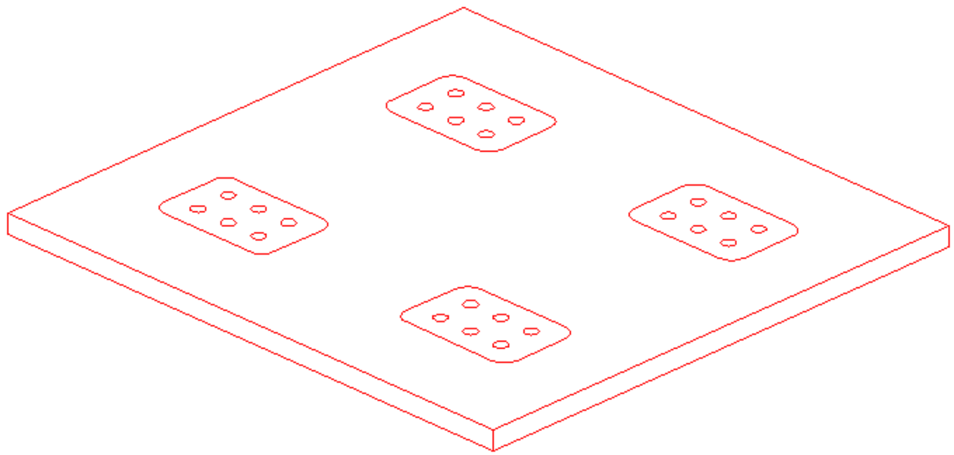
Temporary probes can be inserted and "dissolved" when no longer needed. In this case, we use the manifold to set up a temporary connection to check a possible problem with terminal C on the right panel

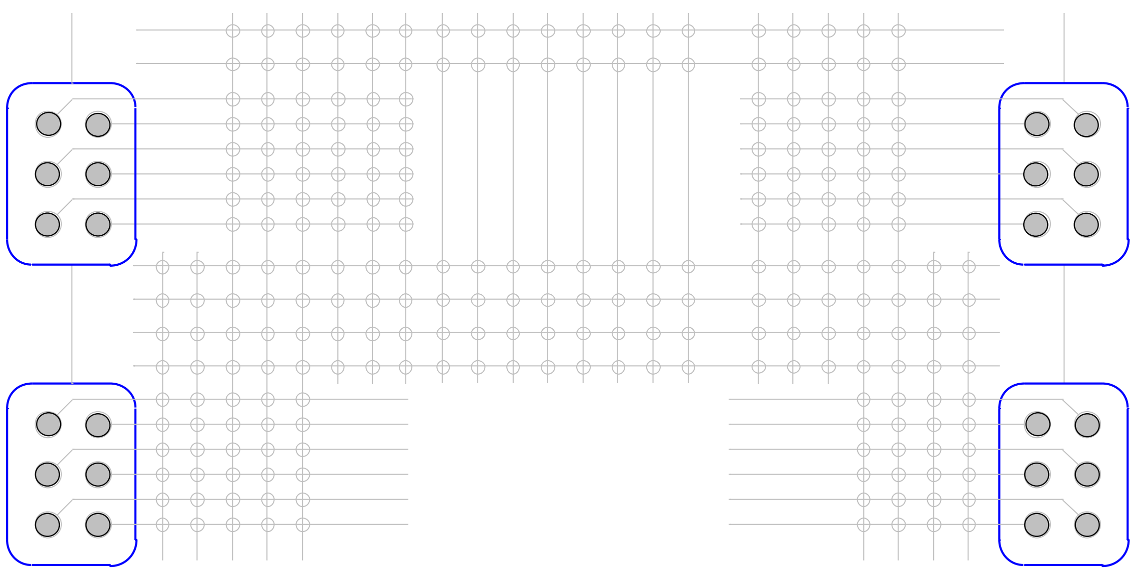


Adaptive manifolds can be reconfigured around defects or faults. In this case, we circumlocute a fault affecting “B” by reprogramming the manifolds in two panels

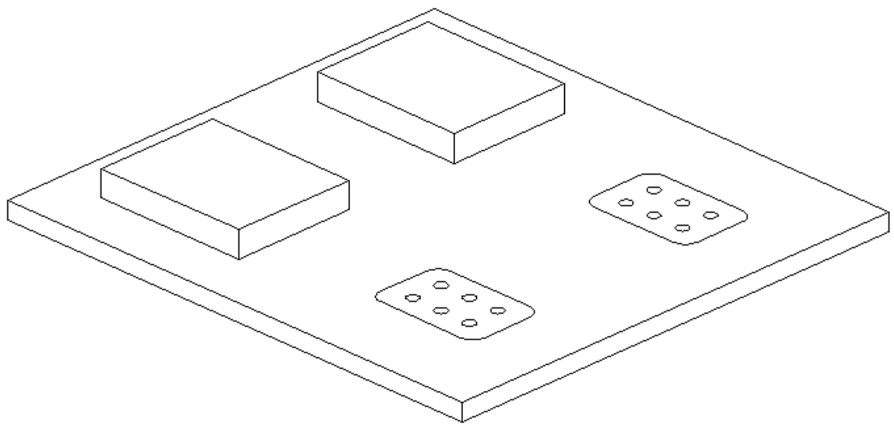


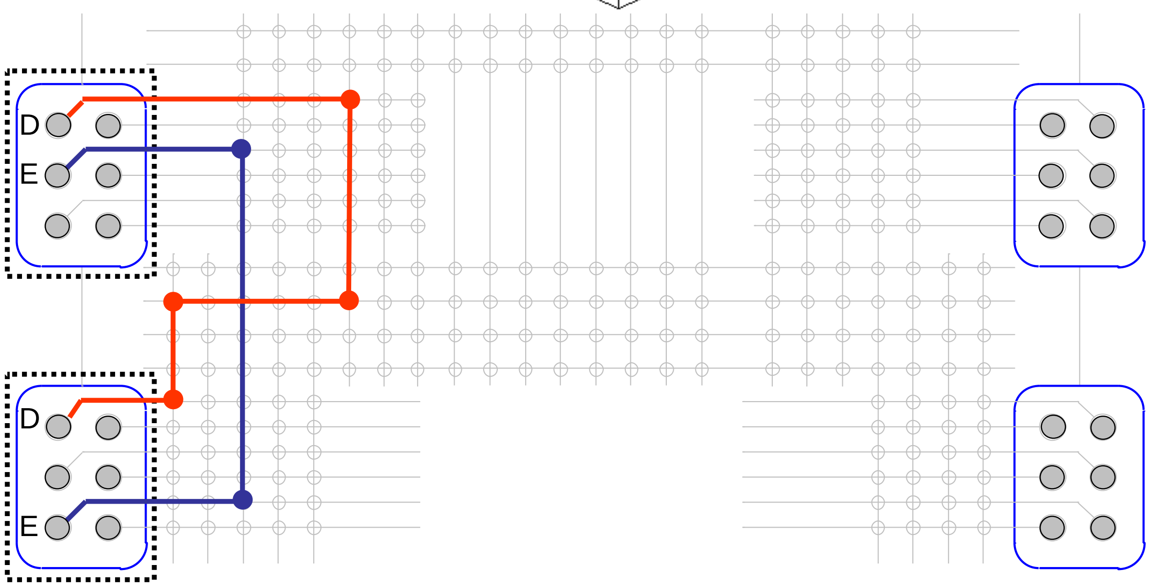
The physical embodiment of an adaptive panel could employ a number of sockets. The internal construction is at one level merely a series of wires (straight lines) and switches (hollow circles)



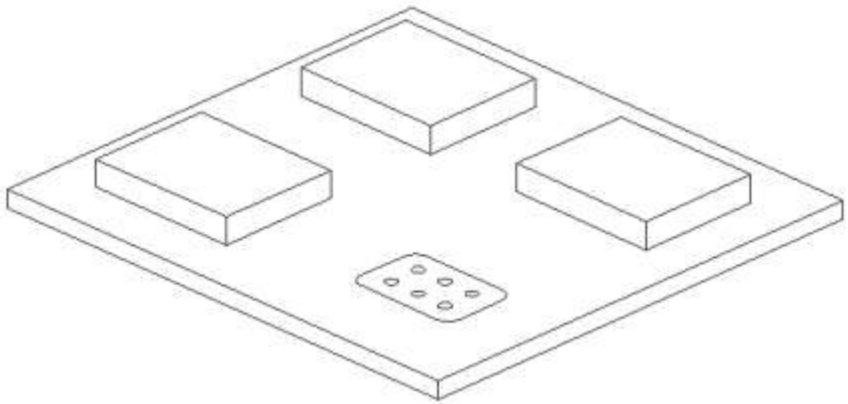


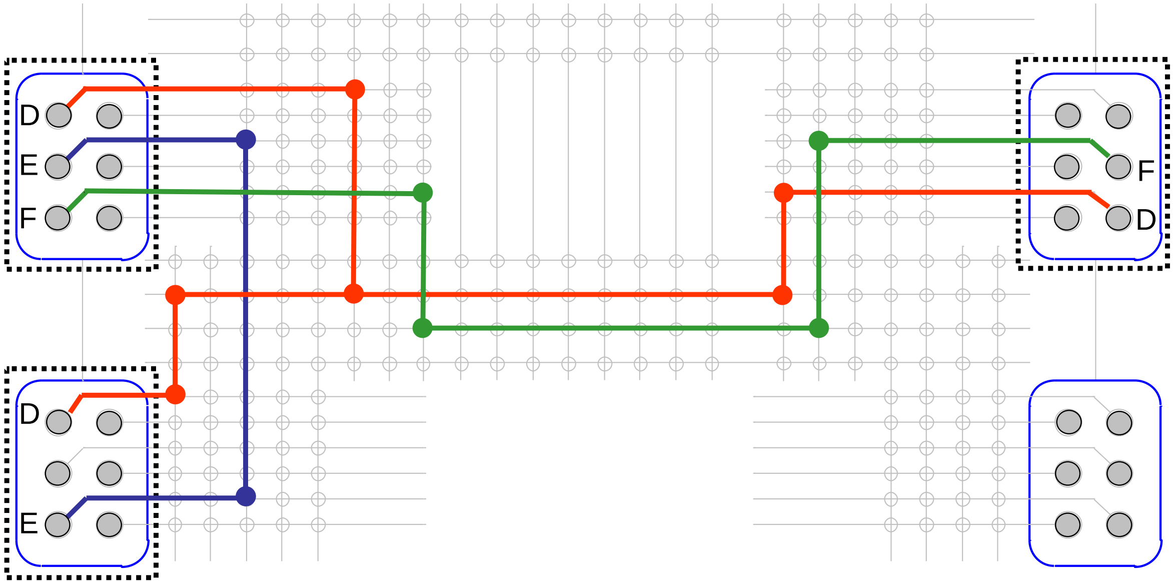
Terminals between different components plugged into the panels are formed by closing the proper switches (the paths are generally non-unique). This approach is very similar to the routing networks in FPGAs, except that the switches might be many small metal electromechanical relays or high-amperage solid state relays



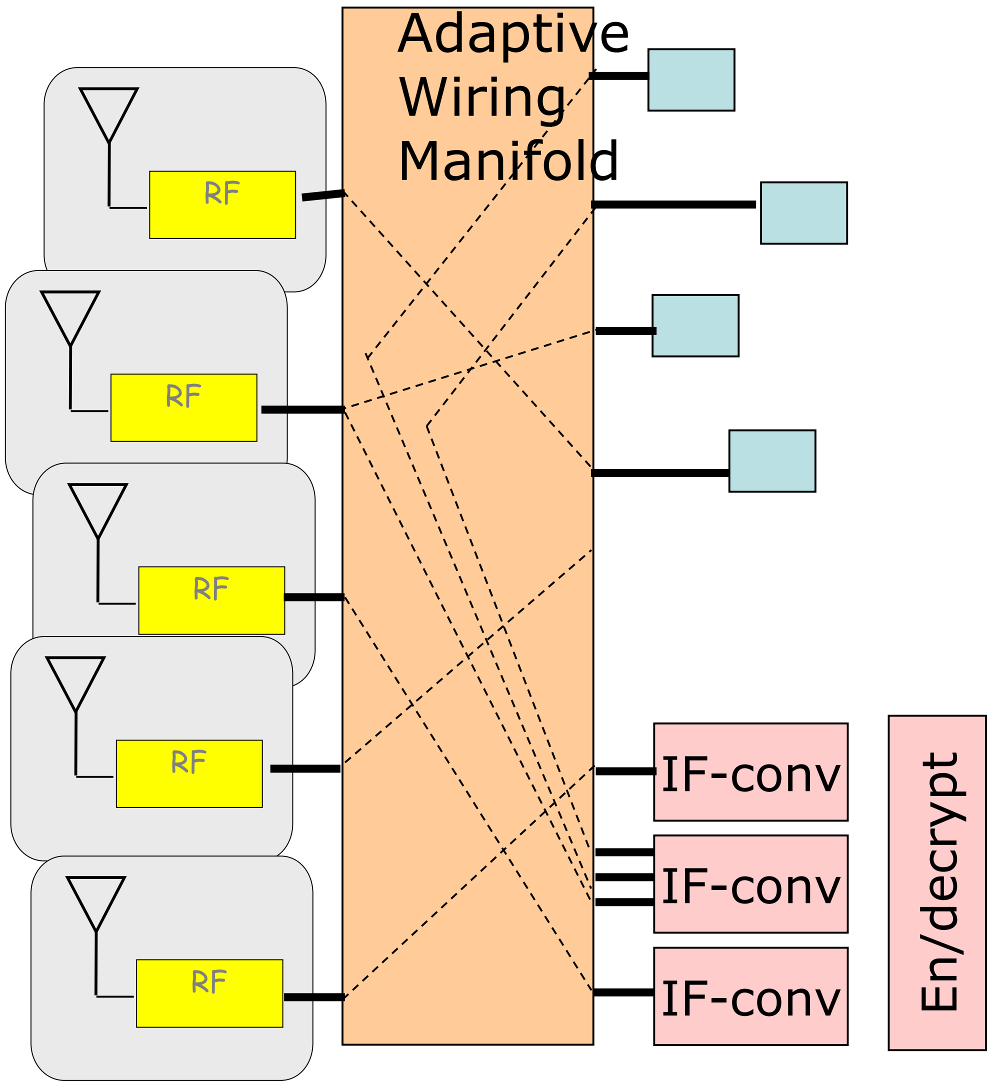


Of course, when more components are added to an adaptive panel, additional connections can be instantiated as needed



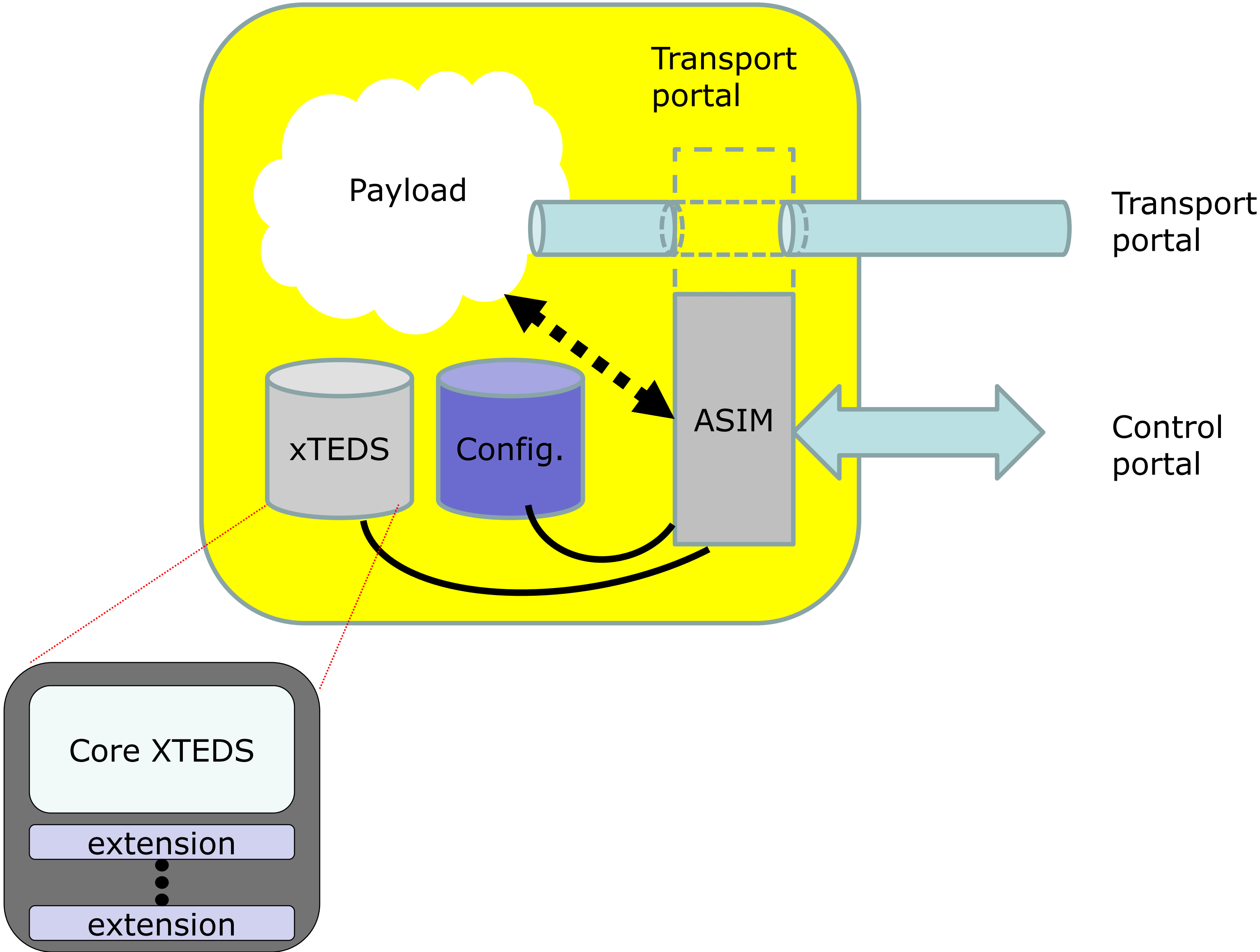


Lego software-definable radios ("Modular comm")

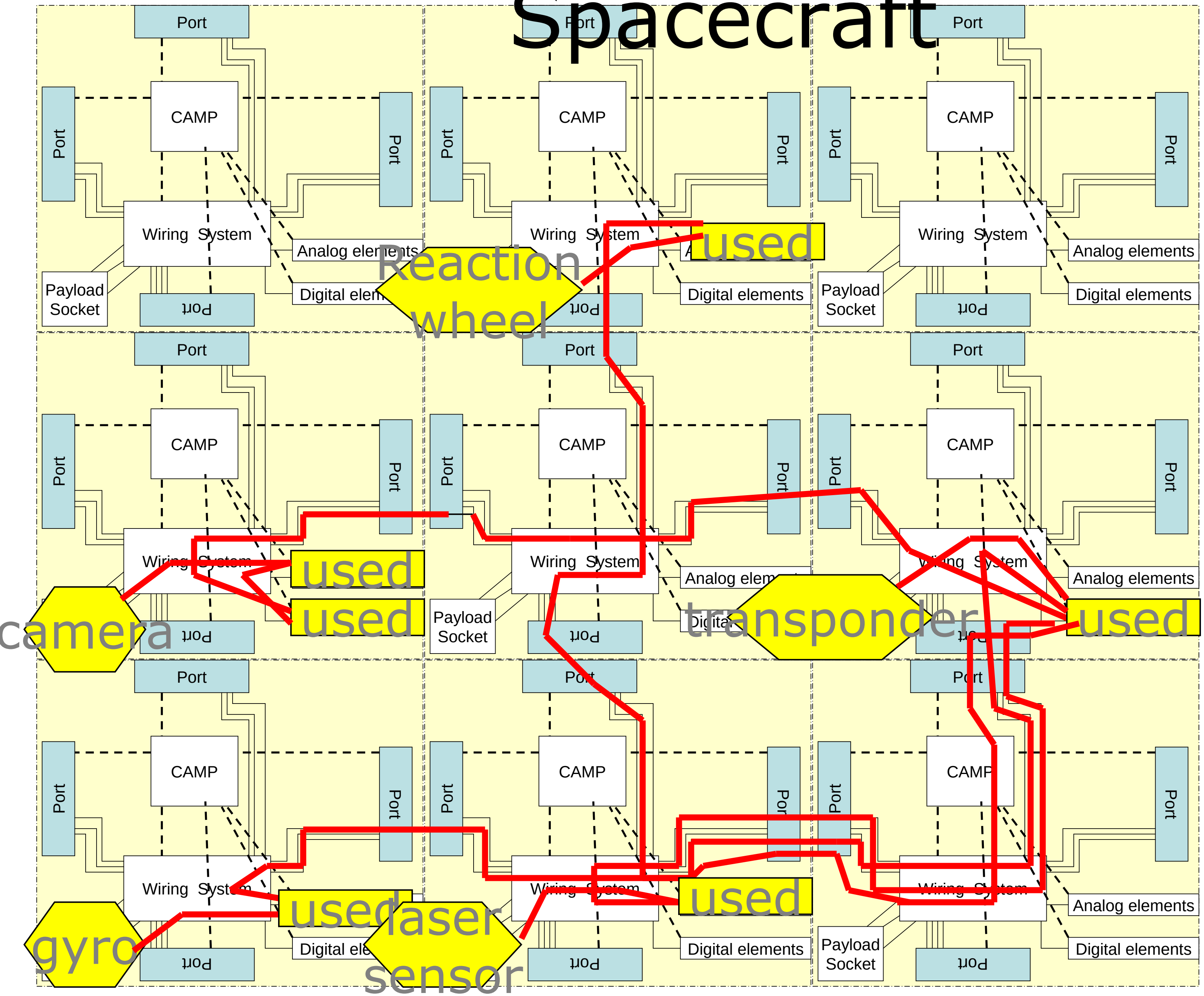


- Ability to comingle elements of a modular rf system fluidly, adaptively
- Provision for more comprehensive spectrum coverage
- "Cognitive radio" (support for plug-and-play waveforms, dynamic waveforms, and adaptive configuration)

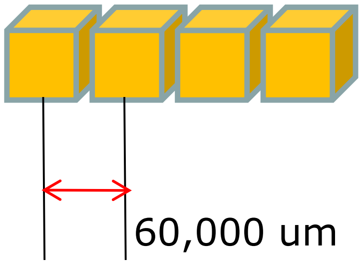
How to “LEGO-ize” Anything
(generalization of plug-and-play)

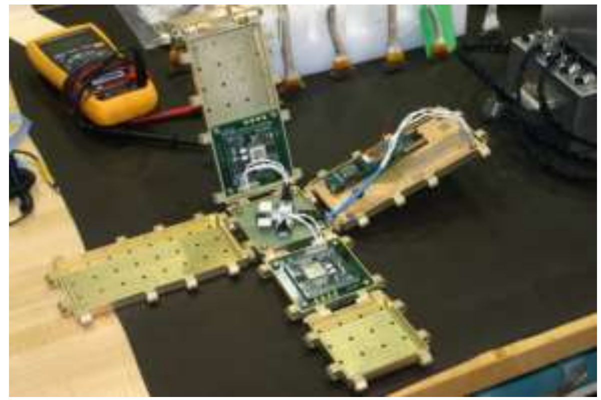


Cellular Building-block Spacecraft

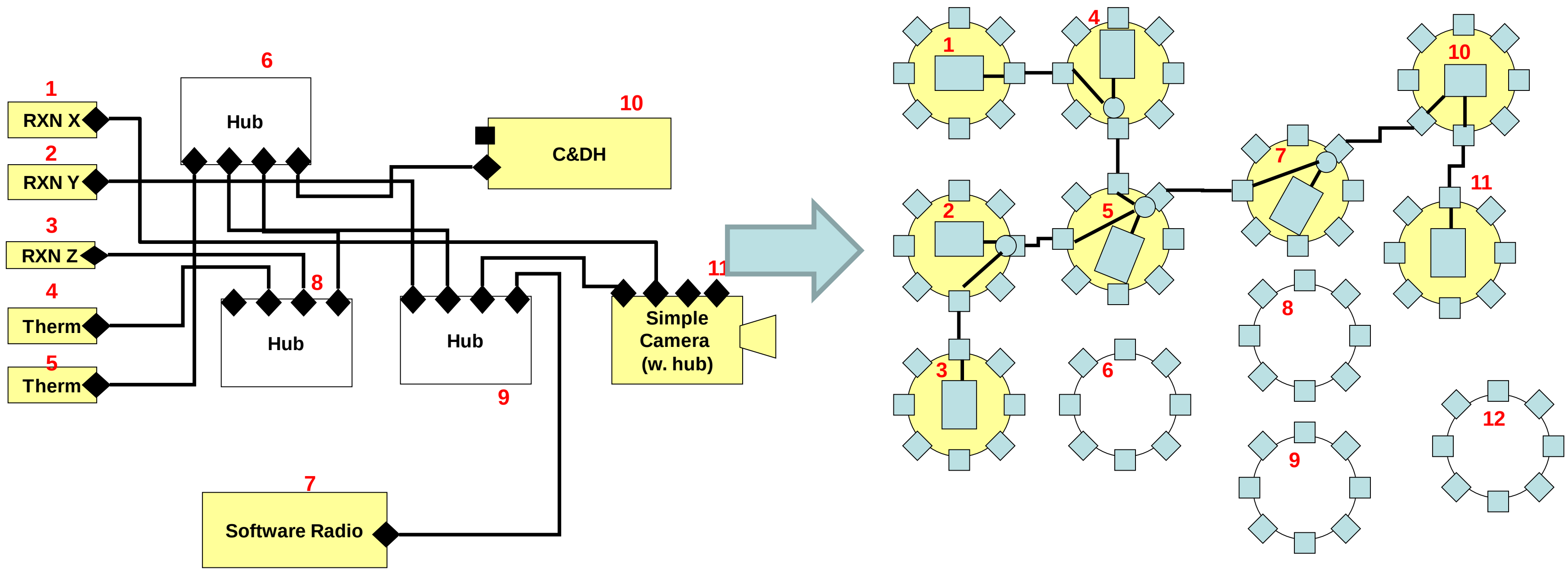


Cellular Interpretation of Plug-and-play CubeSat

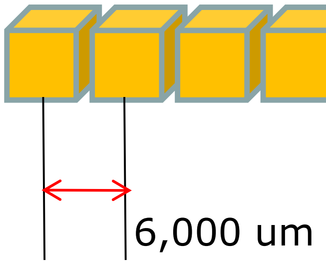


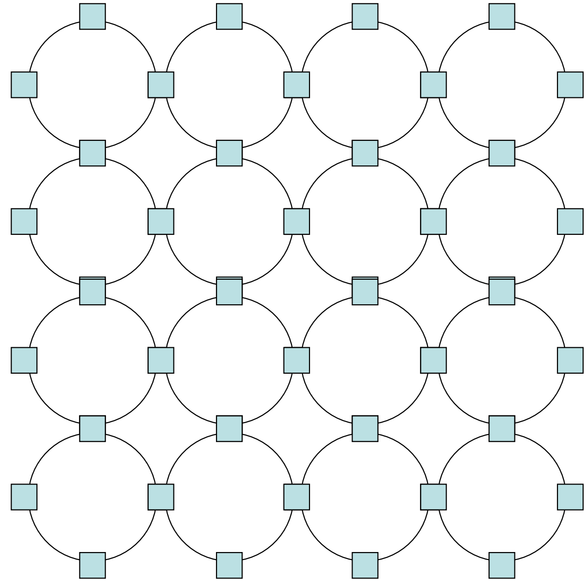


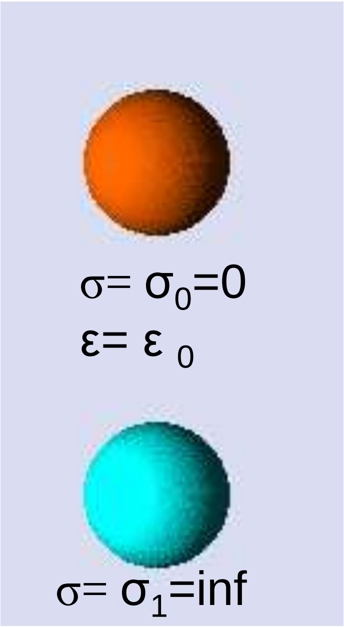
CubeSats

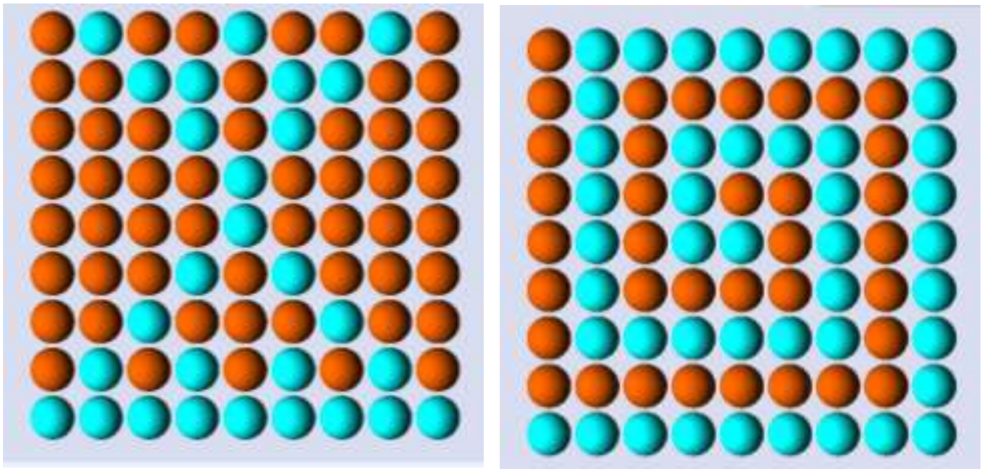


“Milliscopic” Cellularity



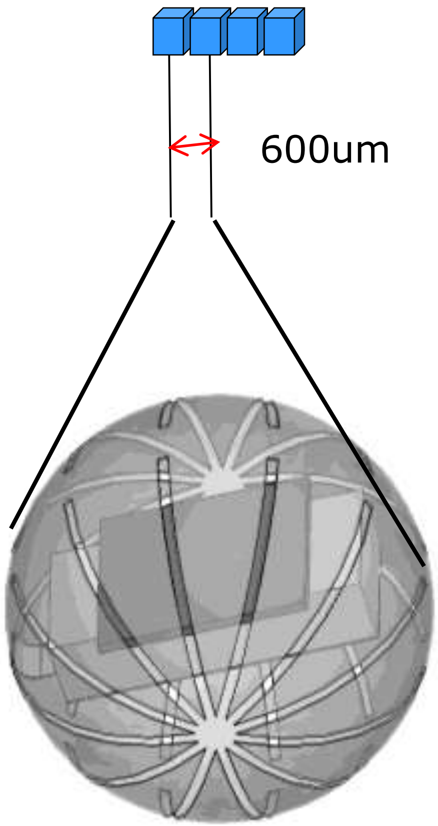


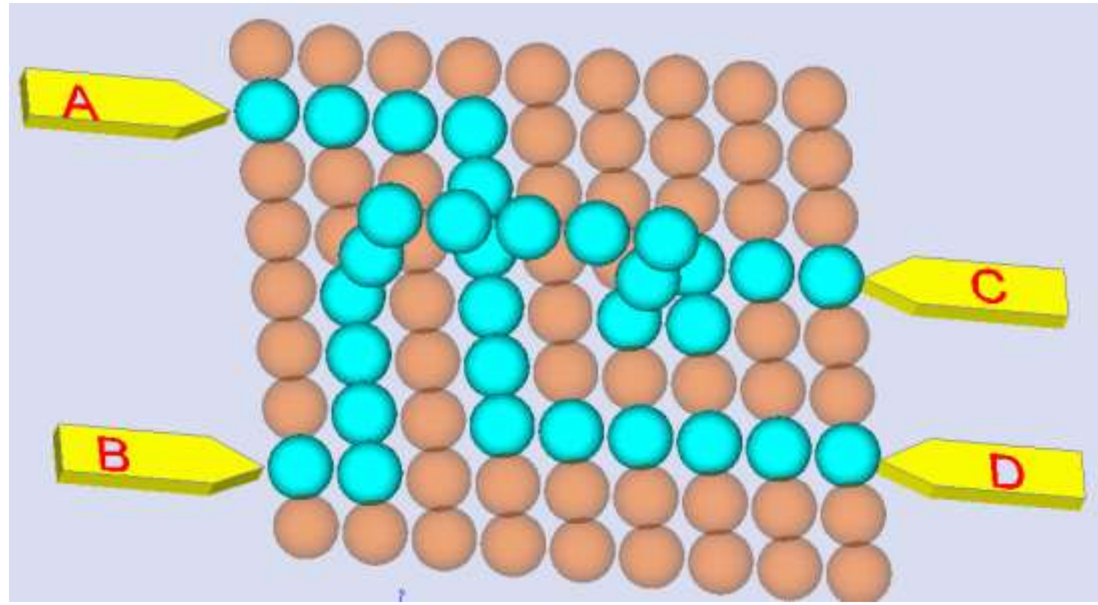


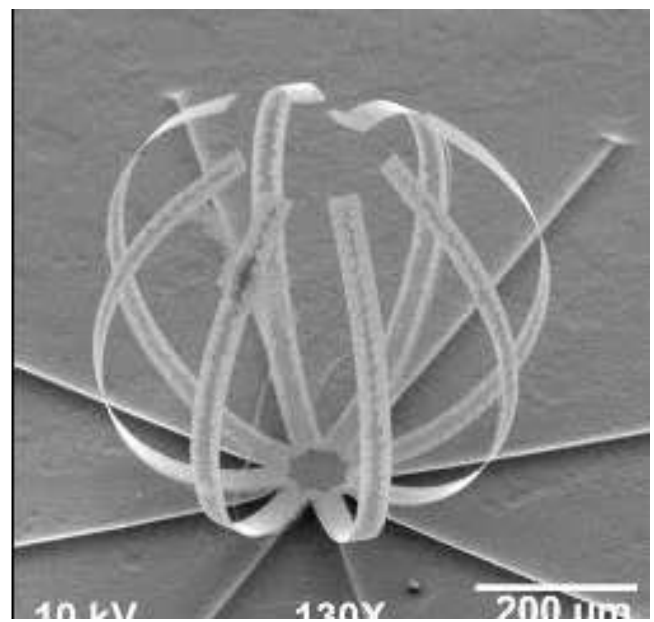


Pixilated Antenna

Microscopic Cellularity

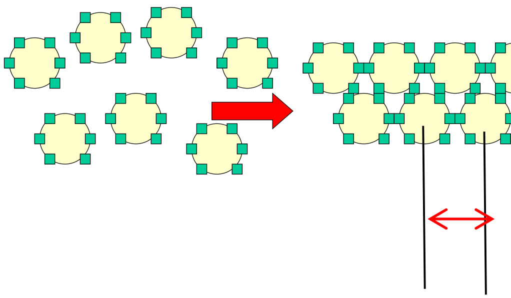


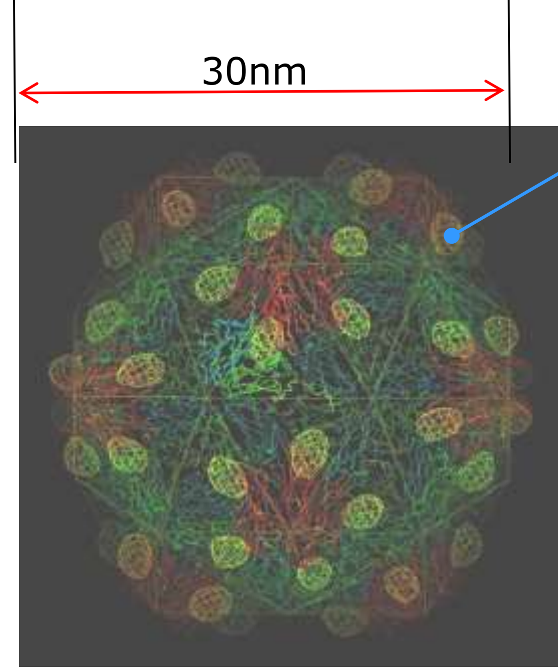




“Microrobots” J. Robert Reid, Vladimir Vasilyev, Rick Webster (AFOSR-funded)

Nanoscopic Cellularity





Cowpea mosaic virus (cpmv) Example from DARPA-sponsored research (NRL/Scripps Institute)

- Alternate lithography / non-lithographic
- Self-assembling
- Defect tolerance
- Massive aggregability (e.g. 10^{18}/cc)

Key ideas

- Cellularity / Atomicity
- Intelligent Configuration Management Framework
- Recursive Reconfigurability
- A new Moore's Law

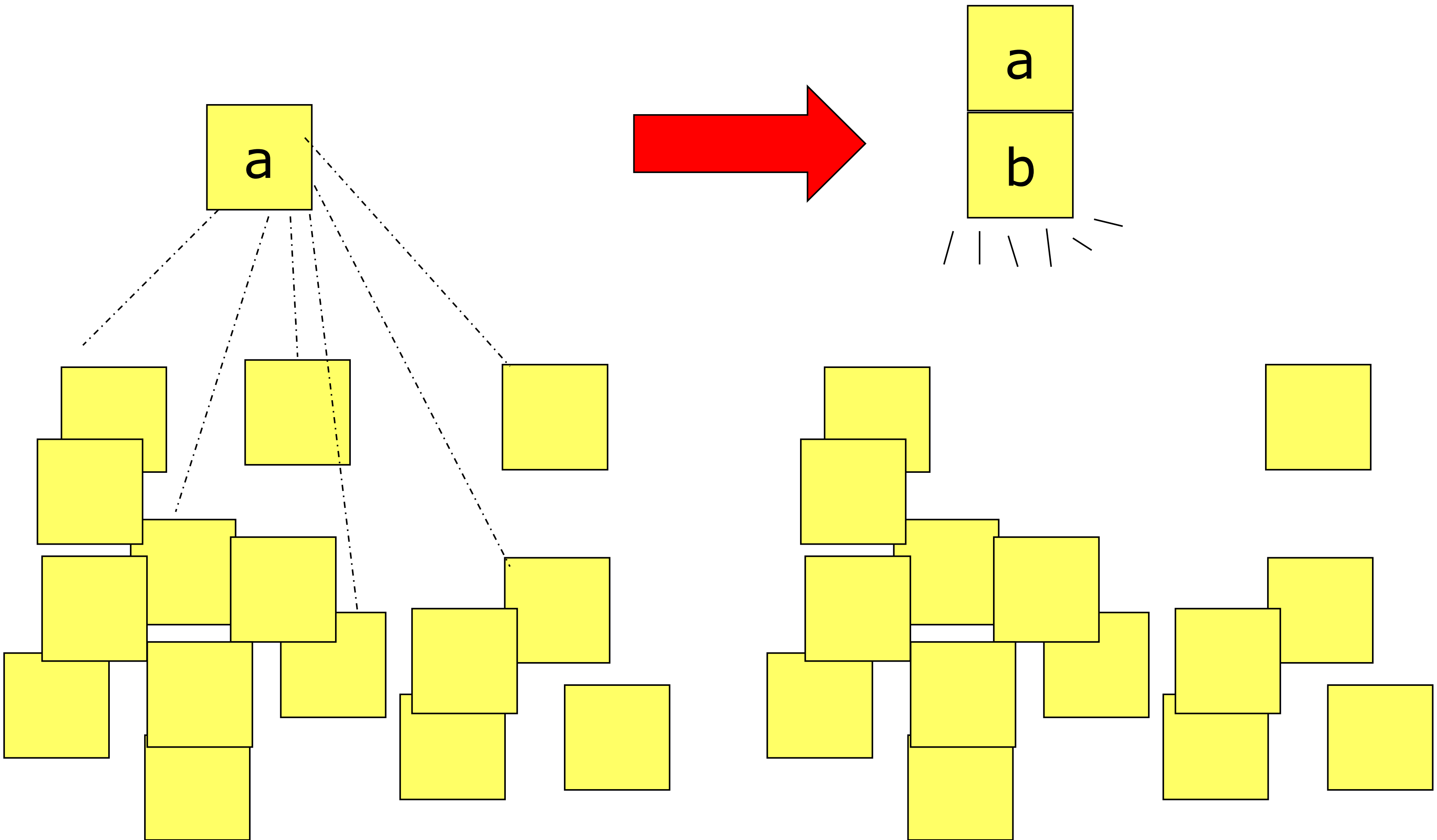
Example Possible Cell types

- σ-cells, a family of cells relating to the exploitation of conductivity;
- L-cells, a family of the familiar lumped element electrical blocks from simple circuit theory (resistors, capacitors, transistors);
- *c*-cells, computation / storage elements (variations of those found in FPGAs);
- *k*-cells, programmable thermal elements;
- *ε*-cells, programmable permittivity;
- *E*-cells, pertaining to energy storage;
- *g*-cells, programmable mechanical attachment;
- *s*-cells, for sensing phenomenologies and converting them to electrical signals;
- *μ*-cells, for programming permeability;
- *η*-cells, for photonic (light-routing) applications;
- α-cells, for transduction / actuation (conversion of electrical signals to some other phenomenology, including locomotion);

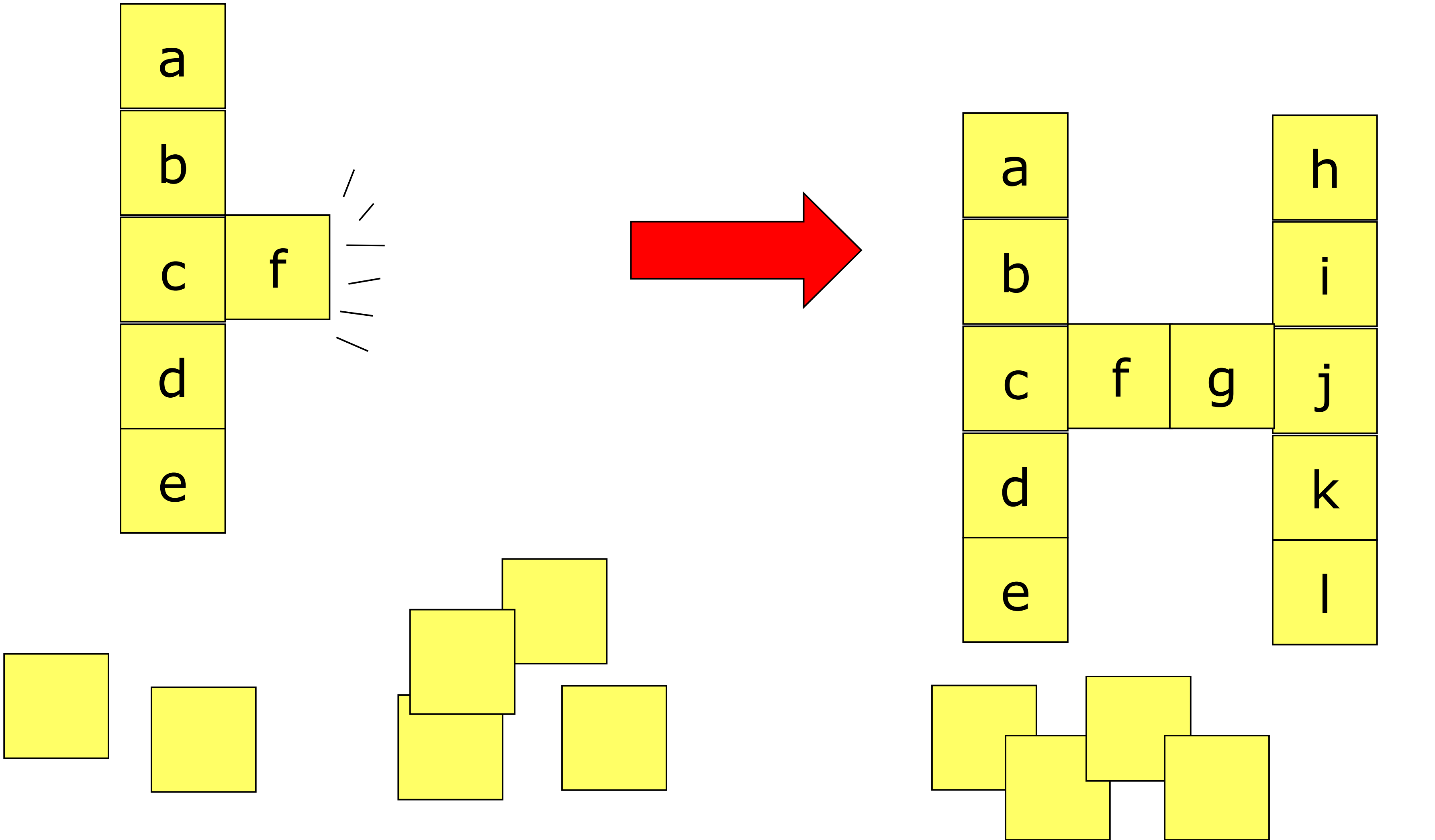
Cellularity / Atomicity

- The idea of “effective” indivisibility in objects of hardware, software, concepts
- Common examples
  - “actual” atoms (i.e., from periodic table)
  - linguistic atoms (letters, words, etc.)
  - logic (transistors, gates, etc.)
- More abstractly
  - Black boxes (as in encapsulated form of hardware and software)
  - Concept of “no user-serviceable parts” within (Vernor Vinge, *Rainbow’s End*)

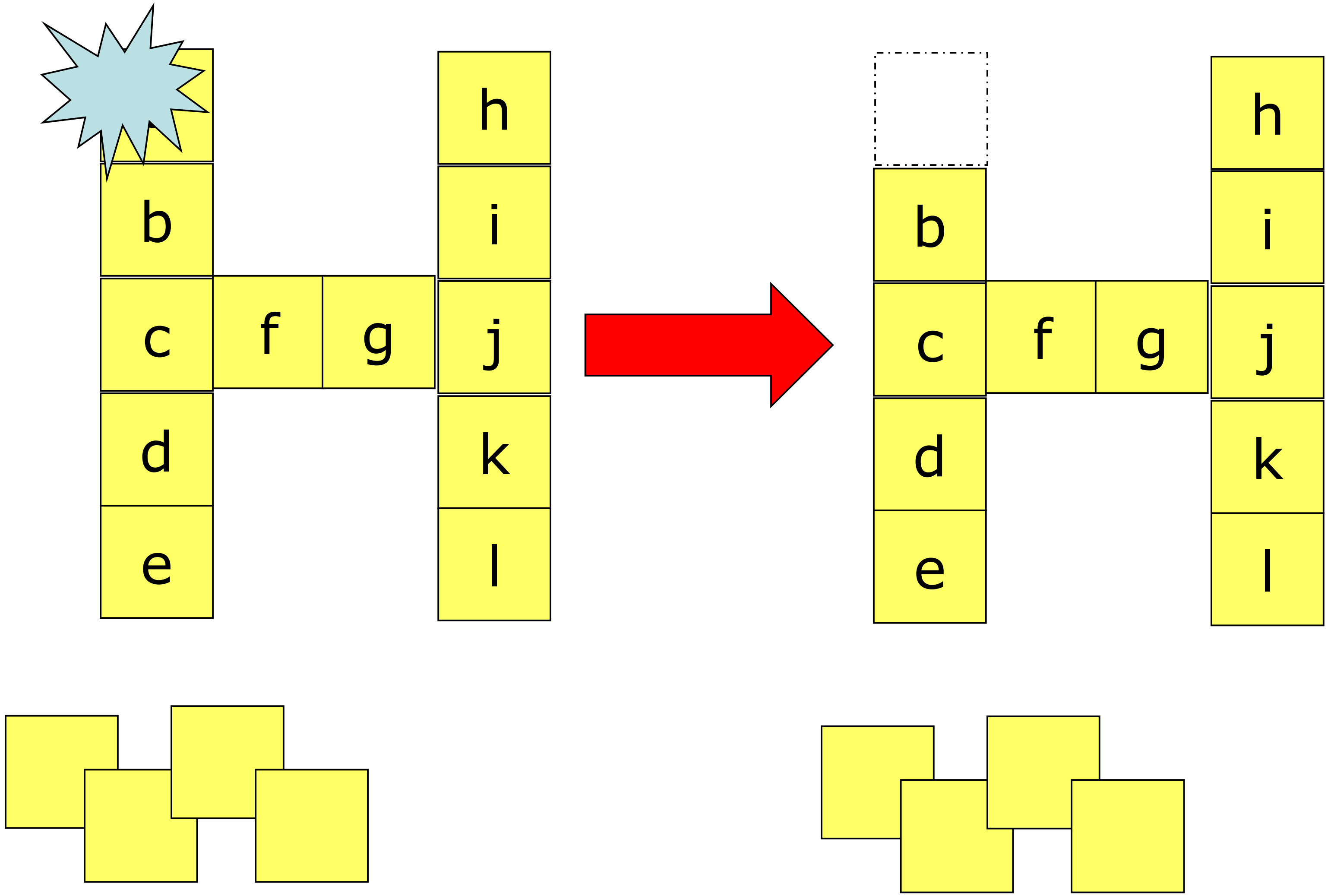
Guided self-assembly



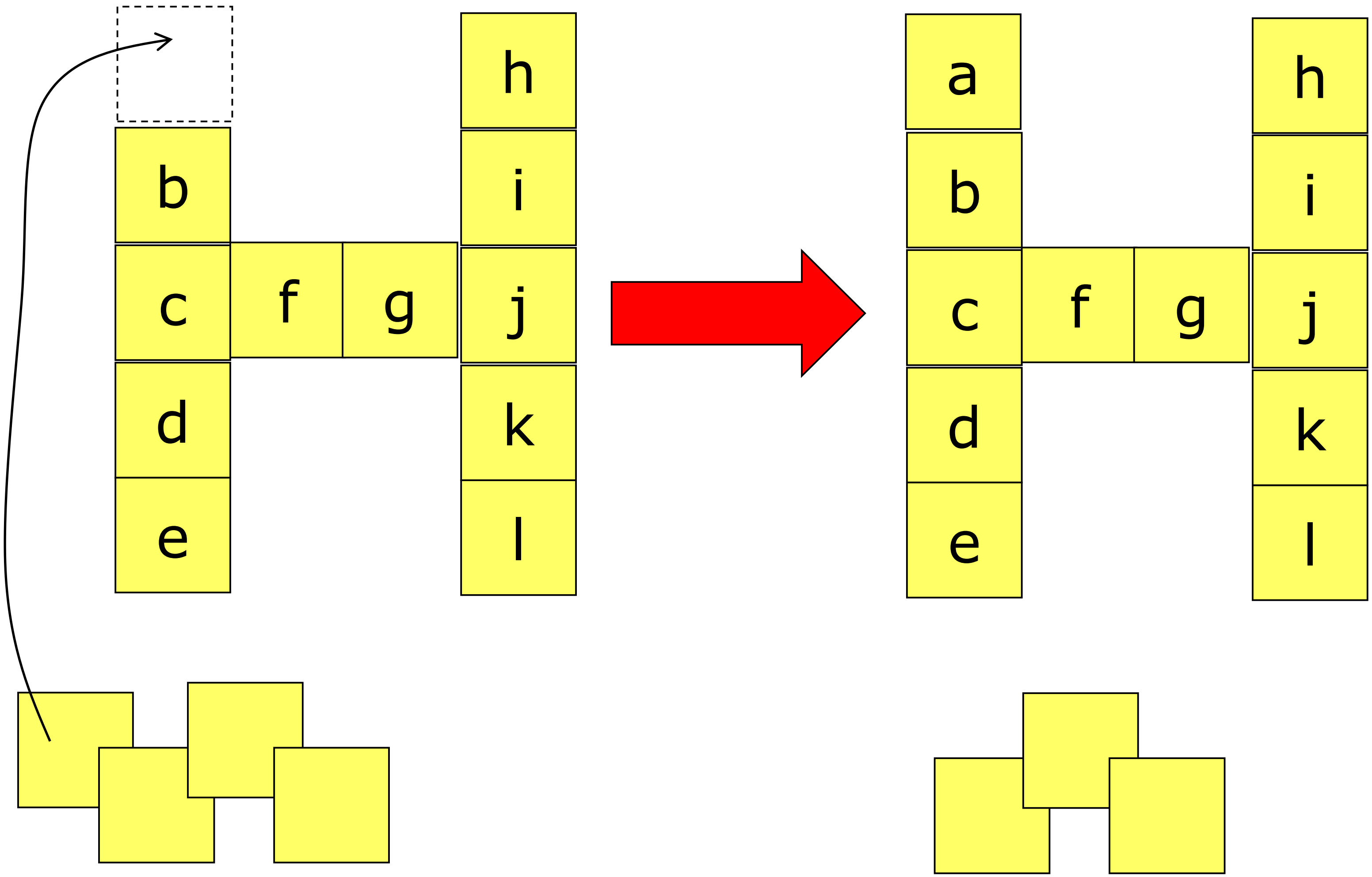
Guided self-assembly



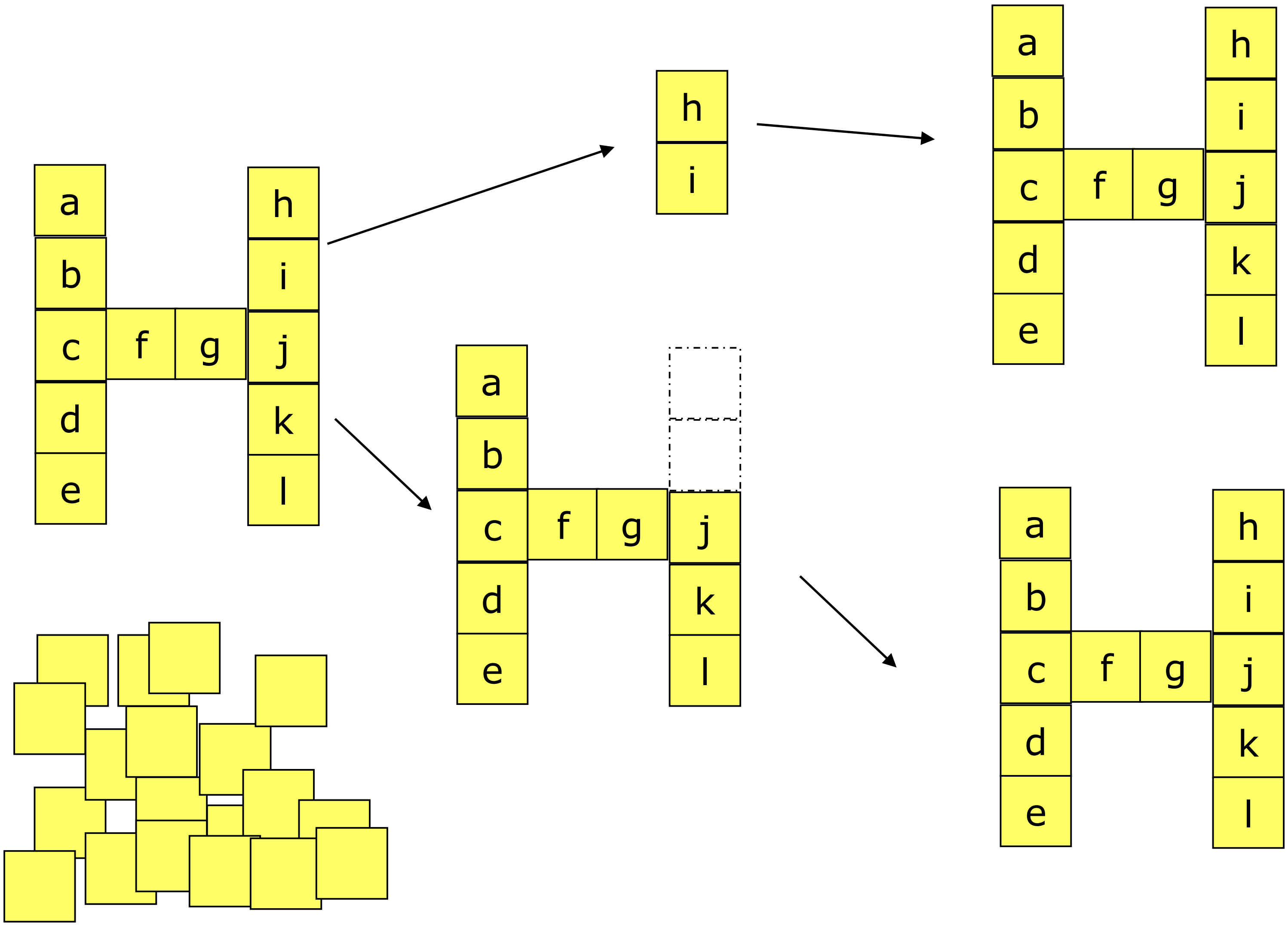
Guided self-assembly – self repair



Guided self-assembly – self repair



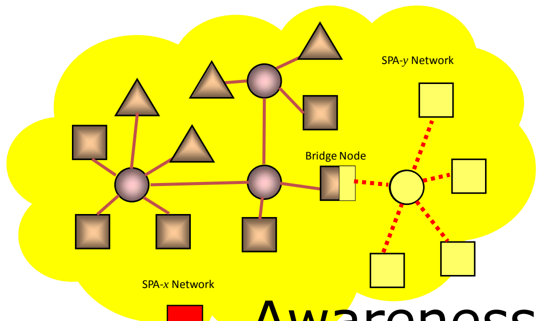
Guided self-assembly – self reproduction



Languages

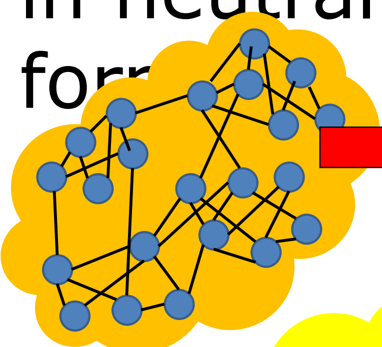
- For computers, we use Matlab, C, Java – synthesize high level languages into binary (machine) instructions
- For digital systems, we use Verilog, VHDL – synthesize high level circuit abstractions into primitive specifications of logic, memory, and interconnect mapped into “fabrics”
- Where are the languages for reconfigurable analog, programmable matter?

Advent of Megacompilers?

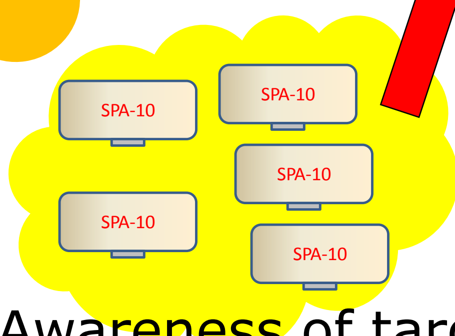


Awareness of network topology constraints

Problem represented in neutral forr



Mega-compiler



Awareness of target architecture

- Number and type of target objects
- Bitstreams for each target object
- Topology for connecting objects
- Provisioning constraints

Where can we go in this study/this workshop?

- In pursuit of cellular architectures for extreme environments to support interplanetary applications
- Characteristics
  - Robust, ultra-low-power, simple, scalable, self-organizing
- Tools to manage, organize
- A type of spacecraft smart, multi-functional fabric

Summary

- Disruptive technologies demonstrate danger of complacency in research and development
- Reconfigurable systems represent an extensive research field for disruptive studies
- Cellularity and “plug-and-play” might provide an approach to engineer disruption