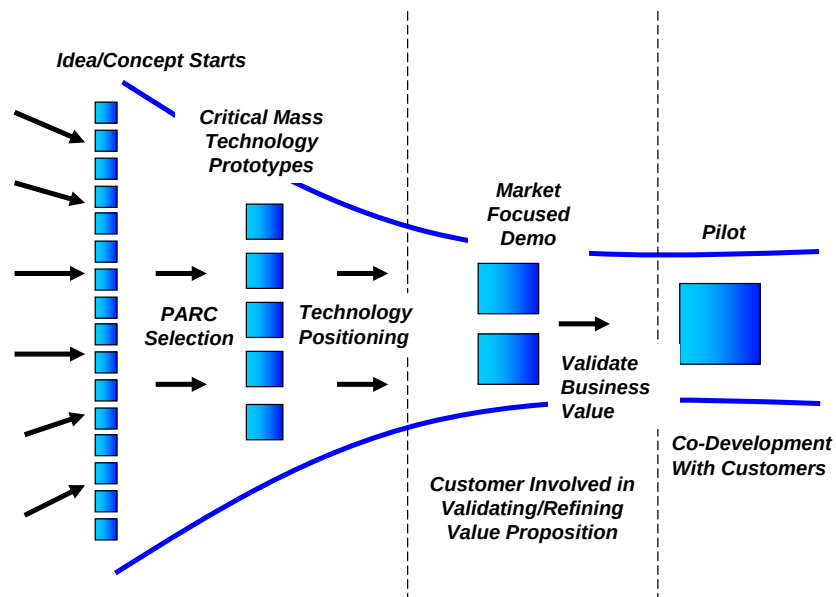


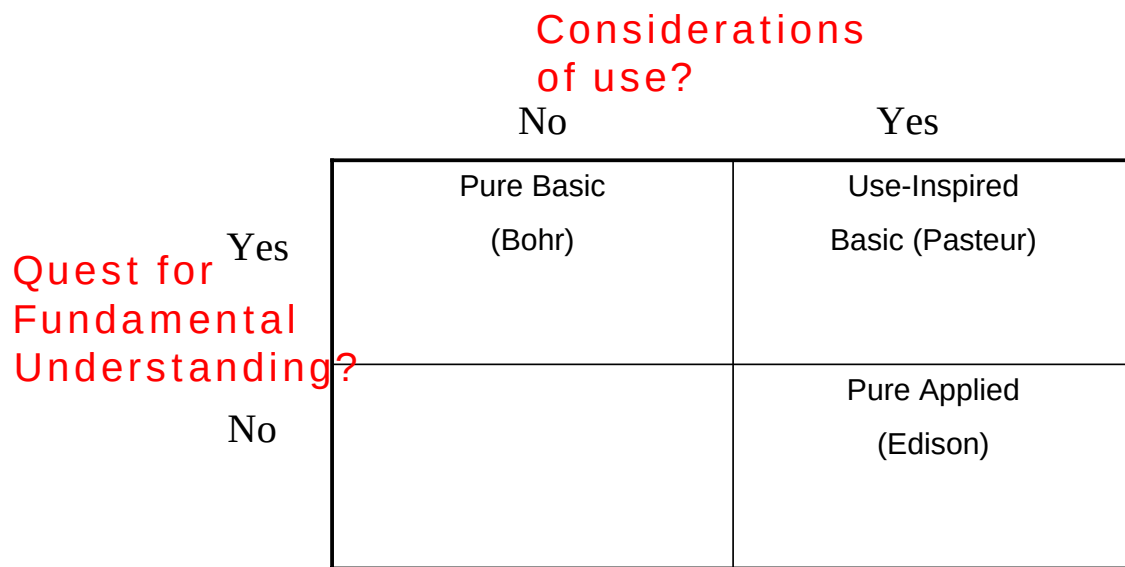
++Smart Matter

April 20, 2004
Johan de Kleer

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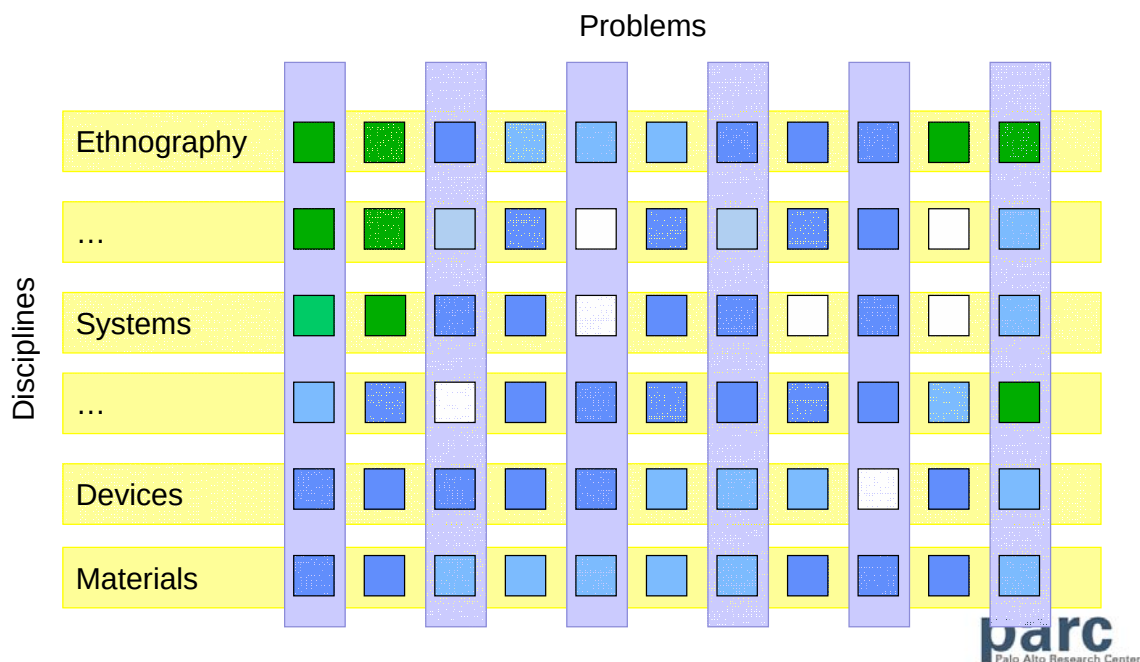
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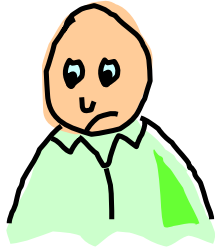
Source: Pasteur's quadrant - Stokes



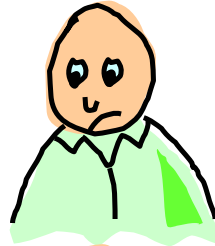
Challenges Cross-Cut Disciplines



Bad Modes

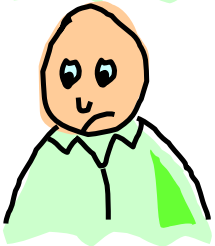


“Don’t bother me. The project will be finished in 1 month and users will love it.”



“No one would use this because

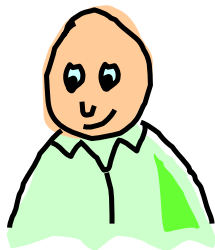
.....
.....”



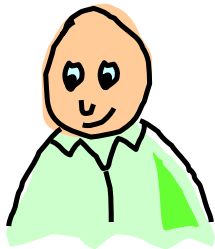
“It simply can’t work”

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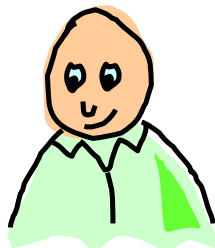
Good Modes



Will attack anything with gusto.



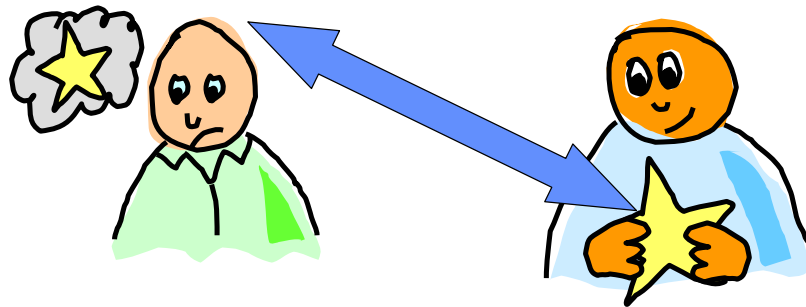
Makes the invisible visible.



Rationally identifies the project’s problems.

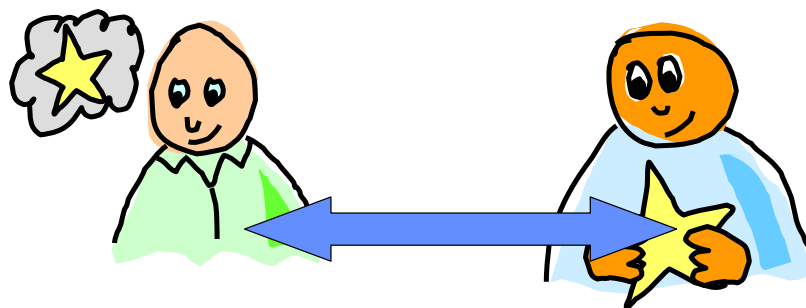
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Hearts and Minds



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Hearts to Hearts



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NETWORKED DEVICES/ DOCUMENT SERVICES

HIGH PERFORMANCE & SECURE
SERVICES ON THE NETWORK.

EMERGING DOCUMENT TYPES

CREATING NEW DOCUMENT TYPES
AND GENRES FOR THE NEW MEDIA.

KNOWLEDGE ECOLOGIES

DOCUMENT TOOLS AND PRACTICES TO SUPPORT KNOWLEDGE
CREATION AND USE IN ORGANIZATIONS.

SMART MATTER

COMBINING COMPUTING AND
MATTER AT NEW SCALES.

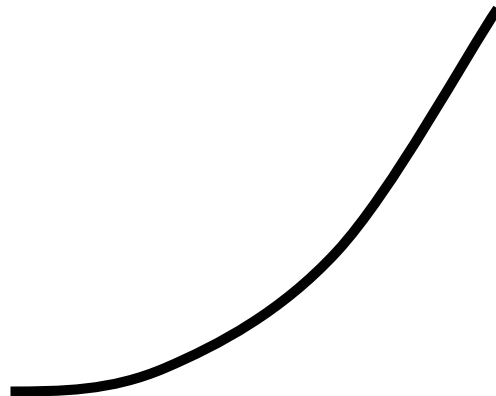
INFORMATION FABRIC

BUILDING A WORLD CLASS
DOCUMENT INFRASTRUCTURE

THE PARC THEMES

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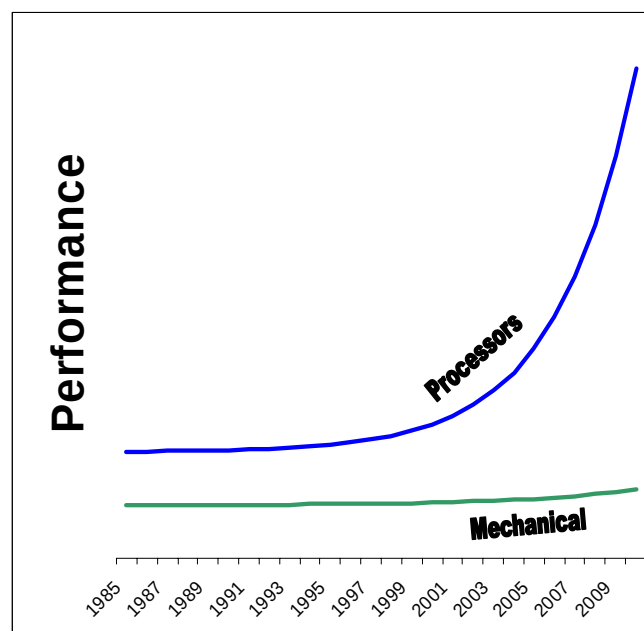
Moore's Law



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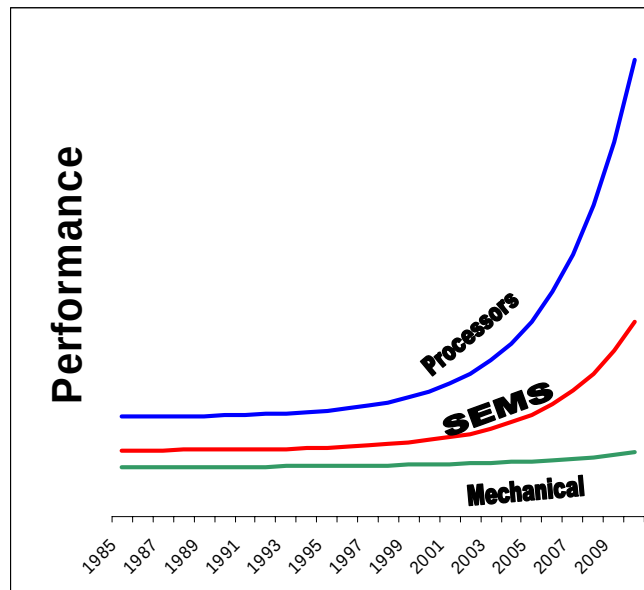


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Leveraging Moore's Law...



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Boundaries are fluid

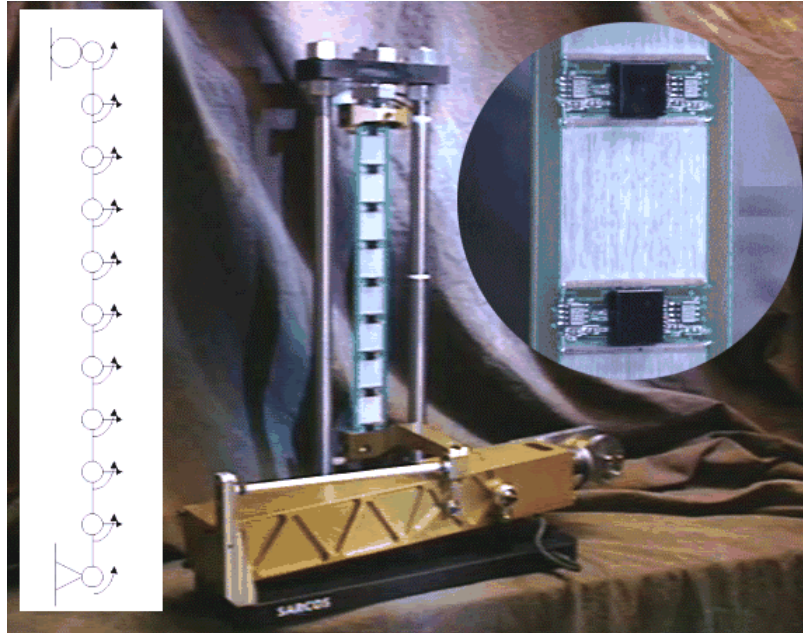
- Computation:
- P vs. NP
- Best-first search
- Distributed
- Turing Machine
- Driven by Moore's Law
- Matter:
- $F=ma$
- Kepler's laws
- Conservation of energy
- Point mass
- Driven by Moore's Law too!

Many of the simplifying assumptions we use to design systems will fail us.

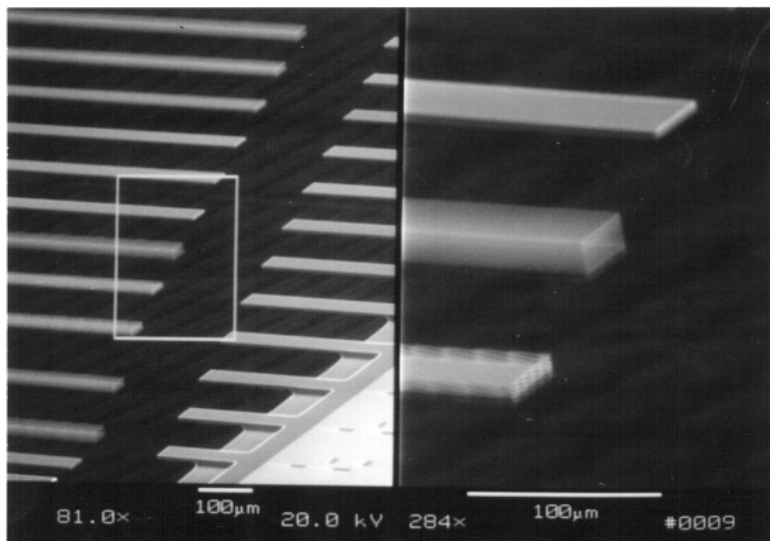
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Matter will move into computation

- MEMS-based structural stabilization
- On-demand adjustment of stiffness and load-bearing capability
- Up to 2.9x increase in load-bearing capability
- UAST strain sensors (18)
- Filamentary PZT actuator patches (16)
- Automated test fixture
- Control strategy:
 - ♦ Optimal buckling control - 360 independent gains

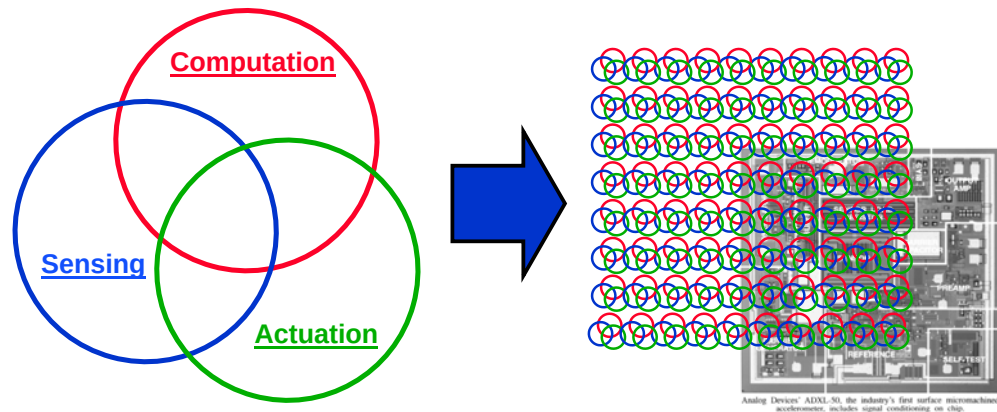


Computation will move into matter



Mechanical computation

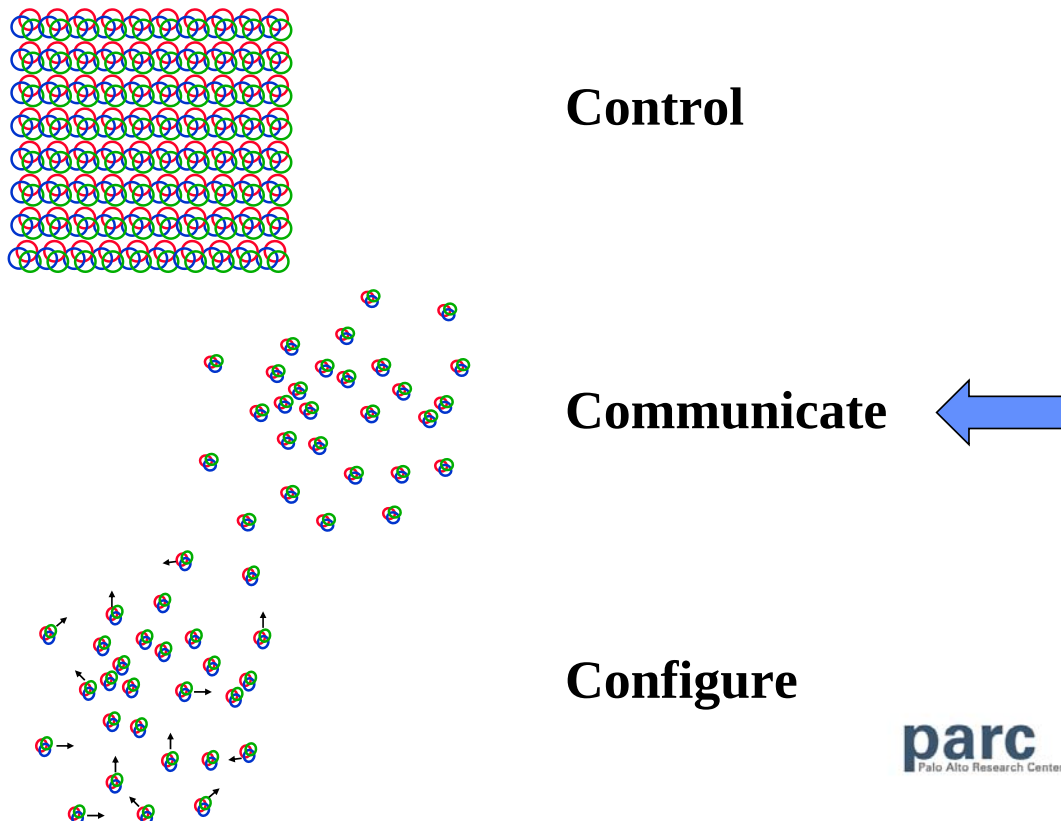
Smart Matter Vision: A new way to build machines and systems



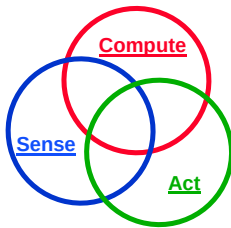
- Integrate sensing, actuation, computation at fine granularity
- Exploit tradeoffs between computational and physical resources
- New: fabrication methods, sensor processing, actuator design, and control systems techniques

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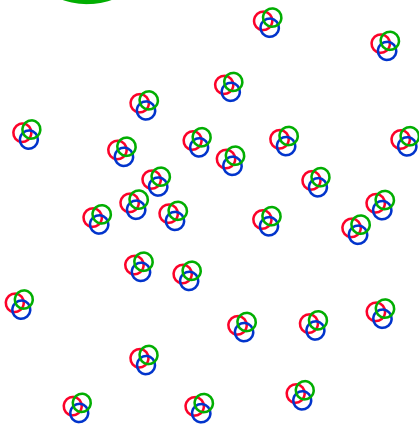
Three Phases of Smart Matter



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Smart Matter: Communication



Berkeley Motes



Rockwell HiDRA



UCLA WINS



UC Berkeley Smart Dust

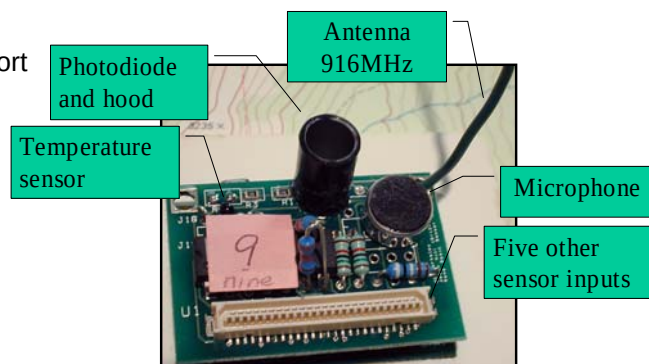
- Freeway traffic analysis
- Environmental monitoring
- Military applications
- Machine health and diagnostics

Untethered micro sensors will go anywhere and measure anything -- traffic flow, water level, number of people walking by, temperature. This is developing into something like **a nervous system for the earth**.
-- Horst Stormer, *Business Week*, 8/23-30, 1999.

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Sensor Hardware: Berkeley motes

- CPU:
 - 8-bit, 4 MHz Atmel processor
 - No floating-point arithmetic support
- Radio:
 - 916 MHz RFM @10Kbps
 - Distance 30-100ft
 - Adjustable strength for RF transmission & reception
- Storage:
 - 8 KB instruction flash
 - 512 bytes data RAM
 - 512 bytes EEPROM (on processor)
- OS:
 - TinyOS, event driven (3.5KB code space)
- Sensors:
 - 10-bit ADC mux'd over 7 analog input channels
 - Sensing: light, sound, temperature, acceleration, magnetic field, pressure, humidity, RF signal strength



Hardware

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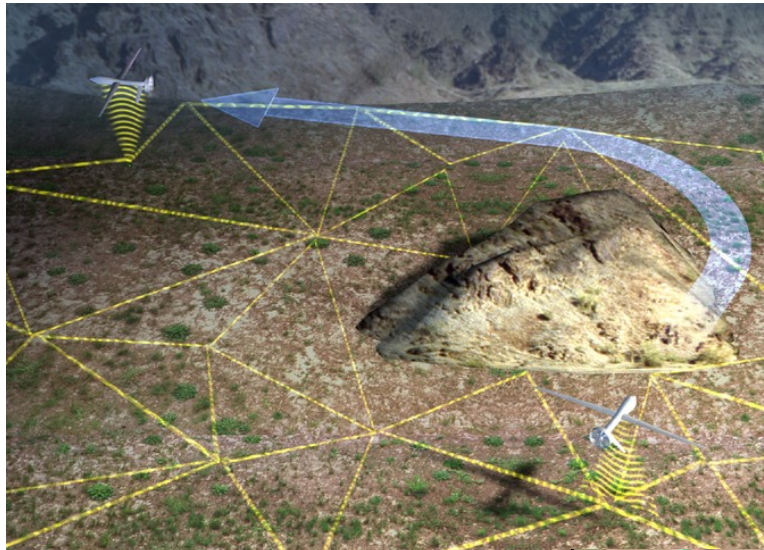
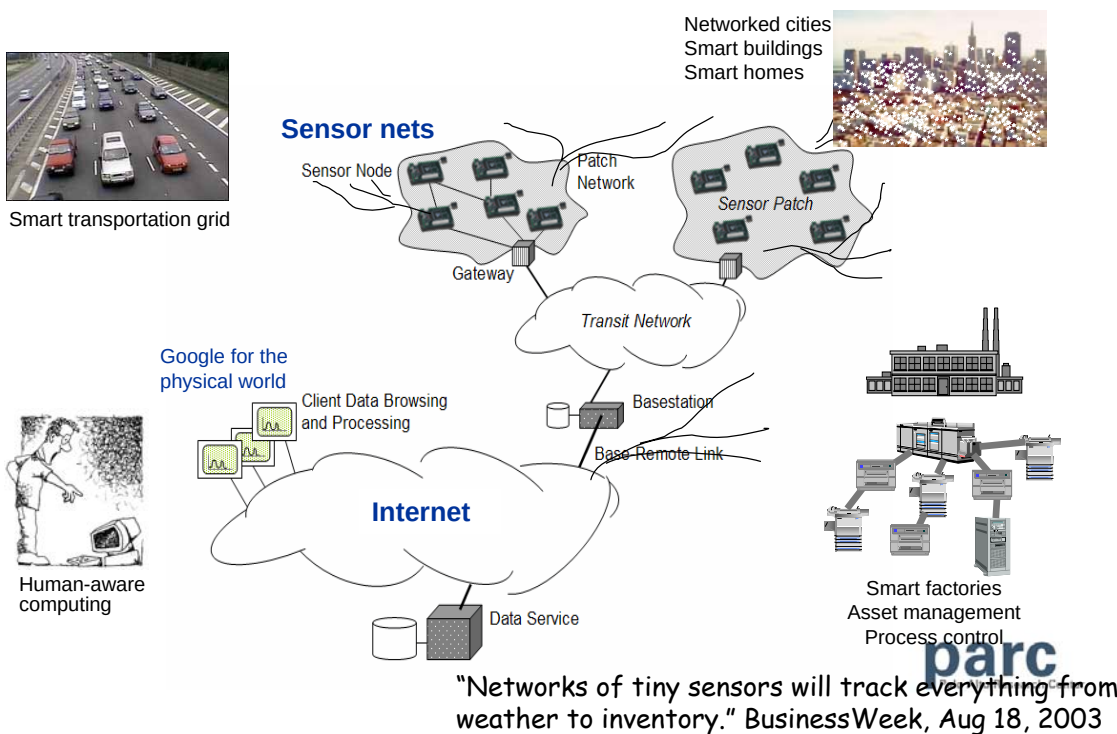


Photo courtesy of Kris Pister



rc
Search Center

Bringing the Off-line World On-line



The Challenges

● Scalability

- ♦ Most systems today are centralized
- ♦ Per node throughput goes to zero as network scales
- ♦ Computing at the edges → bottleneck

● Resource Limitations

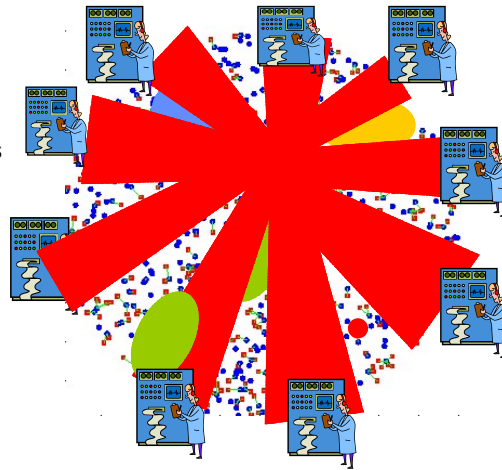
- ♦ Power
- ♦ Computation
- ♦ Bandwidth

● Networking

- ♦ Ad-hoc meshes with unreliable, dynamic links
- ♦ Network demand dynamic, based on *physical phenomena*
- ♦ Cross-layer optimization can produce **very** large gains
- ♦ Management Tools: How can an end-user manage a very large scale network?

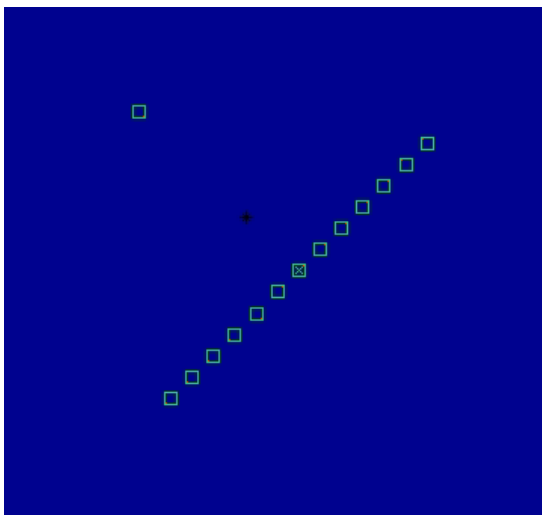
● Programming

- ♦ Sensor Networks break traditional separation between application, networking and operating system details.
- ♦ Need new programming models to “put back” simplicity of layered architectures

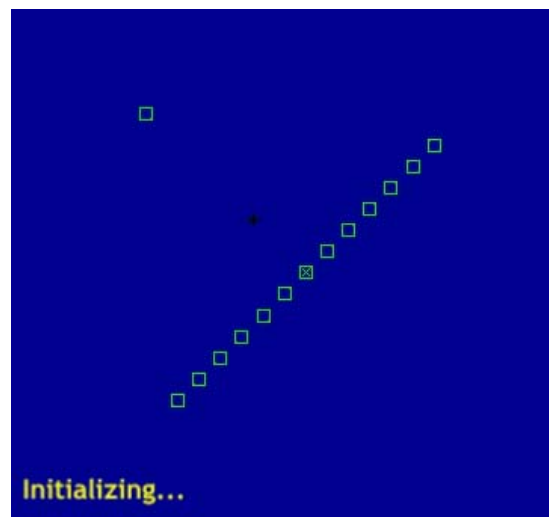


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Comparison: Nearest-neighbor sensor query vs. information-directed sensor query



“Blind” nearest-neighbor sensor query



Information-directed sensor query

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Group Formation in Sensor Network – Information Directed Sensor Query

PARC CoSense Display

Key advantages:

- **Self-organizing**: Form and update ad hoc groups as physical stimuli move across network
- **Scalable**: Multi-tasking, conflict resolution, leaving resources available for emerging tasks
- **Leveraging** research elsewhere: e.g., GEAR by Estrin/Heidemann, TinyOS by Culler

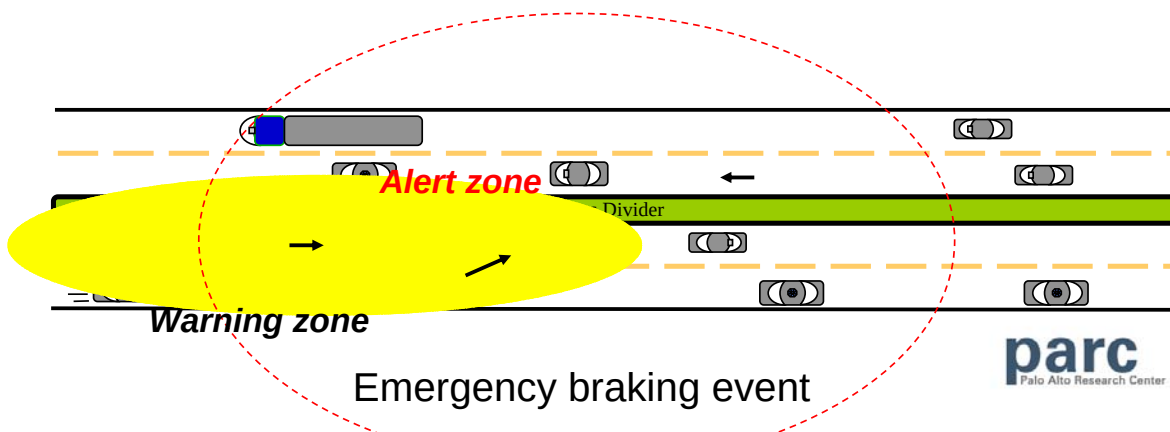
Delivering values to our partners:

- DARPA SensIT: Successful field demos at 29 Palms, Mojave Desert
- Xerox: Signature Analysis Toolbox for machine diagnostics

• 17 nodes (6 DOA, 11 amplitude)
 • Scale: 1 square=5 ft.
 • 0.5 sec update interval
 • Packet loss significant

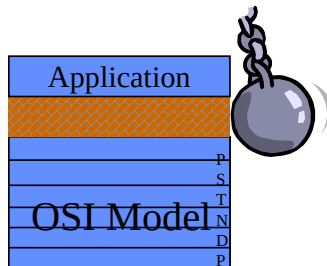
Motion-Cast: Addressing and Networking among Vehicles

- Addressing based on physical parameters of mobile nodes rather than on identity
 - ♦ e.g., “the car to my left front”
 - ♦ e.g., “the cars in my lane behind me”
- Each receiving node decides whether/how to retransmit packets based on relative motion and distance, depending on the application/event



Rethinking the network infrastructure

In wireless ad hoc networks, networking is intimately coupled with sensing, interaction, and control needs and hence application semantics

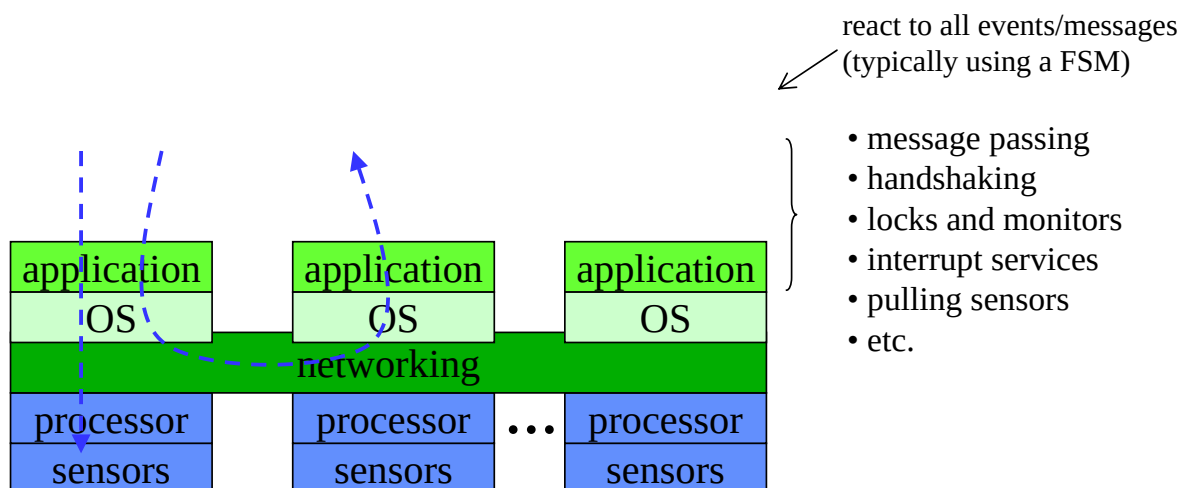


- Break down traditional barriers of OSI model
 - Consider both communication cost *and* information utility using algorithms and dynamic data evaluated at the application level
 - Implemented the node selection *in network*, via routing decision
- Data-centric and ad-hoc
 - Peer-to-peer, mesh topology; dynamic and highly mobile connectivity
 - Developed several routing approaches based on optimizing for both networking and application
- Group management vital to scalability
 - Address nodes based on geography and capability, not by name
 - Limit data propagation to sensors relevant to measurement at hand

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PARC Confidential

Traditional Networked System Architecture

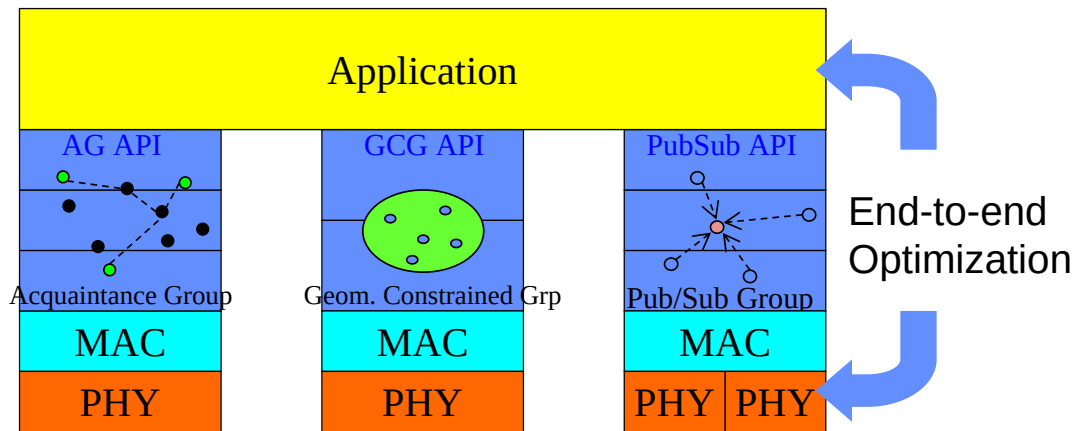


In an object tracking example we developed, 40% of the code and most of debugging time are spent on the "glue logic" that deals with event synchronization and message passing.

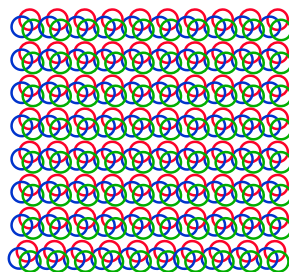
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New Programming Models for Sensor Nets

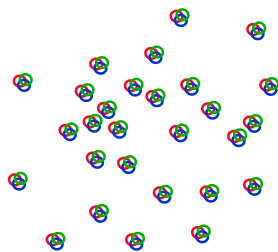
- Support cross-layer dynamic optimization of coding schemes, protocols



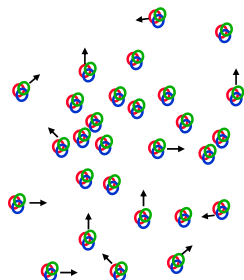
Three Phases of Smart Matter



Control



Communicate



Configure

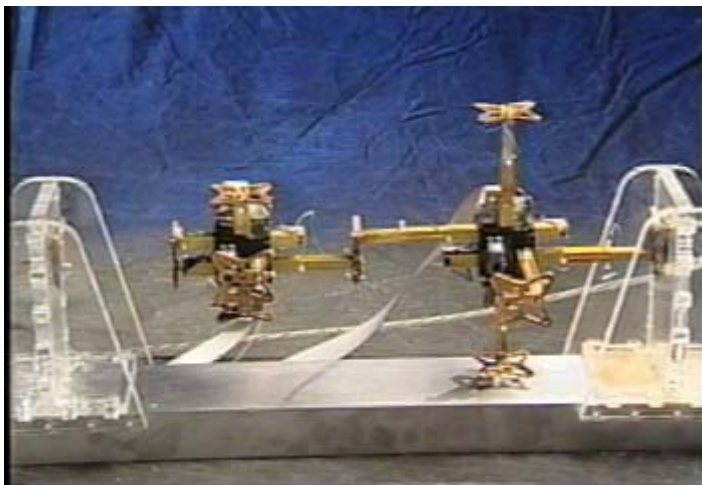


Extreme in Modular Reconfiguration



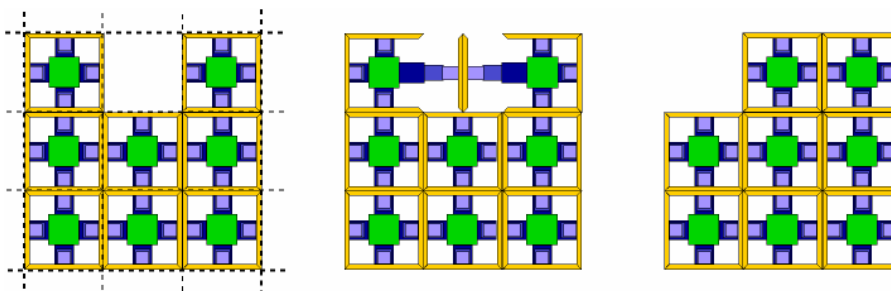
Terminator 2:Judgement Day (1991) was directed by James Cameron, produced by Carolco Pictures, special effects by Industrial Light and Magic.

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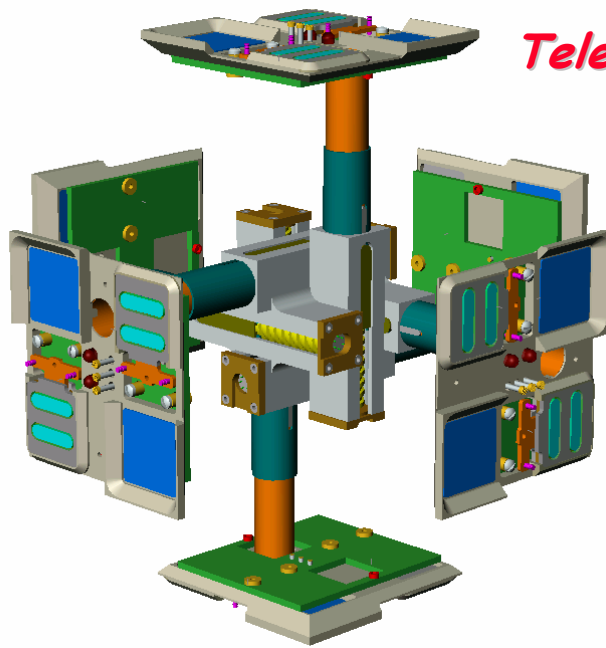


Telecube G1

- Modules expand/shrink and attach/detach



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TeleCube G2

Compact State
 $5.9 \times 5.9 \times 5.9 \text{ cm}$

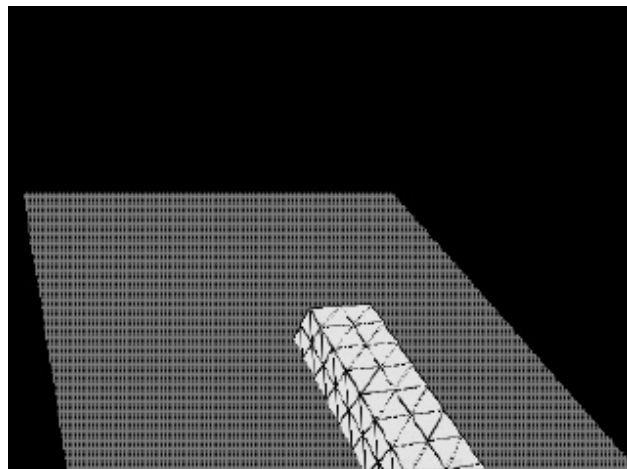


Fully Extended
 $131 \times 131 \times 131 \text{ cm}$

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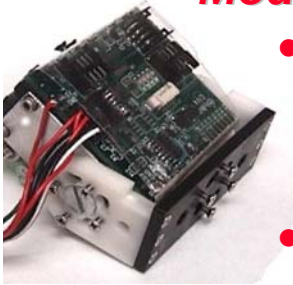
Telecube Programming

- Metamodule 2x2x2 control
- Generalization of "Smart bunkers"

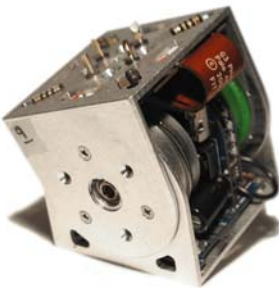
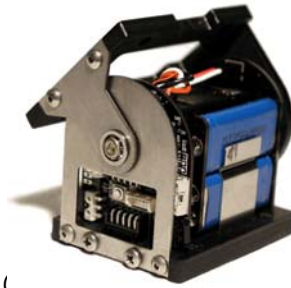


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PolyBot Manual Reconfiguration G1v4, G1v5 Modules



- G1v4 G1v5
 - ◆ Modules manually twist together
 - ◆ On-board CPU (PIC 20MHz)
 - ◆ On-board power (NiMH)
 - ◆ Force/contact sensors
- G2 G3
 - ◆ Integrated Connection plate
 - Hermaphroditic electrical connectors (communications)
 - Active SMA Latch
 - ◆ Power PC, MPC555
 - ◆ Nodes: 6 interface plates



Climbing a Fence



Closed Chain Ratcheting



- Exploit singular positions in the Jacobian for high mechanical advantage in combination with ratcheting mechanism.

(paper at IROS'01)

Climbing Stairs

- Loop conforming to terrain
- Loop can travel .5 kilometers on one charge
- Can climb several flights of stairs



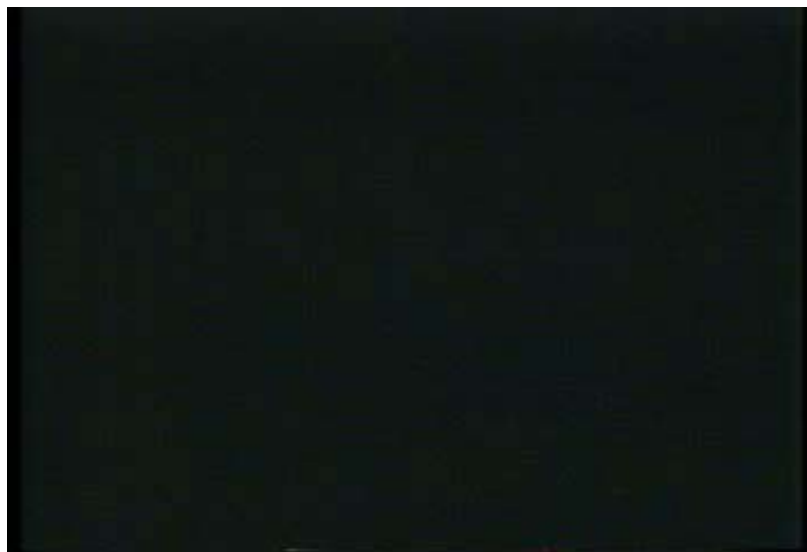
Conforming Over Obstacles



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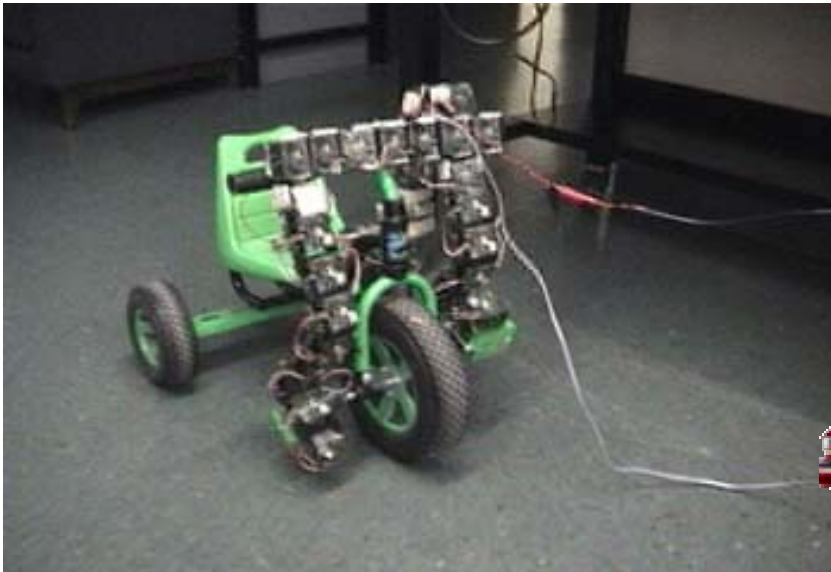
Reconfiguration

- Video from COMDEX 1999



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Using Human Equipment



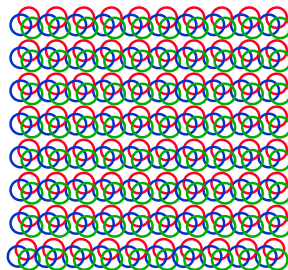
Soon:

- ♦ Ladder
- ♦ Up a vertical pipe
- ♦ Turns in small pipe
- ♦ Monkey bars (2' spacing)

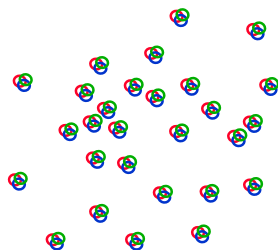
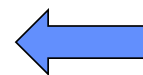


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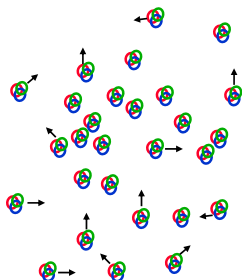
Three Phases of Smart Matter



Control



Communicate



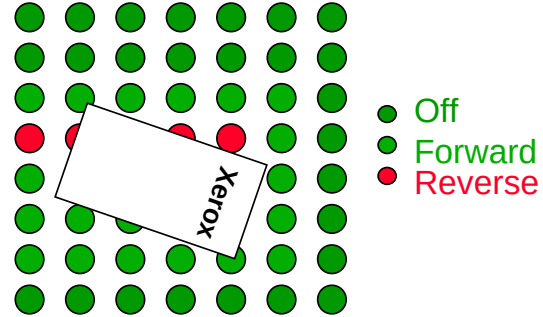
Configure

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An “Active Surface”

Air jet paper mover:

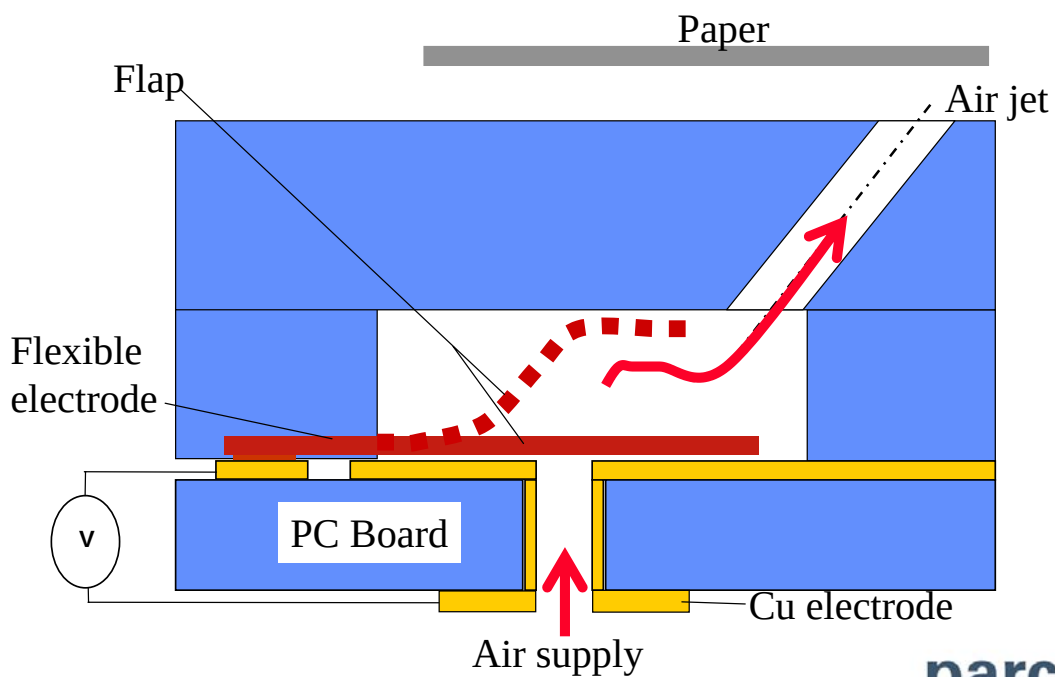
- Individually controlled air jets
- Robustness from redundancy
- Millimeter-scale “mEMS” valve arrays



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Partially funded by DARPA MTO

Active Surfaces: Cantilever Flap Valve



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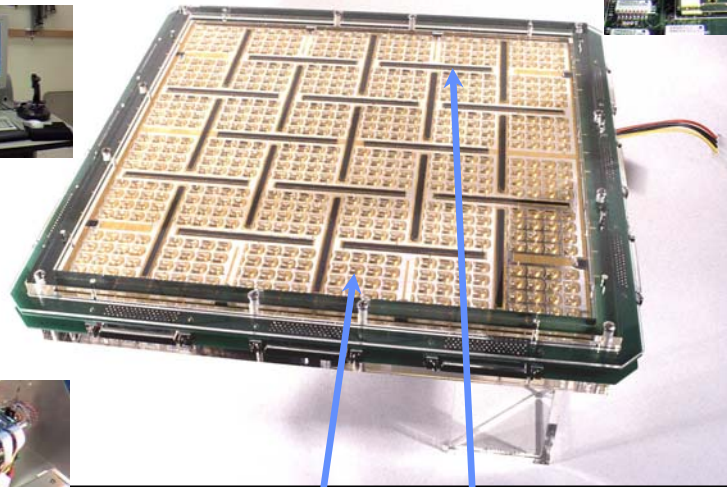
mEMS-based Active Surface

PC-hosted DSP
control @ 1 kHz

12" x 12" board



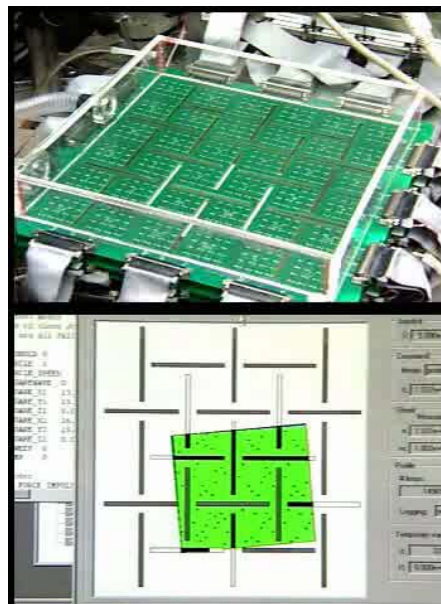
576 valves
(144 per direction)



sensors: 32,000
gray-level pixels
in 25 linear arrays

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Airjet video

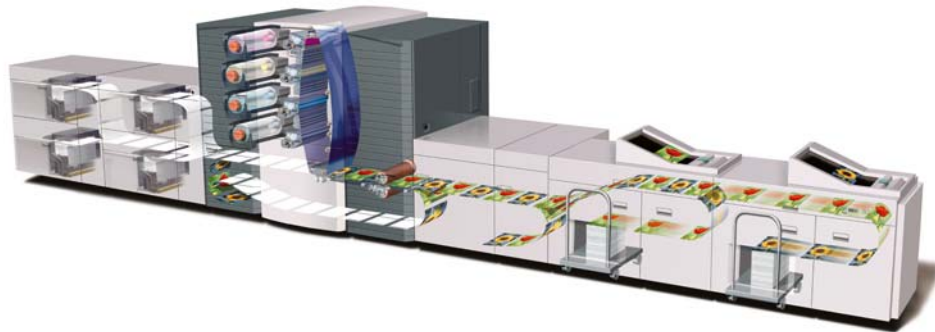


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Print system

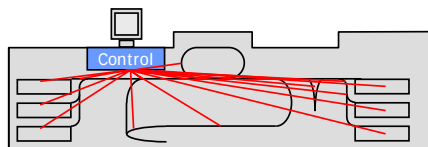
- A complex multi-function device:

- ♦ variety of operations
- ♦ complex interactions
- ♦ real-time, high-speed operations

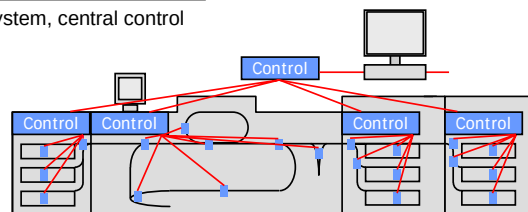


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Toward Reconfigurable Smart Systems

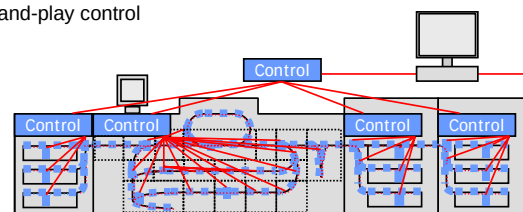


Ca. 1990: monolithic system, central control



Ca. 2000: modular system, plug-and-play control

*Changing the way
products are put together.*



Near future: hyper-modular system, reflective control

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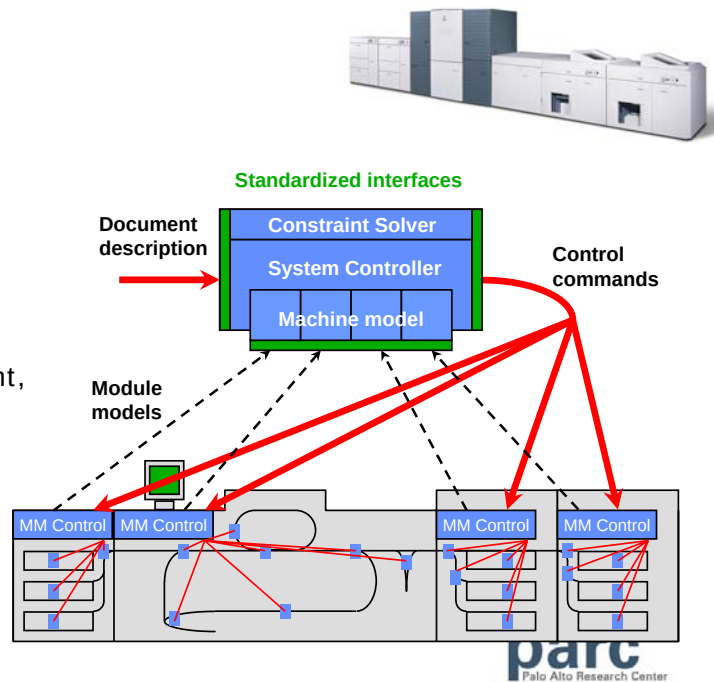
Model-based print-engine scheduling

Problem:

- 3-20 modules, 100s of capabilities
- customer-configurable machines
- scheduling complex interactions

Results:

- auto-configuration
- configuration-independent, optimized control
- toolkit for reactive print engine control



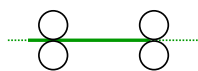
Domain theory

• Components as transducers:

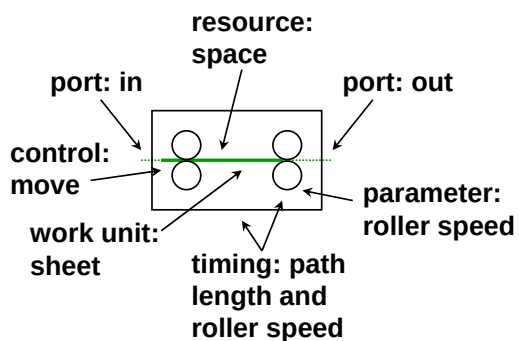
- ♦ work units, transformation, resource allocations
- ♦ feature, timing constraints on combinations of inputs and outputs
- ♦ compositional, "no function in structure"

•

Transport component

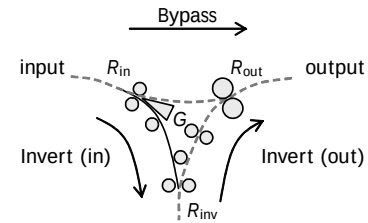


Describing structure, constraints, and interfaces.



Inverter model

- ```
Component Inverter(int length, int speed) {
 ... ports, resources, variables
```
- ```
    Capability Bypass(IntVariable t_in) {  
        in.Input(s, t_in);  
        out.Output(s, t_out);  
        s.width <= 285;  
        t_in + d_byp == t_out;  
        d_byp == length/speed;  
        d == s.length/speed;  
        r_in.Allocate(t_in, d); ...  
    } // Capability Bypass
```
- ```
 Capability Invert(IntVariable t_in) {
 in.Input(s_in, t_in);
 out.Output(s_out, t_out);
 s_in.width <= 285; s_in.length <= 436;
 s_out == s_in except {orientation};
 s_in.orientation == 1 - s_out.orientation;
 t_in + d_inv == t_out;
 d_inv == (length+s_in.length)/speed;
 d == s_in.length/speed;
 r_in.Allocate(t_in, d); ...
 } // Capability Invert
```
- ```
} // Component Inverter
```



Impact of model-based scheduling

- Provable properties:
 - ♦ correctness
 - ♦ optimality
- New control capabilities:
 - ♦ adaptive software
 - ♦ use of redundancy
 - ♦ generic fault recovery
- Software engineering concerns:
 - ♦ modular architecture, standard interfaces
 - ♦ write and debug once, reuse often
- Time To Market!

Embedded Reasoning

● Vision:

- ♦ Highly reconfigurable systems through embedded reasoning
- ♦ Enabling systems that are versatile, effective, robust, safe
- ♦ Providing radical platforms for future products

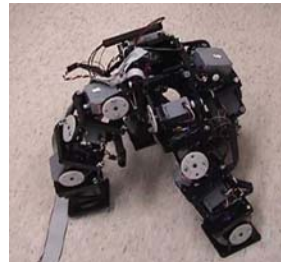
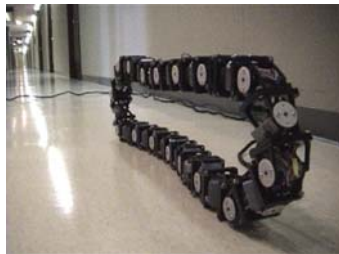
● What we need:

- ♦ model-based planning and scheduling
- ♦ reflective control and coordination
- ♦ distributed diagnostics, learning, adaptation
- ♦ explicit interfaces, dynamic architecture

● *Reasoning technologies are becoming an important part of advanced control software for smart embedded systems.*

Question: Reconfigurable control

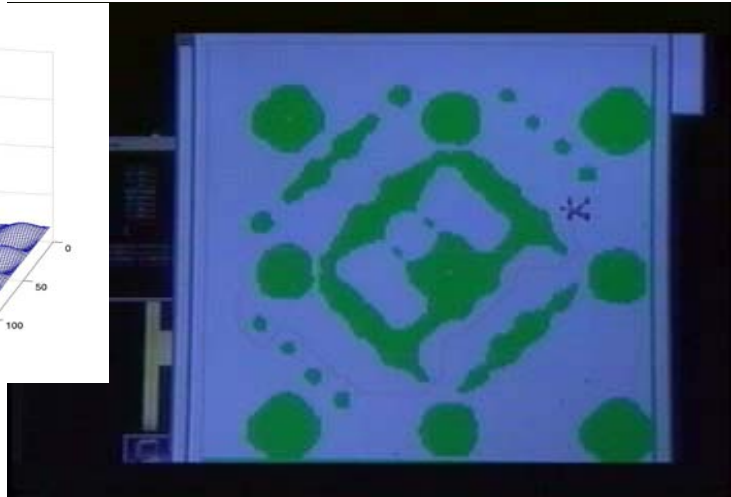
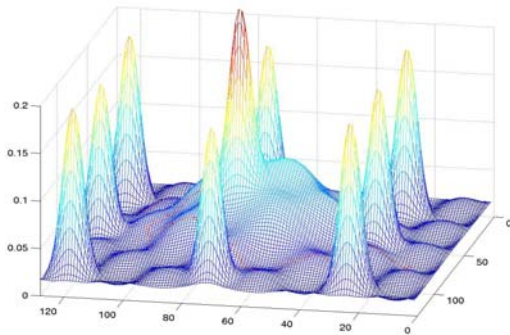
- How to map the logical structure of the control algorithms onto the physical structure of the modules?



- Minimize communication
- Remap computation when modules reconfigure
- Remap computation when modules fail

Path Planning in Unstructured Environments

- What is an obstacle?
- How to distribute computation?



Path Planning/Execution

- External Sensor
- Multi-mode
- Initial tests with snake like gaits



Extreme in Modular Reconfiguration



Terminator 2:Judgement Day (1991) was directed by James Cameron, produced by Carolco Pictures, special effects by Industrial Light and Magic.

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Questions to Leave you With

- As our technology becomes more biological, does biology become a better teacher?
 - ◆ Deep insight?
 - ◆ Stupid metaphor?
- Even though processing power is growing with Moore's Law, it is outstripped by our ability to fabricate ever new pieces of Smart Matter which require even more processing power.
- Processor power is not enough – we lack the principles, theories and methodologies to truly enable Smart Matter. Ironically, the lack today lies not with the mechanical engineering disciplines but in computer science.

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