Realizing Programmable Matter

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2006 DARPA ISAT Study

What is Programmable Matter?

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We imagine a material made up of very large numbers of small devices. These devices, each of which would be sub-millimeter in diameter, or roughly the size of a pixel on a computer display (but in three dimensions), would work in concert to render, dynamically and with high fidelity, physical objects. Each device would contain the processing power, networking capability, power, actuation, programmable adhesion, sensing, and display capabilities to accomplish this.

The programmable matter concept is not new. In fact, DARPA has previously contemplated this and related concepts (such as "smart dust"). A purpose of this study is to determine the technical feasibility, today, of programmable matter and the extent to which targeted investment by DARPA would accelerate its realization and impact on DoD capabilities. Our study considered the manufacturing, software, and application issues in developing programmable matter. We conclude that manufacturing of programmable matter devices, while posing a number of significant technical challenges in integration, power, heat management, etc., can be made feasible, and in a relatively short (less than 10 year) time frame with appropriate investment.

This briefing describes the programmable matter concept as we envision it, and then discusses the technical challenges and a possible roadmap for overcoming them. We also present an analysis of the potential military impact of programmable matter.

What is Programmable Matter?

A programmable material…

…with actuation and sensing…

…that can morph into shapes under software control…

…and in reaction to external stimuli

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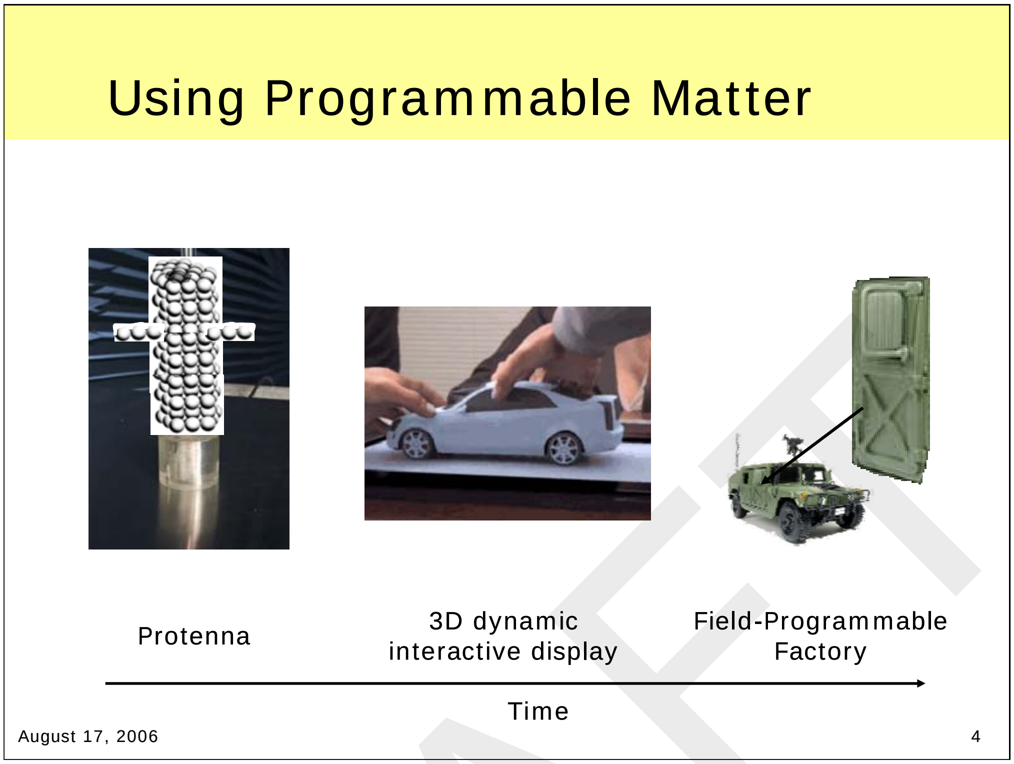
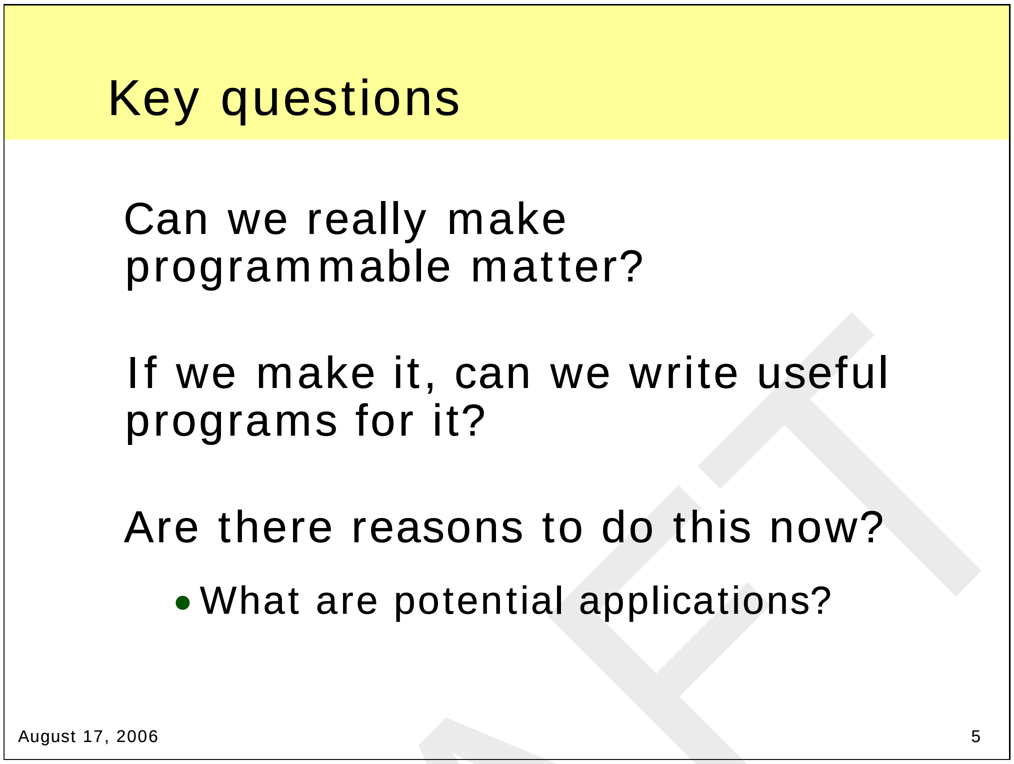
At a high level, programmable matter can be viewed as an intelligent, or programmable, material that contains the actuation and sensing mechanisms to “morph” into desirable/useful shapes under software control, or in reaction to external stimuli.



If and when realized, programmable matter would be a remarkably versatile tool. *In this briefing, we will describe several specific application concepts that have military relevance. As shown in the previous video, programmable matter is, in its simplest application concepts, a true 3D display, providing tremendous improvements in visualization, for example for battlefield or urban environments. In the electronic domain, our study investigated the use of programmable matter to improve radio technology, through shape-shifting antennas (the "protenna" concept) and reconfigurable internal connections for software-defined radios. A third class of applications involve the ability of programmable matter to make a versatile and scalable fabrication facility, which we refer to as the "field programmable factory".*

These and other concepts will be described in the last part of this briefing.

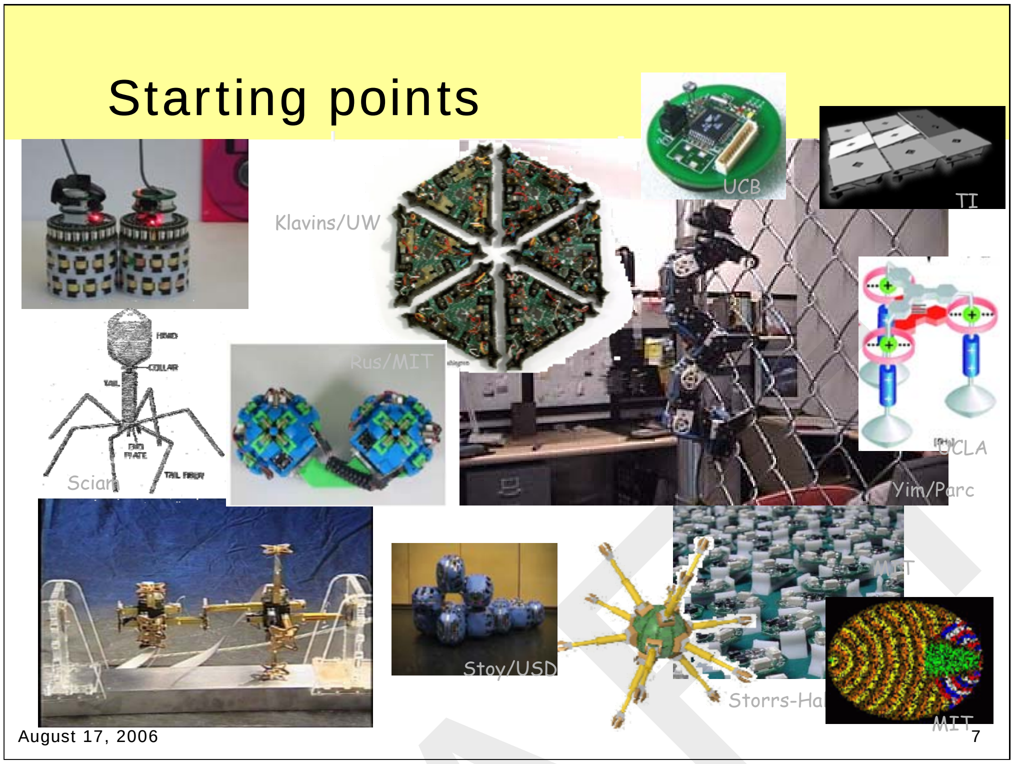


When first contemplating the programmable matter concept, there are a number of key questions to consider. Perhaps the most basic question is whether we can really build the devices that would make up programmable matter. If we assume that such devices can in fact be built, there is the very serious question of whether it is at all reasonable to think we can program such a large mass of mobile computing devices. And then, of course, assuming that the devices can be built and useful programming models developed, are there compelling reasons to do this now, and specifically for DARPA to to do it? What would be the path going forward?

Can we really make programmable matter?

When can we make programmable matter?

What kind of “matter” will it be?



Programming matter builds on progress that has been made in many disparate fields, e.g., modular robotics, programming ensembles, materials, MEMS, nanomaterials.

A fundamental goal: Scaling

Consider applications that involve rendering macroscale objects

- High fidelity rendering implies
  - sub-millimeter-scale units (voxels)
  - massive numbers of units

Units must be inexpensive

- mass-produced
- largely homogeneous
- simple, possibly no moving parts

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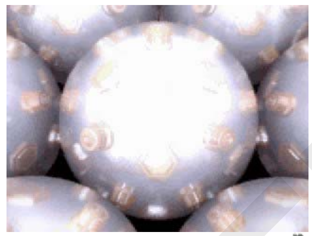
Change “human scale” to “macroscale”

Confusion on inexpensive. Not ensemble, but units. Conclusions are about units. i.e., robustness

A fundamental goal: Scaling

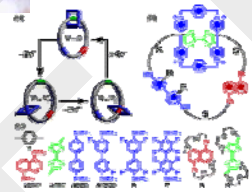
Modular robotics



Focus of this talk:

micron (MEMS) scale

Nano/chemistry



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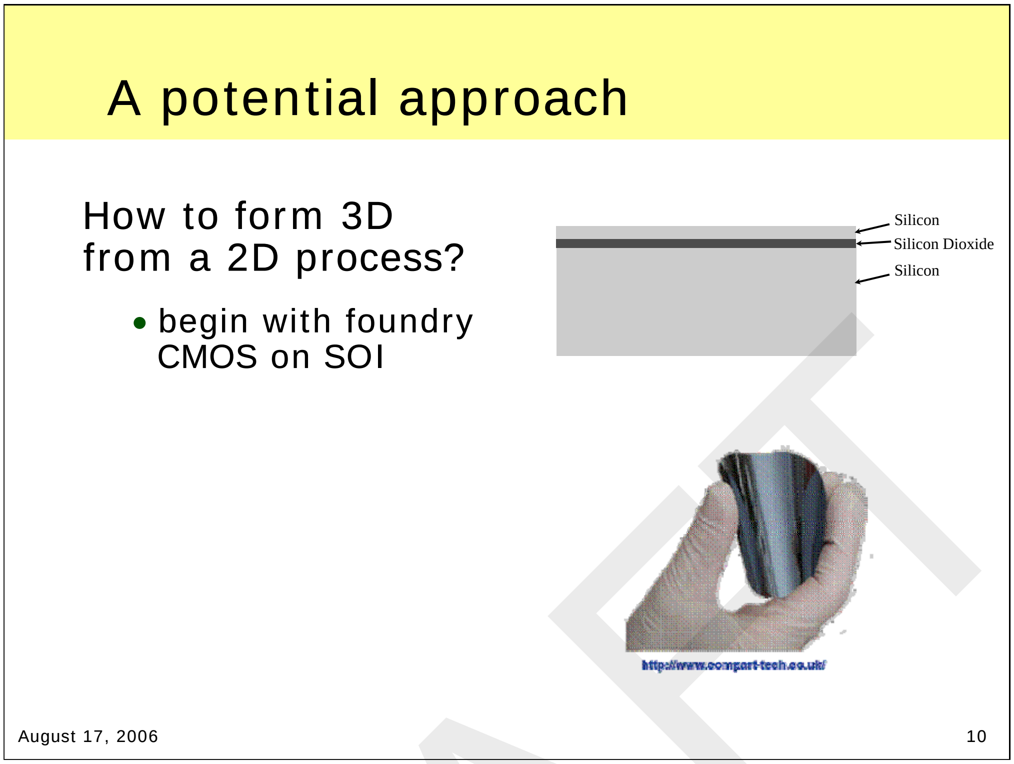
Stoddard 9



The key to this approach is to begin with well established technology and expand on it. Foundry services that provide full BiCMOS on silicon-on-insulator wafers are widely available at a reasonable cost (<$50k for a prototype run including multiple delivered wafers). This immediately provides processing and internal signal routing. But now, it is necessary to take this CMOS "chip" and turn it into a compact, sub-mm scale, mechanical unit.

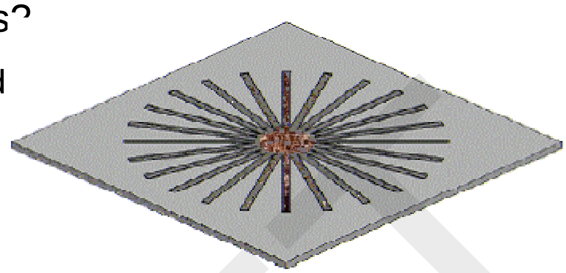
Bring in second image

This can be done by realizing that silicon can be bent if it is thin enough.

A potential approach

How to form 3D from a 2D process?

- begin with found CMOS on SOI
- pattern a flower that includes structure and circuits



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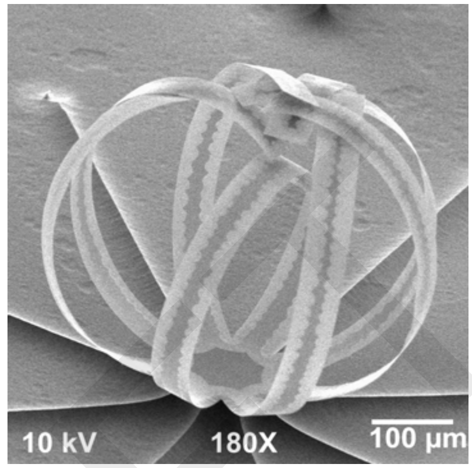
Put in picture a circuit on top of the gray metal.

Using the CMOS process, a circuit can be shaped into a flower pattern. The circuit is completely enclosed by the passivation layer on top and the insulator layer below.

A potential approach

How to form 3D from a 2D process?

- begin with foundry CMOS on SOI
- pattern a flower that includes structure and circuits
- lift off silicon layer
  - flexible
  - harness stress to form a sphere



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Get better picture of rob's progress

Include in graphic under picture a cube to represent the supercap

A sanity check

1 mm diameter sphere

Mass < 1 mg

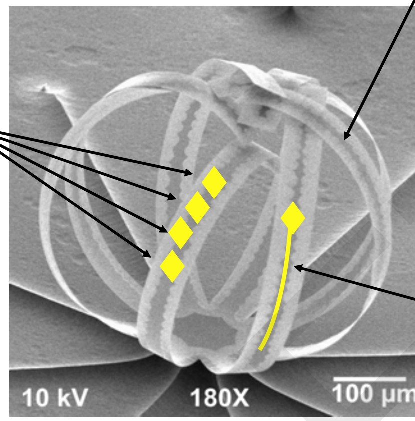
Electrostatic Actuators

~5 body lengths / sec

Communication Capacitors

Power Storage

Supercapacitor stores enough energy to execute over 200 million instructions or move 2 million body lengths



Computation Capability

8086 Processor with 256KB memory

SOI-CMOS 90 nm process with > 2M transistors.

Power distribution

Transmission of "energy packets" using capacitive coupling fills reservoir in < 1µs.

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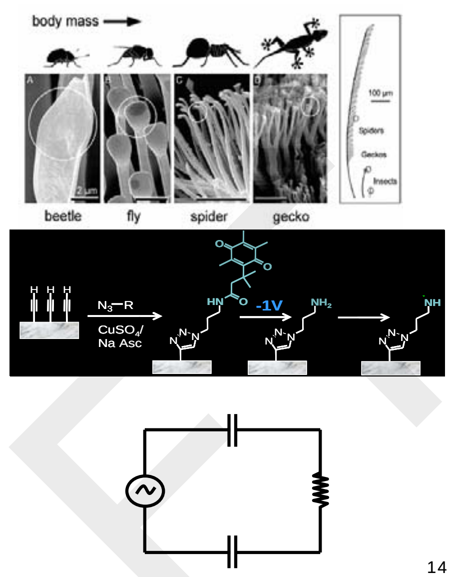
Additional challenges

We investigated concepts in integration of

- adhesion mechanisms
- power distribution
- energy storage
- communication
- heat management



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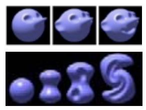
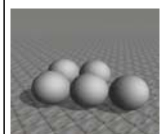
In addition to checking the sanity of this design with respect to number of transistors, electrostatic actuation, power distribution, and storage, we also investigated plausible concepts in integrating other needed mechanisms, such as adhesion. For example, for adhesion mechanisms we studied the current state of the research in biomemetic materials (e.g., "gecko hairs"), as well as a chemical "click" process that achieves reversible covalent bonds.

Major milestones (hardware)

time →

					
functionality	communication and **localization** for sensing of (interior and exterior) shapes	dynamic localization and active **adhesion** for a "digital clay"	control for simple coordinated **actuation**	**integration** for coordinated sensing and actuation	macro-scale rendering and **dynamic** shape shifting
hardware requirements	device integration; network; initial power	programmable adhesion; power and heat management	actuation	sensor integration	display; biomemetic and/or chemical adhesion

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With the MEMS-based concept described here, as well as others, a development roadmap begins to emerge. In the beginning, the major challenges will involve design and device integration. The initial requirements will be on processing and network infrastructure, to allow not only communication but also power management. With this much implemented, it would be possible to pursue the programming of "shape-sensing" applications, for example to pour programmable matter into a cavity (e.g., a lock) or over an object, and then sense its (negative) shape.

The next major stage of functionality would demand program-controlled adhesion. Achieving this would enable the use of PM as a "digital clay", where external forces (e.g., gravity or a person's hands) provide all of the actuation forces but the devices adhere as appropriate to achieve a desired shape. Very likely, the increased processing and communication requirements of such an application would mean more sophisticated power and heat management.

Up to this point there is no need for independent actuation. Actuation, perhaps achieved via an electrostatic mechanism, would most likely start with very small ensembles of devices, and early on incorporate coordination with sensory inputs. This would then be followed by a scaling up in number of devices, to achieve the macro-scale, interactive rendering depicted at the start of this briefing.

Finally, in the very long term, exploitation of the large numbers of processors in a PM mass would become exploitable through the development of advanced new distributed programming models, to achieve, ultimately, "inteligent" objects. Depicted here is a chess board

When can we make programmable matter?

Soon.

But then can we program programmable matter?

Programming large machines

Concepts in parallel, distributed, and high-performance computing

- Can scale to thousands of nodes for “embarrassingly parallel” applications, …
- …with known, regular interconnect

But how do we program millions of mobile, interacting devices?

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Algorithms vs control

Our study considered the programming problem at two levels

- Programming the Ensemble: How does one think about coordination of millions of elements?
- Programming the Unit: What is the programming model for a (single) element?

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Physical rendering

To simplify our approach, we focus exclusively on physical rendering:

- How to coordinate the movement of the units to form a desired physical shape

Today: Motion planning

- But with a large number of units, central motion planning is not tractable
- A *stochastic* approach appears to be necessary

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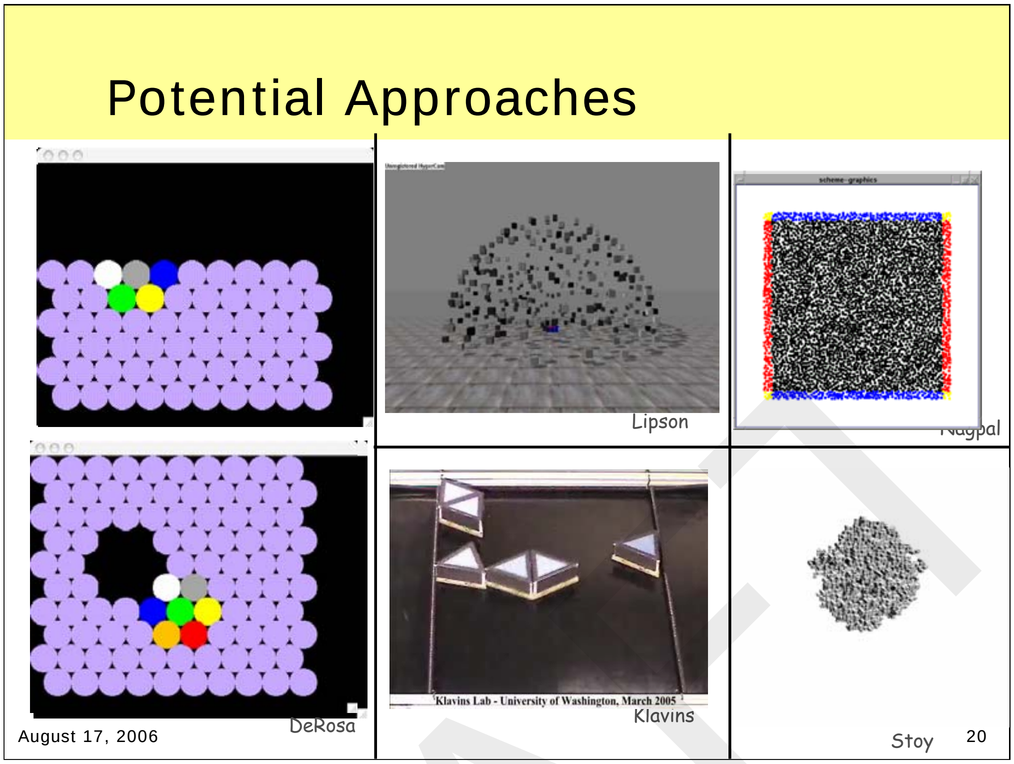
Potential Approaches
Lipson
Nagpal
Klavins Lab - University of Washington, March 2005
Klavins
DeRosa
Stoy
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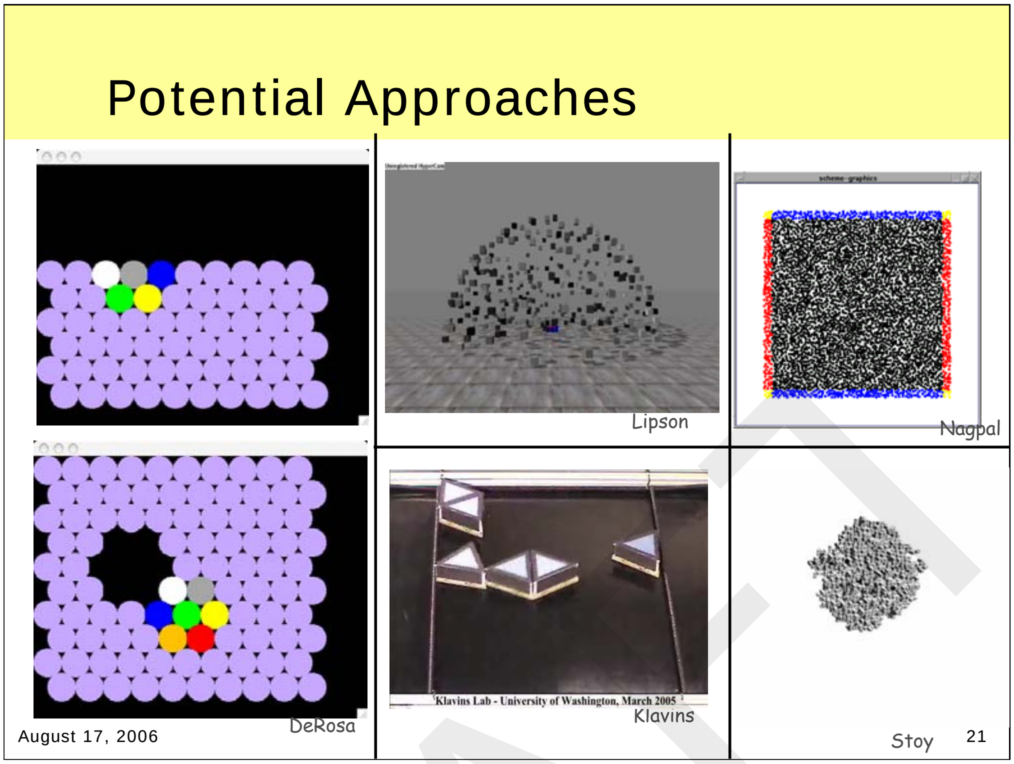
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Klavins
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DeRosa
Stoy
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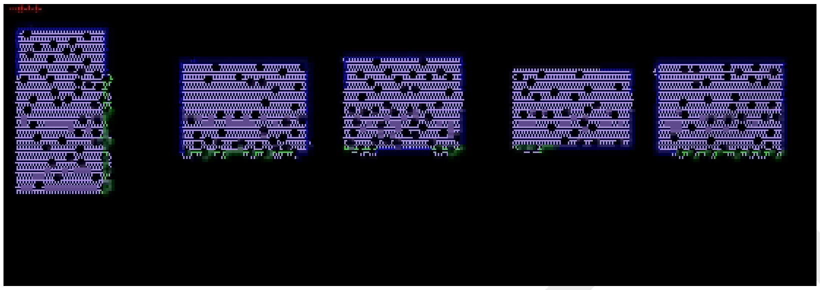
Hole flow methods



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Rendering

Conclusion: For rendering, a stochastic approach appears to have several advantages:

- exploits large numbers
- requires no central planning
- simple specification
- scale-independent
- robust to failures in individual elements

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Embrace Stochastic Approaches

Need reliable (but not exact) outcomes from unreliable components and information

Information Based Complexity shows:

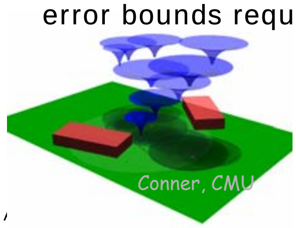
when information is:

- costly,
- tainted,
- partial

Programmable Matter has:

- costly communication,
- noisy sensors,
- no one unit has the whole picture

Worst-case error bounds require exp-time. “with high-probability” error bounds require *poly-time!*



Emerging paradigms for unit control

- hybrid control
- Programming work
- Advances in convexity

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Robustness

Large distributed systems ...

(6 nines for each unit $\Rightarrow$ less than 1 nine for the ensemble)

... Acting in the real world

- Environmental uncertainty
- Parametric uncertainty
- Harsher than the machine room (plain old faults/defects)

Known problem in robotics and distributed systems

Current approaches don't scale or are not integrated

Make Uncertainty Tolerance first class

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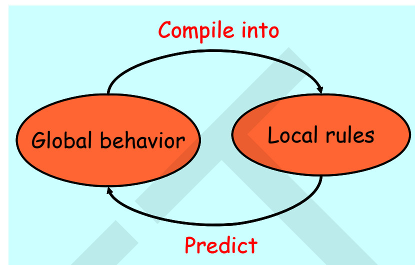
Global Behavior from local rules

Concise specifications

Embarrassingly parallel

Examples:

- Amorphous computing [Nagpal]
- Graph grammars [Klavins]
- Programming work [Kod.]
- CA+Gradients [Stoy]
- Hole motion [DeRosa]
- Boyd model [Boyd]
- Turing stripes



Goal: Compile Global specification into unit rules
Predict global behavior from set of unit rules

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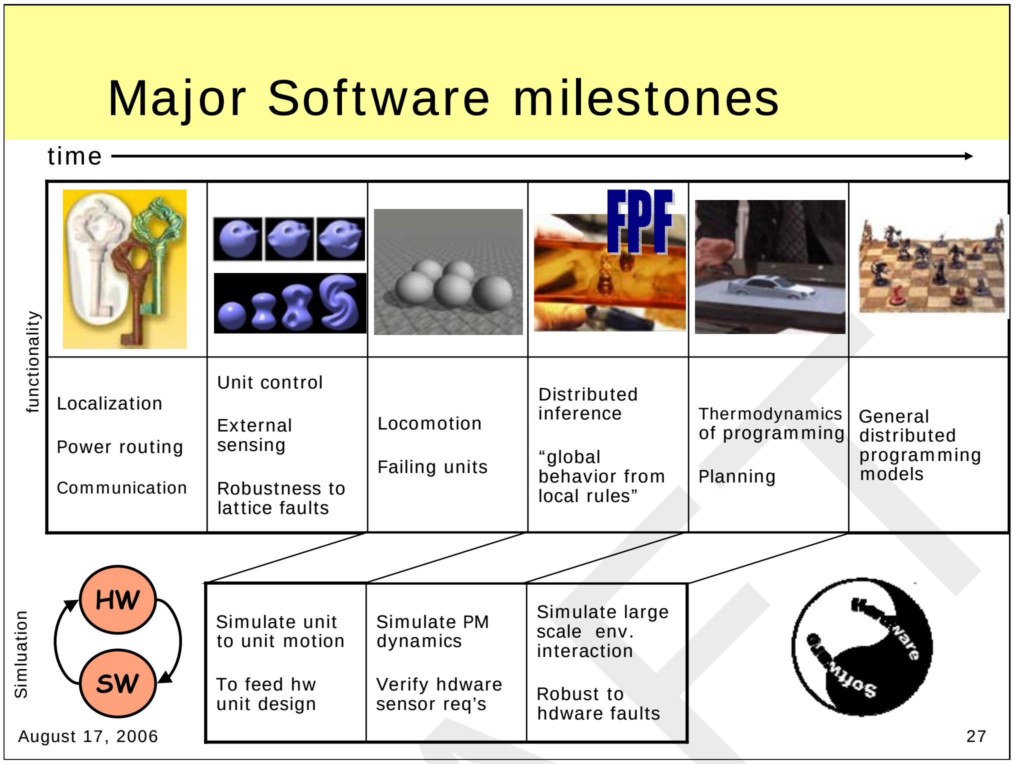
Programming the ensemble is a major challenge in realizing programmable matter. One approach that has been taken is to create a program for the ensemble by describing the behavior of the individual units and then rely on the emergent behavior of the ensemble to achieve the users goal. With a few exceptions the only way to determine the global behavior that will emerge is to simulate the ensemble.

There are, however, some examples in the area of rendering, where the global behavior can be predicted from the local rules and the local rules can be compiled, automatically, from the desired shape.



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Software trajectory

There is path:

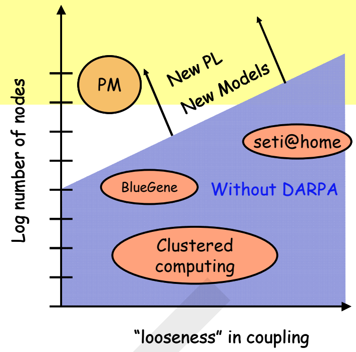
- Rendering is sweet spot

Research directions:

- Embrace stochastic behavior
- Make uncertainty tolerance first class

Outcome:

- Develop a thermodynamics of programming languages which will lead to
  - Compiling specification into “unit” rules
  - Predict global behavior from local rules



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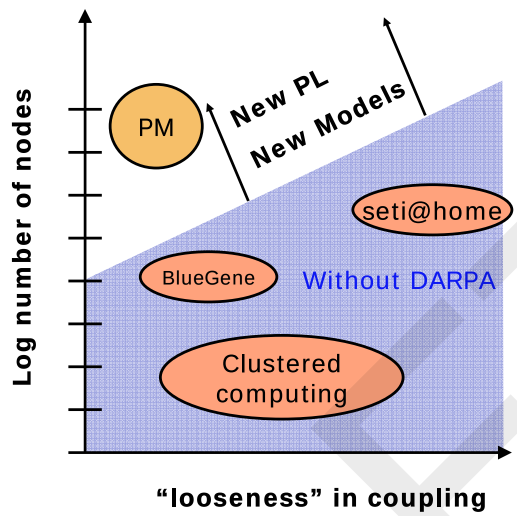
Towards
Thermodynamics of Programming



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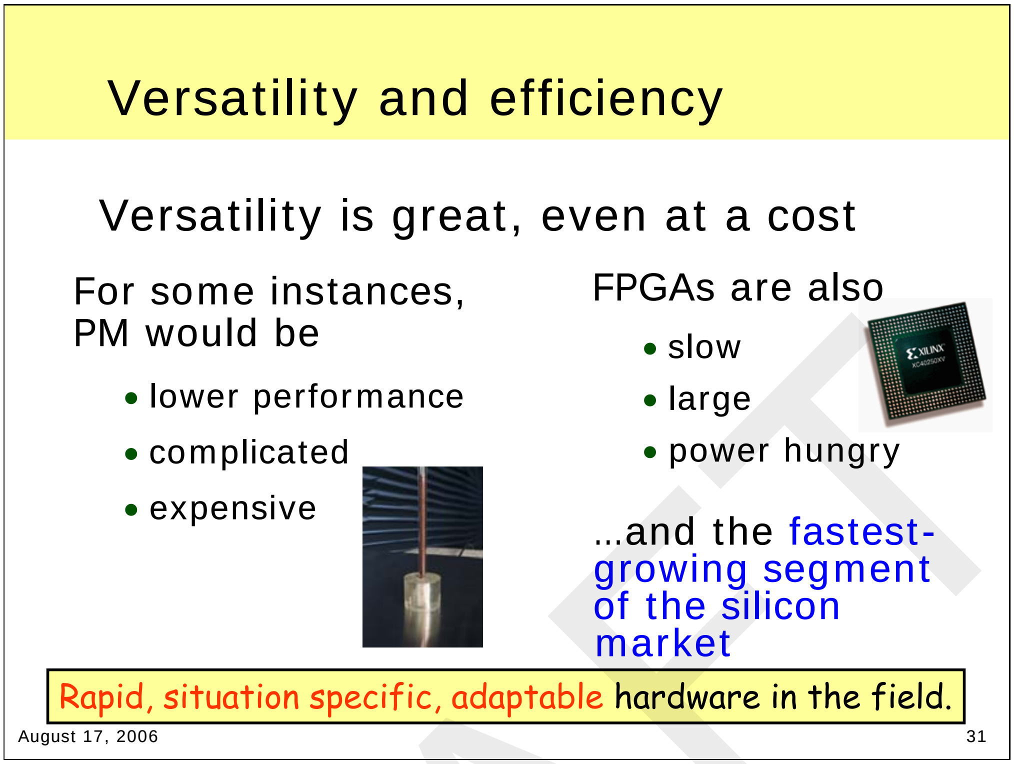
Why should DARPA invest in programmable matter?

Would a soldier use an antenna made out of PM?



For many particular applications, the Programmable Matter solution would have worse characteristics than a tailor-made solution.

A custom solution would certainly be less expensive (in volume), simpler, stronger…

By similar metrics, today's Field-Programmable Gate Arrays (FPGAs) are often much worse than an ASIC alternative that performed a particular task. The FPGA is slower, larger, and more power hungry than the ASIC.

Despite these characteristics, FPGAs are the fastest growing segment of the silicon market today.

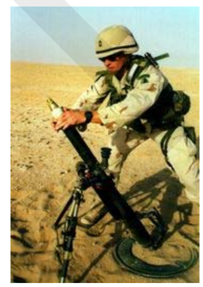
Furthermore…

…Programmable Matter is

- scalable and separable
  PM carried by many soldiers can be combined for larger objects
- computational / reactive
  reconfiguration can be dynamic, reactive to environment

Valuable in situations where time and distance matter

- space, ships, embassies, convoys, …
- quick fixes, decoys, improvisation



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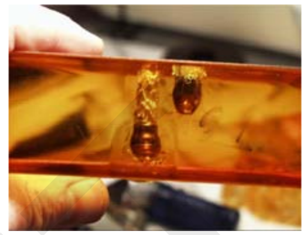
Beyond its versatility, programmable matter has other important properties. Because programmable matter consists entirely of homogenous units, it is inherently scalable. A given amount can be divided among multiple soldiers to lighten load and then recombined at need to construct larger objects. And unlike ordinary material, programmable matter can sense and react to its environment, which means it can do a better job at some tasks than ordinary material. One example where this would help is a mortar base plate. A base plate is large, heavy, and flat. It must be so in part because the exact shape and condition of the ground underneath is not known in advance. With PM, the load of a big object like this could be evenly distributed among a group of soldiers, and then the base plate itself could form itself to the exact contour of the ground.

In military situations, time and distance often matter, due to some form of isolation. For example, a small ship at sea would have no access to a fully functional machine shop. Space-based platforms are also similarly isolated. In such cases, when new needs arise, programmable matter could provide the necessary parts, on a short time frame, based on needs that could not be predicted in advance. As part of this study we met staff at the Natick Soldier Systems Center XXX and XXX to identify various uses for programmable matter in these situations.

Uses in the field

PM in the field takes on useful shapes

- physical display / sand table
- specialized antennas
- field-programmable mold
  - shape dirt and elastomeric cross-linked polymer into bullet-proof objects
  - mold customized shaped charges



3D fax:

- In CONUS, needed object is designed or PM-captured, then sent to the field

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Here are some of the specific ideas we've had about how programmable matter might be used in the field. Clearly it can be used as a 3D visualization aid, like a sand table that can construct a building and its interior. It could also be used to create antennas that adapt to their local environment.

And programmable matter doesn't have to be the object you need. Instead, it could be used as a programmable mold to create other objects. By filling the mold by an 80/20 mixture of locally found material and an elastomeric cross-linked polymer, a bullet-proof object can be created in a matter of minutes. P molds could also be used to create highly effective shaped explosive charges customized precisely to the job they are needed for.

The shapes programmable matter takes don't have to be determined locally. They could be transmitted from a remote location where the shape is determined either by a design process or by shape capture using PM itself. This gives you a kind of 3-D fax.

Understanding Complexity

Nanotechnology is more than just "small"

Future applications of nanotechnology at the macroscale require study of Systems Nanotechnology:

> The science and technology of manipulating massive numbers of nanoscale components

Programmable matter is a key enabler for studying large complex systems

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Programmable matter requires tacking the problem of building reliable systems from large numbers of components. Therefore, we see programmable matter as useful for understanding other important research directions. Nanotechnology exists at a much smaller scale than programmable matter, and therefore the number of nanotech components needed to build any object at macroscopic scale is truly huge. We can imagine a field we might call "systems nanontechnology", which focuses on how to coordinate nanoscale components in massive numbers. Building programmable matter is a key step toward understanding this and other extremely complex systems.

Heilmeier questions

What are we trying to do?

- Build a programmable material that is able to morph into shapes, under software control and in reaction to external stimuli. Bring power of programming to the physical world.

How is it done today? What are the limitations of current practice?

- Preplanning, prepositioning, and many specialized objects. This means big loads and lack of flexibility to handle unforeseen needs.

What is new in our approach & why do we think it can succeed?

- Potential designs indicate feasibility of the hardware. Physical rendering is a “sweet spot” that is tractable, software-wise.

Assuming we are successful, what difference will it make?

- New capabilities in low-volume manufacturing and 3D displays. Antennas may achieve radical improvements. New programming models for and understanding of large-scale systems.

How long will it take? How much will it cost?

- Basic units can be built in the near term. Integration of adhesion, sensing, locomotion several years later, leading to initial deployable applications in the 5-10 year time frame.

Conclusions

Manufacturing PM elements poses challenges, but appears to be feasible and may lead to new 3D concepts

Software for PM applications, while raising significant questions, appears algorithmically feasible for physical rendering but still requires breakthroughs in distributed computing

Application domain of rendering can form springboard for advances in models and languages for massively distributed programming of reality

There are leap-ahead military applications, in both longer and shorter time frames

Participants

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Alan Fenn (MIT-LL)
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Seth Goldstein (CMU)*
James Heath (CalTech)
Maurice Herlihy (Brown)
Peter Kind (IDA)*
Eric Klavins (Washington)
Tom Knight (MIT)*
Dan Koditschek (UPenn)
Peter Lee (CMU)*
Pat Lincoln (SRI)*
Hod Lipson (Cornell)
Bill Mark (SRI)*
Andrew Myers (Cornell)*
Radhika Nagpal (Harvard)
Karen Olson (IDA)*
George Pappas (UPenn)
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Rob Reid (AFRL)
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Daniela Rus (MIT)
Vijay Saraswat (IBM)
Metin Sitti (CMU)
Jonathan Smith (DARPA)
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Tom Wagner (DARPA)
Janet Ward (RDECOM)
Mark Yim (UPenn)
Marc Zissman (MIT-LL)*

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*ISAT member

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BACKUP SLIDES FOLLOW

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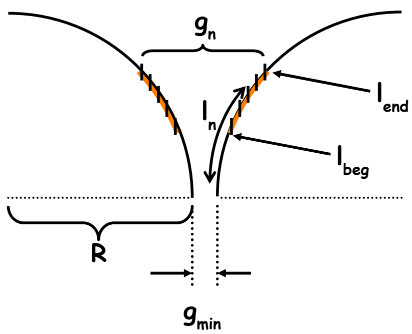
Calculating the voltage

$$g_n = g_{min} + 2 \cdot \left[R \left(1 - cos \left(\frac{l_n}{R} \right) \right) \right]$$



$$F_{req} = 12 \cdot F_{gravity}$$

$$F_{es} = \sum_{1}^{N} \frac{\epsilon_0 A V^2}{2 g_n^2}$$

$$V_{min} = \sqrt{\frac{2 F_{req}}{\epsilon_0 A V^2 \sum_1^N \frac{1}{g_n^2}}}$$

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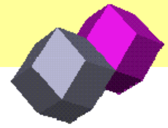
The required voltage is calculated using an electrode beginning 26 micrometers from the contact point and projecting out to 76 micrometers. This electrode is assumed to be 50 micrometers wide. A force 11 times the force of gravity is required based on the the electrode moment compared to the gravitational moment being a ratio of 100. The electrodes are broken down into multiple segments and the forces summed. This allows the required voltage to be calculated as shown.

Relative Locomotion on mm scale



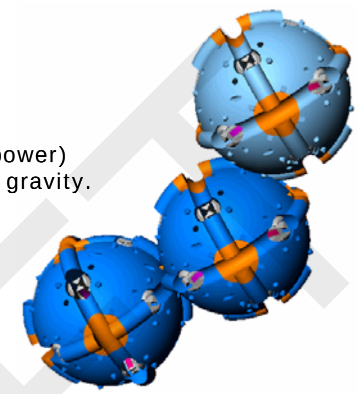
2 rhombic dodecahedrons n BCC lattice

Locomotion Constraints:

- Modules motions are discrete on lattice (e.g. simple cubic, body-centered-cubic).
  - Face detaches
  - Module moves along simple 1DOF path
  - New face-face latches
- Constraints
  - Modules move only self (or neighbor)
  - Assume modules remain connected (for power)
  - Worst case forces lift one module against gravity.

Actuation Technology

- Electrostatic (baseline)
- Electromagnetic
- Hydrophillic forces
- External actuation



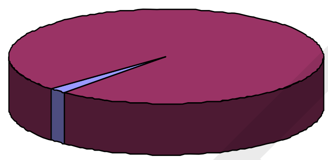
2 Spheres on cubic lattice (one moving)

Embedded computers

Embedded processors dominate

300 million PCs and servers

9000 million embedded!



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Costs of micro-scale device

Module: 1mm x 1mm x 1mm MEMS (silicon)

Silicon cost ~ $1/sq inch

- 2003 Revenue $5.7billion / 4.78 billion sq inch silicon
- $200 / 12" diam, $30 /8" diam wafers
- 100um-2000um thick (choose 1mm)

Assume processing costs ~$9/sq inch

- Modules cost 1.6¢

Average person weighs 65 Kg -> 65,000 cm3

- Assume density of water (1kg = 1000 cm3)

65,000,000 modules:

- 1000 modules per cm3

Cost: $1,007,502

More realistic, rendering of the shell: 1,500,000 modules: $24,000

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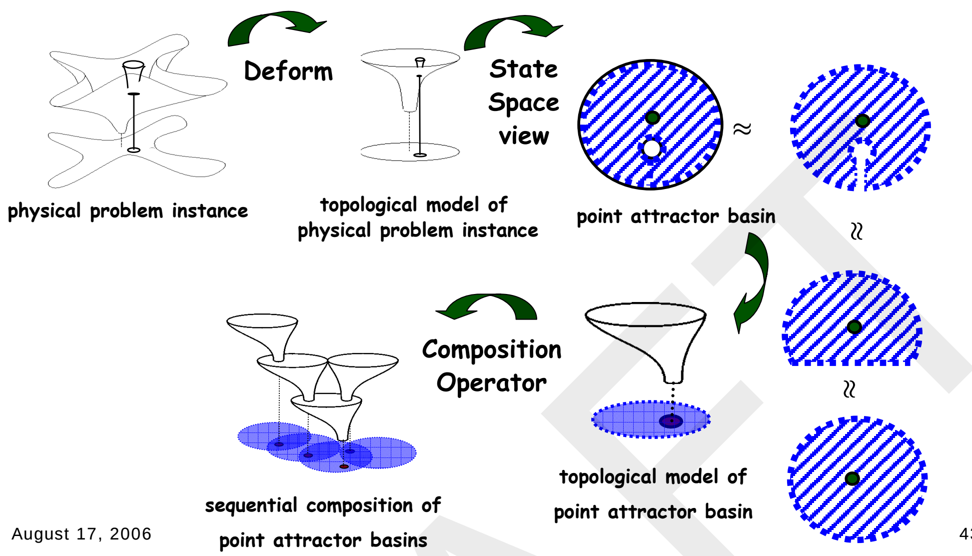
Topological Approaches
to Unit Control and Composition



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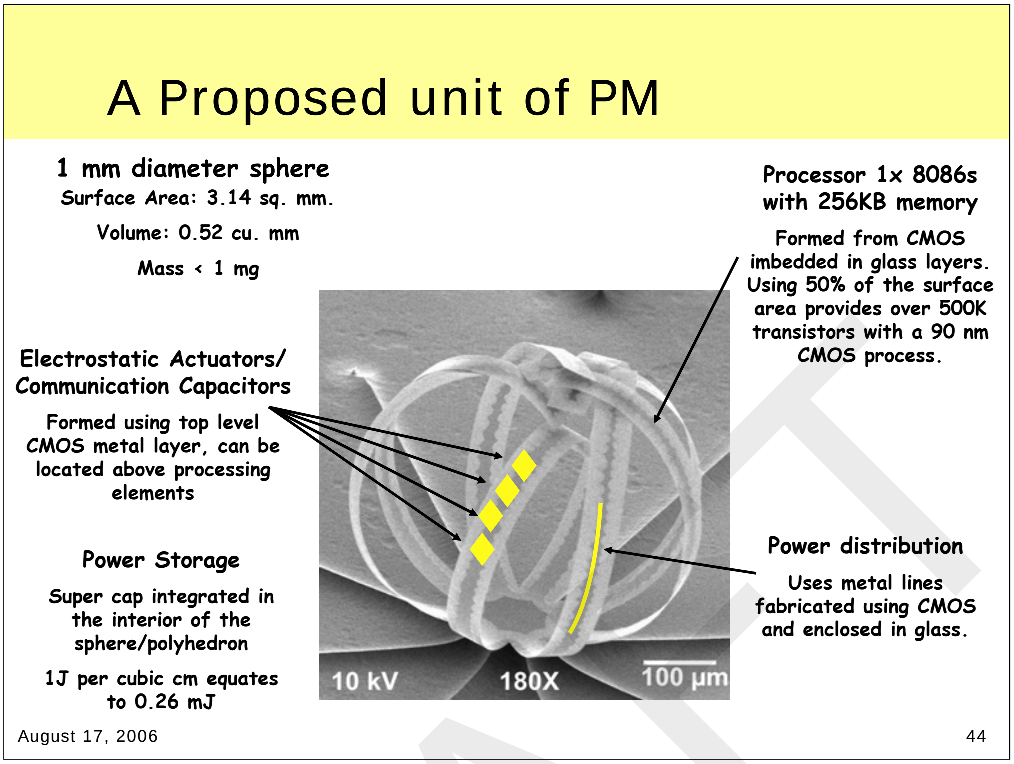

Mass assumes sphere is half filled with glass: 2600 kg/m^3

Power storage assumes a Supercap with 1J/cm^3 - Tayo is checking the number

Transistor count is based on 1 transistor per (9*lambda)^2at 90 nm each transitor then takes up 0.66 sq. microns so approx. 1.5 million transistors/sq. mm

8086 was built with 30K transistors. This is level of processor that we used to go to the moon.

BiCMOS process with two metal layers provides metal routing for power distribution, transistor connections, and capacitor electrodes. These will be fabricated and passivated in a commercial foundry.

Feasibility

- Area: 1mm diameter, π mm^2
  - 50% for circuits
  - 90nm: 2M transistors
  - 180nm: 500K transistors
- Computation + Memory
  - 8086 (30K Ts) 1 Mip
  - Program size: 64K
  - Total RAM: 256K
- Energy
  - supercap 50% volume .26mJ
  - 1pJ/instruction
  - 70 pJ/body length
- mass (density of glass)
  - .7mg
- Locomotion by electrostatic coupling
  - <400V generates 80 μN
  - <50 ms for 180 degree rotation
- Energy transfer by cap coupling
  - Deliver .026mJ in .24ns
  - Fill reservoir in 24ns
- Adhesion
  - Fast ES: several units in worst case
  - Others: surface tension, covalent bonds
- Cost
  - \$9/in^2
  - Unit: \$0.016

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Locomotion is based on the need to generate 12x the gravitational force to overcome the moment arm. The time is based on how long it takes to close one electrode gap assuming the force remains constant throughout the motion.

Supercap number is conservative compared to http://www.eeproductcenter.com/passives/review/showArticle.jhtml?articleID=19505585, which currently offers energy density of 10mJ/mm^3!

Field programmable concepts

From the Natick Soldier Systems Center and Special Operations:

- precisely shaped explosive charges
- mortar base plate
- gun magazines
- PJ equipment
- field radio
- one-handed bandages
- ...

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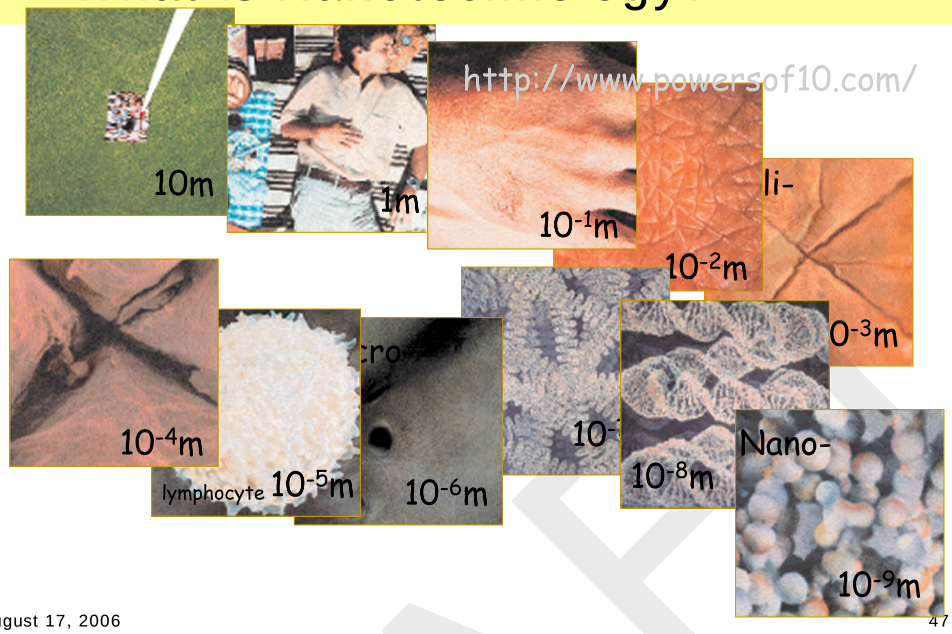
What is Nanotechnology?



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A sanity check

1 mm diameter sphere

Surface Area: 3.14 sq. mm.

Volume: 0.52 cu. mm

Mass < 1 mg

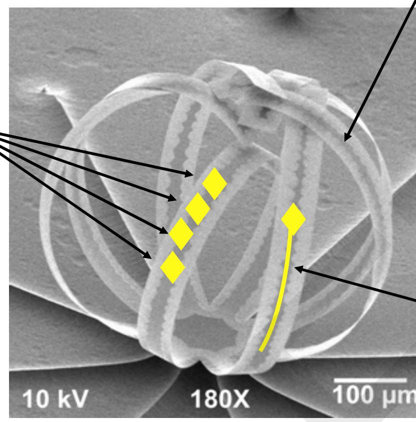
Electrostatic Actuators/ Communication Capacitors

Formed using top level CMOS metal layer, can be located above processing elements

Power Storage

A supercap integrated in the interior of the sphere/polyhedron

Stores enough energy to execute over 200 million instructions or move 2 million body lengths



Processor 1x 8086s with 256KB memory

Formed from CMOS imbedded in glass layers. Using 50% of the surface area provides over 2M transistors with a 90 nm CMOS process.

Power distribution

Unit-unit via capacitive coupling and transmission of "energy packets". Interior routing to central storage capacitor.

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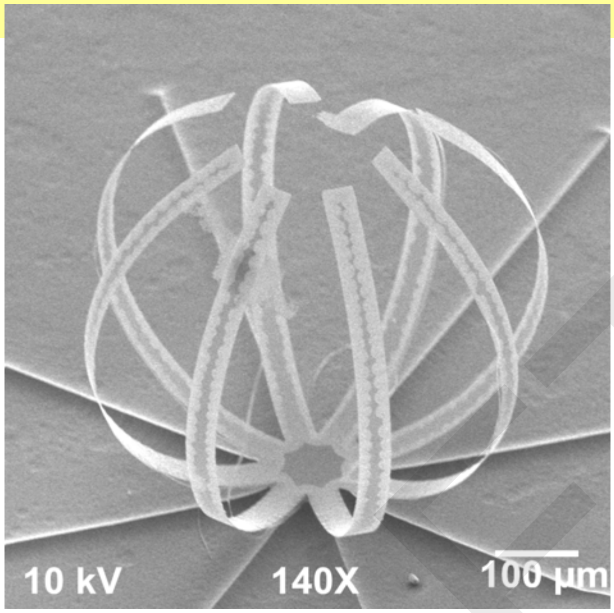
Mass assumes sphere is half filled with glass: 2600 kg/m^3

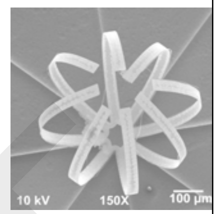
Power storage assumes a Supercap with 1J/cm^3. Commercial supercaps provide higher energy density.

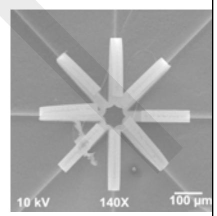
Transistor count is based on 1 transistor per (9*lambda)^2at 90 nm each transitor then takes up 0.66 sq. microns so approx. 1.5 million transistors/sq. mm

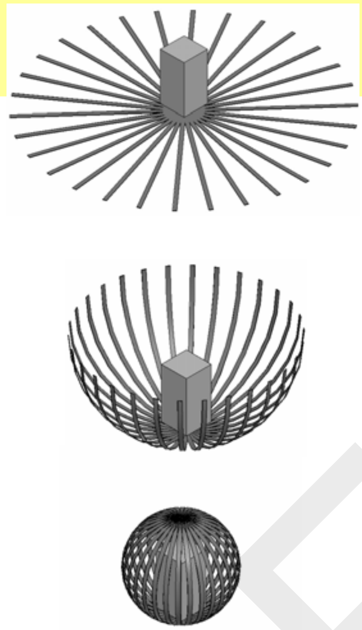
8086 was built with 29K transistors. This is approximately the computational power used to go to the moon.

BiCMOS process with two metal layers provides metal routing for interior power distribution, transistor connections, and capacitor electrodes. These will be fabricated and passivated in a commercial foundry.


10 kV
140X
100 µm


10 kV
150X
100 µm


10 kV
140X
100 µm



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Field programmability for the physical world

	Benefit	*Capability*
Production volume	Copes easily with low volumes typical in military applications	Rapid production with lowered factory retooling costs
Time to market	Fast response to military needs	Situation-specific hardware on demand
Upgrades	Easy upgrades in the field	Adapt equipment to lessons learned in the field
Functionality	One device for many purposes, combinable with those carried by others	Reduce SWAP and logistics load
Adaptability	Change and create equipment for new conditions	Specialized equipment for unpredictable situations

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Despite the larger area, lower performance, and larger area, FPGA use is growing.

To understand why, we have to look at a broader set of utility axes.

One of the key reasons FPGAs are actually more economical than fixed ASICs is the enormous costs and time associated with cutting-edge ASIC design (including the complexity associated with deep-submicron design). With FPGAs (or PM) you get to ride the volume manufacturing curve of the FPGA (PM) vendor. Each application then, does not pay for these NREs. Even companies shipping 30K units/month are finding it economically preferable to use FPGAs than ASICs.

Another key reason for starting (and often staying) with FPGA designs is time-to-market. In the commercial world, time-to-market is often essential to capturing and being competitive in the market. It is worth making the part more expensive to start selling parts earlier.

To fix bugs or add features, it is useful to be able to change the functionality in the field. Many applications are willing to pay some cost premium for the peace-of-mind and flexibility that comes from allowing in-field firmware upgrades.

In situations where many functions are needed, but only one is needed at a time. The flexibility of the FPGA can result in a net solution which is actually maller and cheaper than the collection of fixed-function devices it

Preparation:

2-step chlorination/alkylation chemistry.

Attachment:

Cycloaddition or "click" chemistry

Cleavage:

electrical potential across surface

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A general method for the non-oxidative functionalization of single-crystal silicon(111) surfaces is described. The silicon surface is fully acetylenylated using two-step chlorination/alkylation chemistry. A benzoquinone-masked primary amine is attached to this surface via Cu(I)-catalyzed Huisgen 1,3-dipolar cycloaddition ("click" chemistry). The benzoquinone is electrochemically reduced, resulting in quantitative cleavage of the molecule and exposing the amine terminus.

From

J. Am. Chem. Soc., **128** (29), 9518 -9525, 2006. 10.1021/ja062012b S0002-7863(06)02012-9
Web Release Date: July 1, 2006

 A Non-Oxidative Approach toward Chemically and Electrochemically Functionalizing Si(111)

Rosemary D. Rohde, Heather D. Agnew, Woon-Seok Yeo, Ryan C. Bailey, and James R. Heath*