Claytronics

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And, lots of other people!
www.cs.cmu.edu/~claytronics

November 8, 2007

Programmable Matter

- A programmable material…
- …with actuation and sensing…
- …that can change its physical properties …
- … under software control…
- …and in reaction to external stimuli

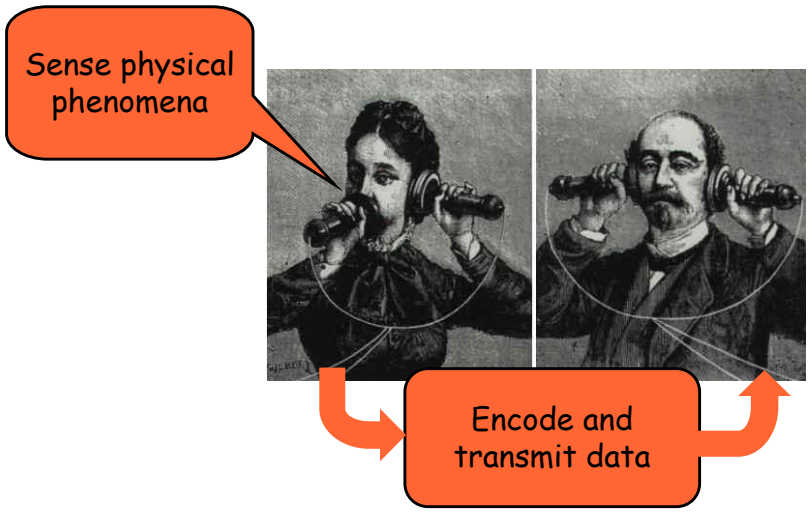
For movie see www.cs.cmu.edu/~claytronics/movies/cardesign.wmv

Challenge At End

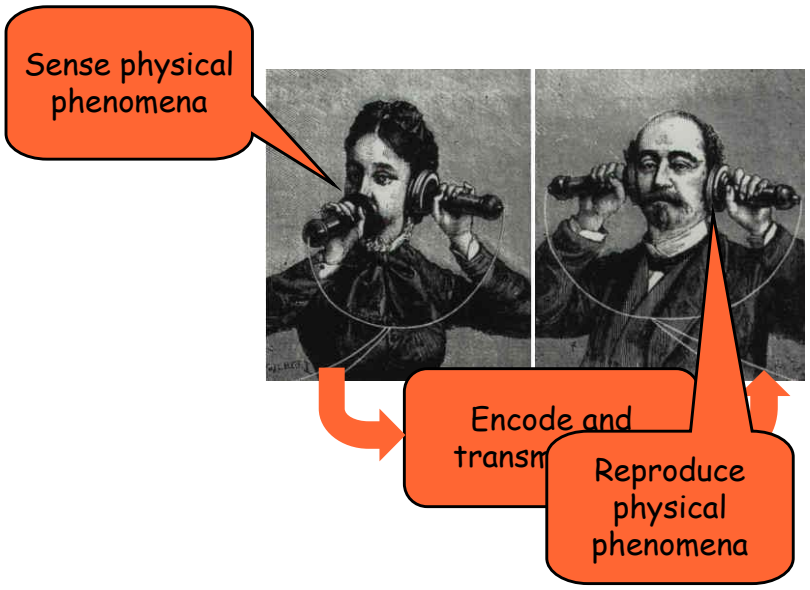
- Or, unabashed request for help.

Basic Human Need

An Abstract Communication Device

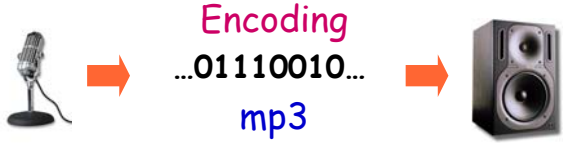


An Abstract Communication Device

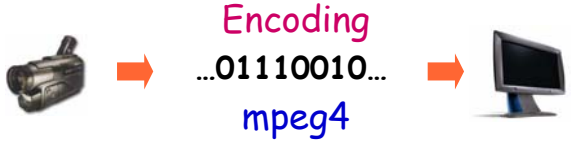


Communication: a CS point of view

audio



video



Can we do better?

- Audio: sound waves
  - Microphone
  - Speaker
- Video: light
  - Camera/CCD
  - Display
- Pario: 3D model
  - Multiple cameras
  - ?

Can we do better?

- Audio: sound waves
  - Microphone
  - Speaker
- Video: light
  - Camera/CCD
  - Display
- Pario: 3D model
  - Multiple cameras
  - Claytronics

An Advertisement from 2012

For movie see www.cs.cmu.edu/~claytronics/movies/cardesign.wmv

What we need to do

Today

And don't forget …

Today Tomorrow

And, of course, movement

A Computer Architects View

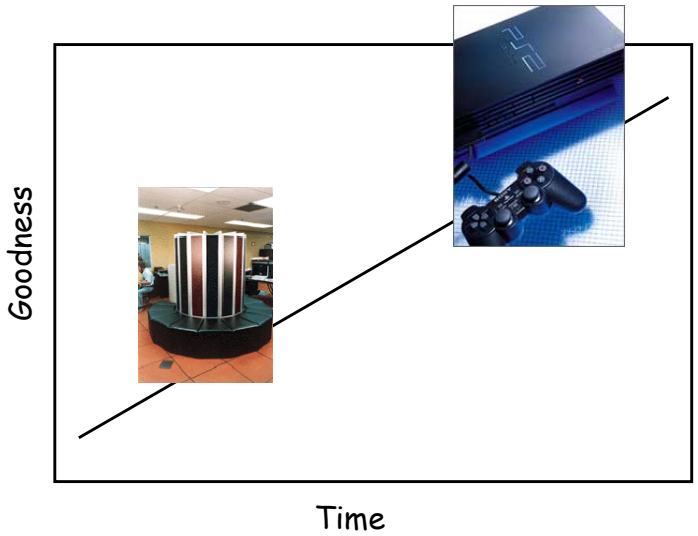
- Human need:

  what we want to do

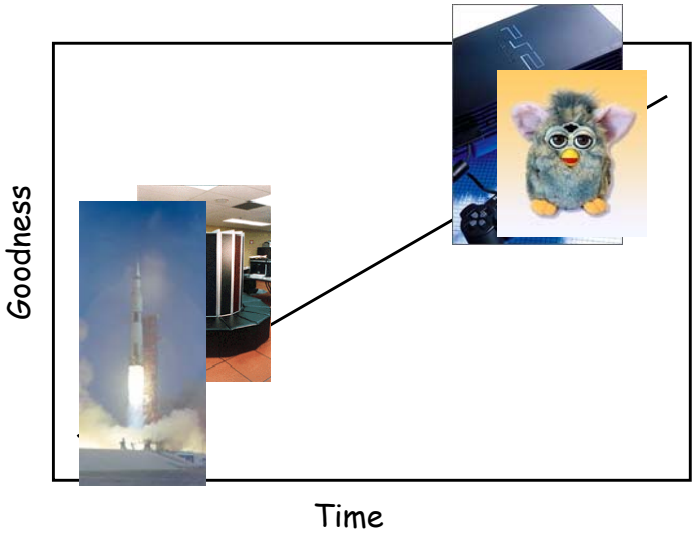
- Moore's law:

  what we can do

Moore's Law



Moore's Law



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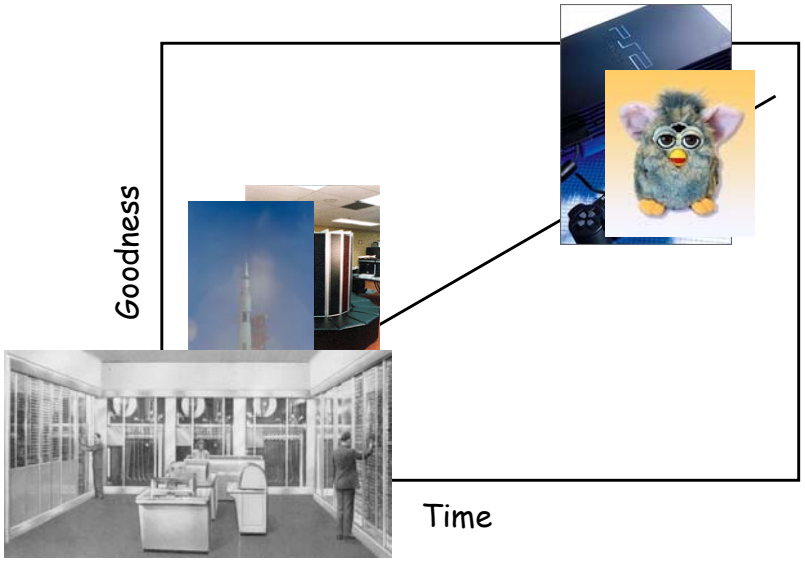
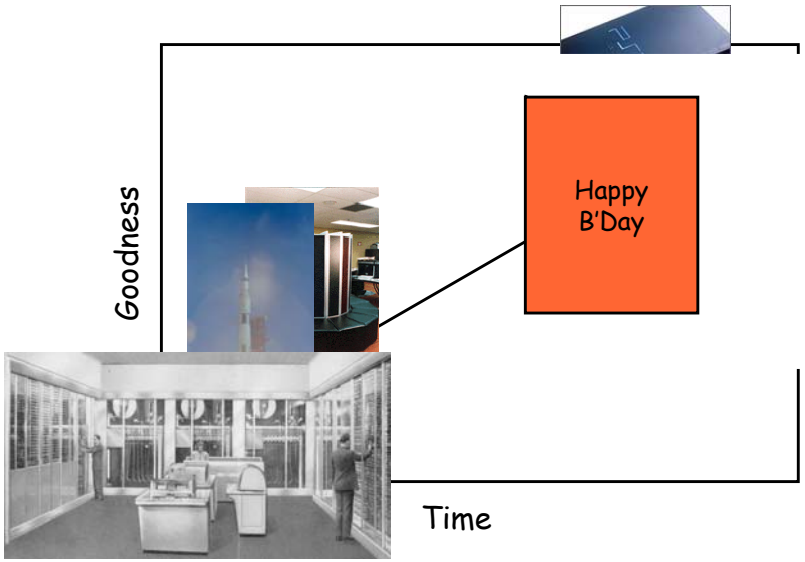


Moore's Law ?



Where are we in 50 years?

	1949 Eniac	2003 greeting card	2050 Programmable matter
Cost	5M-23M (2002 $)	1$	1 millicent
Weight	30 tons	1 oz	20 μg
Volume	450 M^3	1 cm^3	1 nm^3?? (1 μm^3)
Power	200KW	20mW	2 attowatts
Cycle time	>200μs	25ns	2 picosec
Storage	<800B	4KB	16KB

Cogent arguments for both sooner and later exist

Claytronics

- A programmable material…
- …with actuation and sensing…
- …that can morph into shapes under software control…
- …and in reaction to external stimuli

For Movie see: www.cs.cmu.edu/~claytronics/slice-of-cardesign.avi

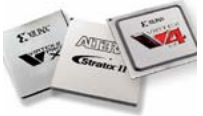
Types of "Programmable Matter"

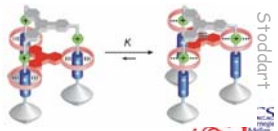
- Modular Robots
- Sensor Network
- Claytronics
- Synthetic Biology
- FPGAs
- Nanotechnology


Stoy


Guestrin

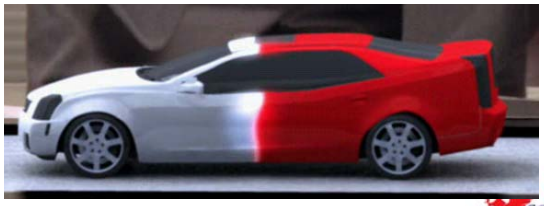
UT-Austin/UCSF




Stoddart

Scaling

- Goal: Form dynamic high-fidelity macroscale objects



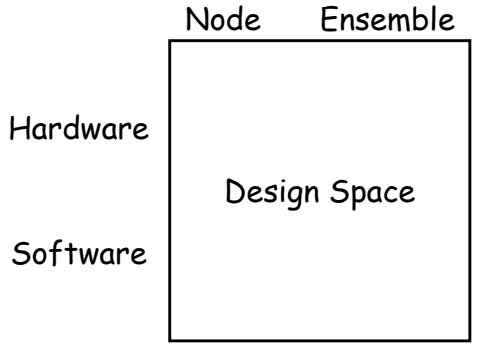
Scaling

- Goal: Form dynamic high-fidelity macroscale objects
- High-fidelity ⇒ sub-millimeter units
- Macroscale ⇒ millions of units
- Scaling: Down in size
  Up in number
- Method:
  Ensemble
  Effect

Node Requirements

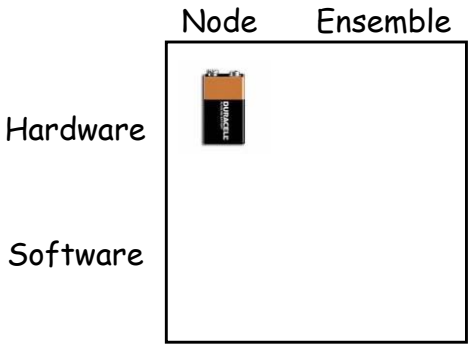
- Each node must have
  - Computation+Memory
  - Communication
  - Energy Storage
  - Sensing
  - Actuation
  - Adhesion
  - Display
- Yet, scaling demands nodes be:
  - Simple
  - Small
- Ensemble Axiom:
  A node should include only the functionality necessary to achieve the desired ensemble.

Challenges



- Challenges are all intertwined
  - Hardware/Software trade-offs
  - Ensemble Axiom
- Example: Energy

Challenges



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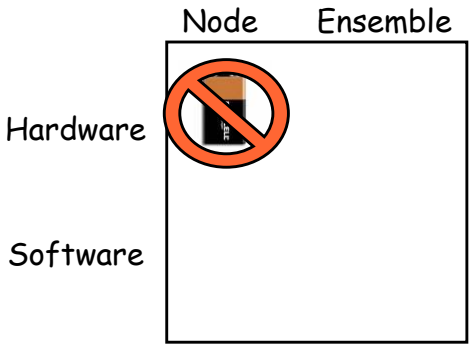

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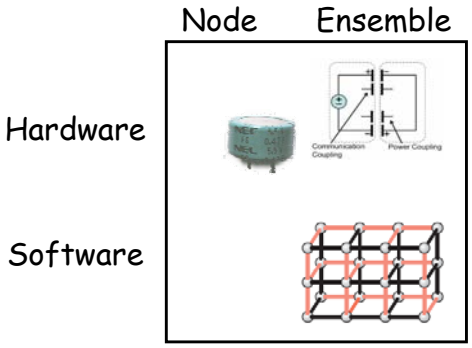

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  - Hardware/Software trade-offs
  - Ensemble Axiom
- Example: Energy

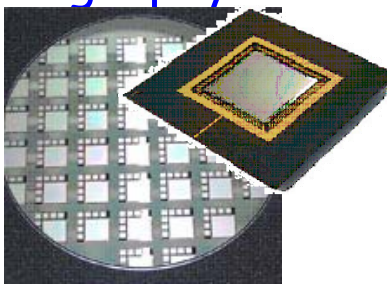
One Possible Path

Today Tomorrow

Harness Photolithography

- Use Moore's law!
- Challenge:

  How to create a 3D object from a 2D process?



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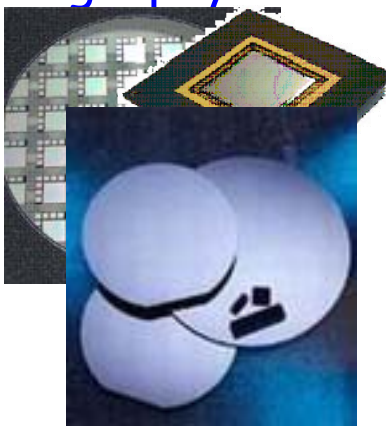

- Start with standard Wafer

Harness Photolithography

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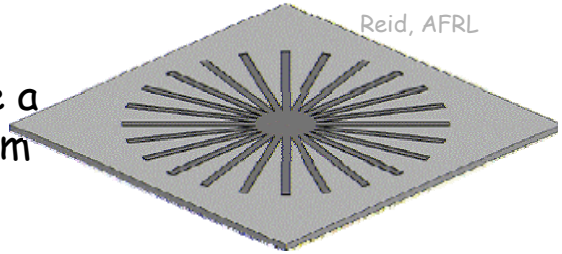

- Start with standard Wafer
- Create our circuits in a special pattern

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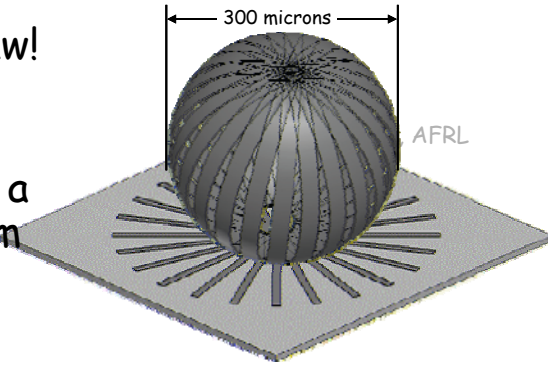

- Start with standard Wafer
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- Post-process to create sphere

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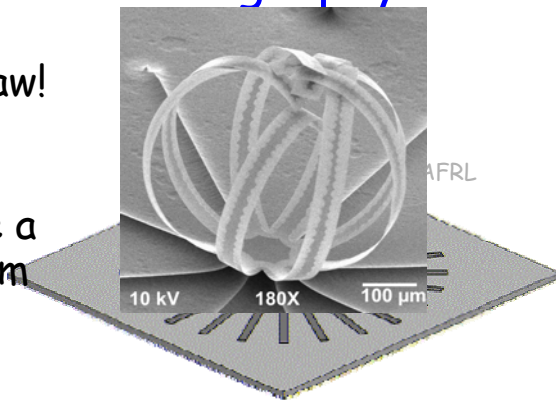

- Start with standard Wafer
- Create our circuits in a special pattern
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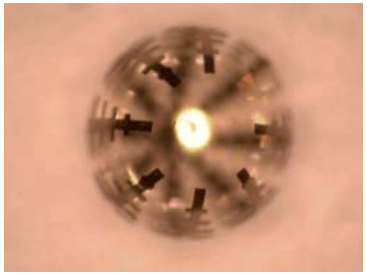
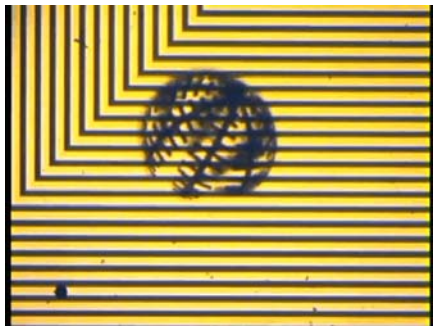
Some recent progress





Rob Reid, AFRL

A sanity check

1 mm diameter sphere

Mass < 1 mg

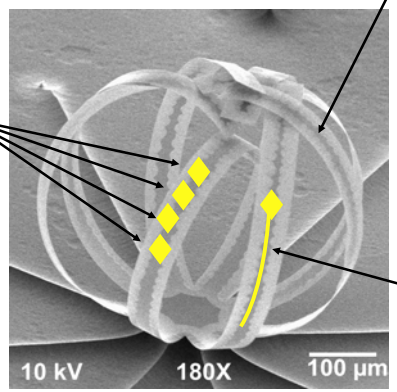
Computation Capability

8086 Processor with 256KB memory

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

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

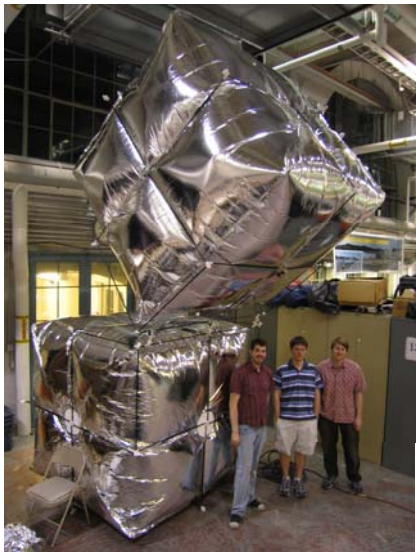
Power distribution

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

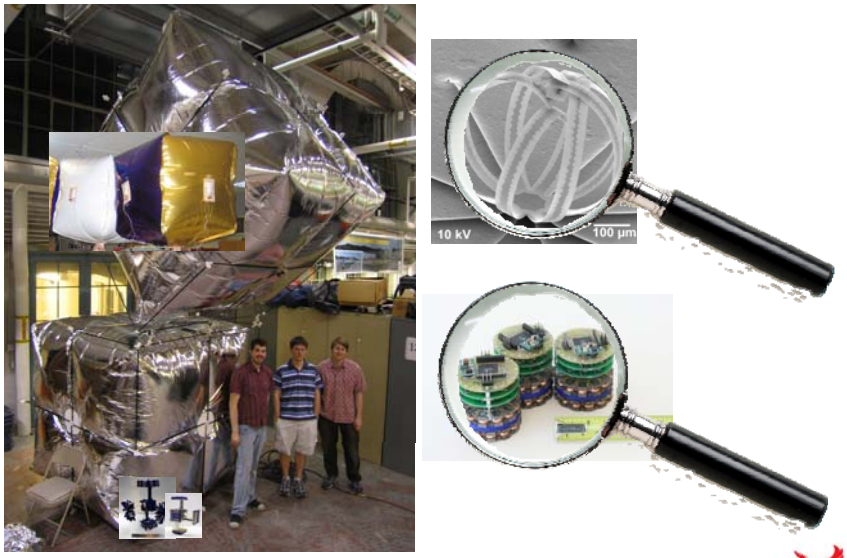
Research Plan

- Investigating hardware
  - Mechanisms
  - Systems
- Investigating Software
  - Languages and models
  - Algorithms
  - Tools

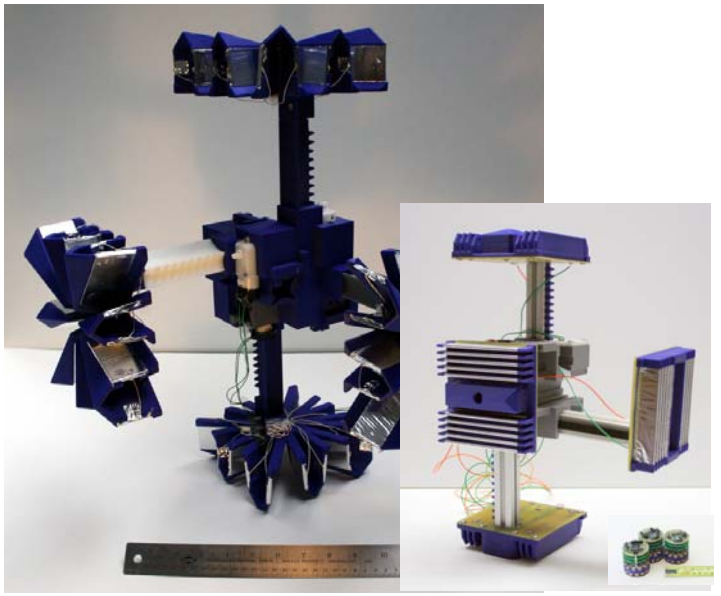
Investigating many size scales



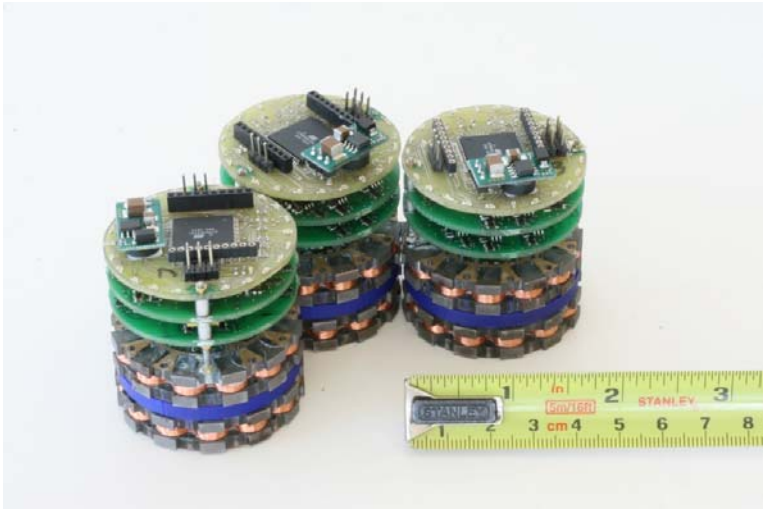
Investigating many size scales



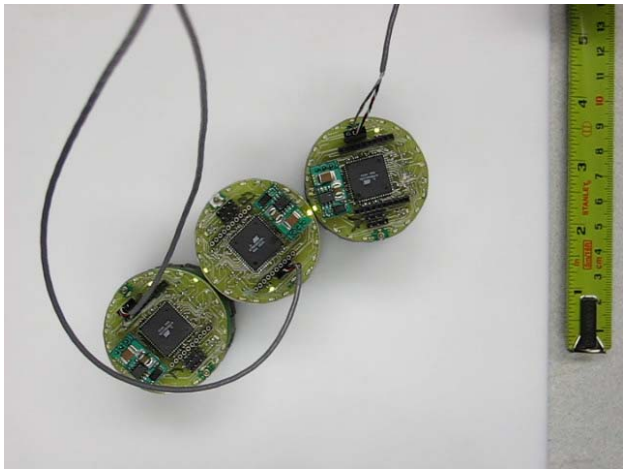
Stochastic Catoms



Magnetic Based Catoms

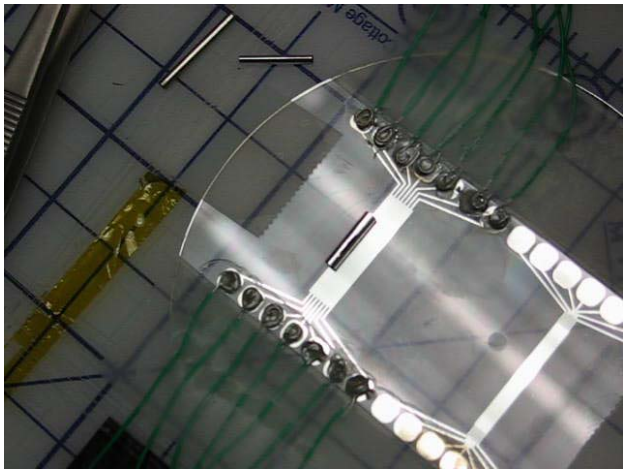


Ensemble Effect & Motion



For movie see: www.cs.cmu.edu/~claytronics/movies/3catoms.avi

Initial Experiments at <1mm-scale



For movie see: www.cs.cmu.edu/~claytronics/movies/es-tube.avi

What about the software?

Today Tomorrow

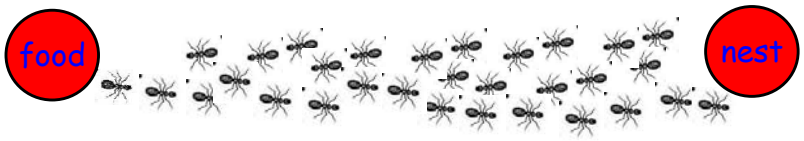
Two Broad Problem Areas

- 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?

- Let's focus on the ensemble

"Emergent Behavior"

- Incredibly seductive
- Witness ants



- They proceed from nest to food and back via pheromone trail

"Emergent Behavior"

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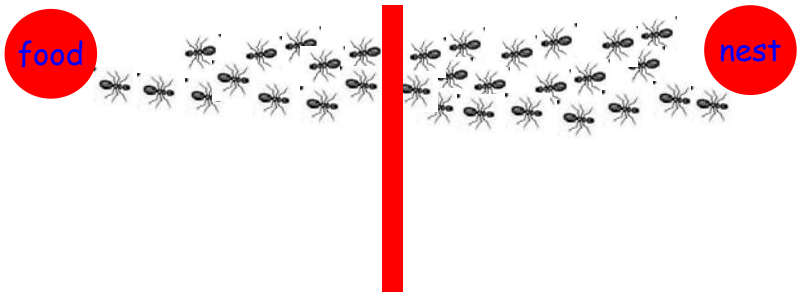
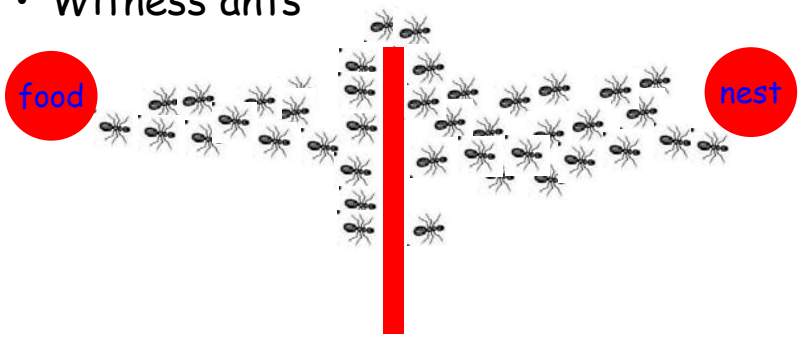
- Witness ants



- What happens when it is blocked?

"Emergent Behavior"

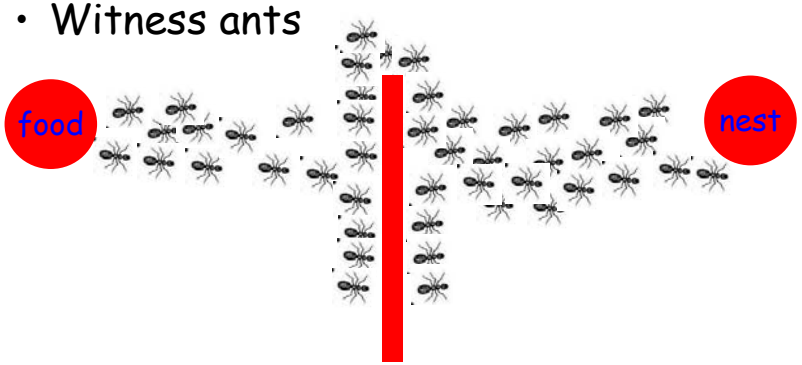
- Incredibly seductive
- Witness ants



- Ants that hit obstacle turn right or left randomly!

"Emergent Behavior"

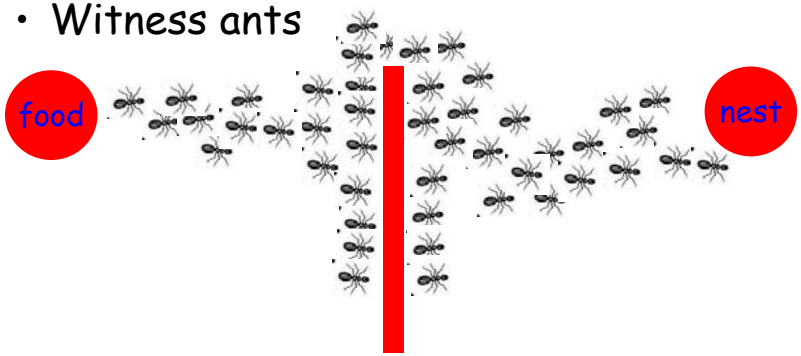
- Incredibly seductive
- Witness ants



- Ants prefer to follow a path with pheromones on it.

"Emergent Behavior"

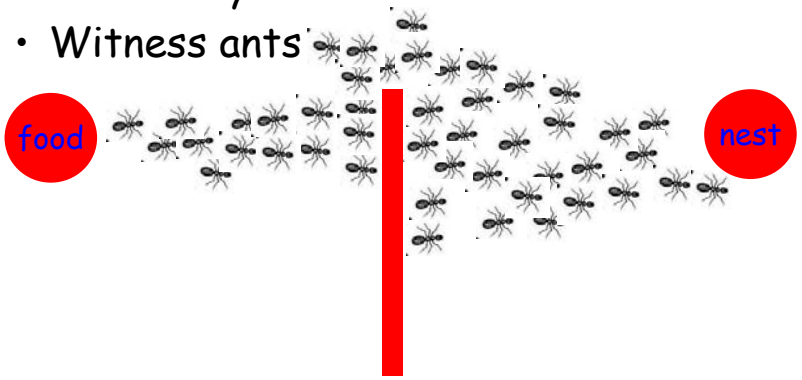
- Incredibly seductive
- Witness ants



- Shortest path has more pheromones on it

"Emergent Behavior"

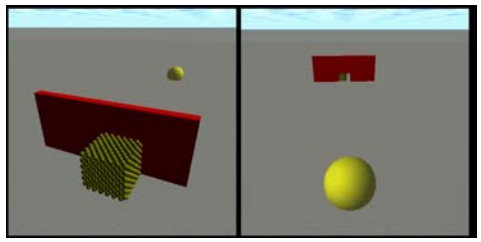
- Incredibly seductive
- Witness ants



- Voila: They find the shortest path!

Emergent Engineering

```
moveAround( X, Y, Point ) :-
    neighbor( X, Y ),
    brightness( X, N ),
    brightness( Y, M ),
    vacant( Y, Point ),
    N <= M.
```

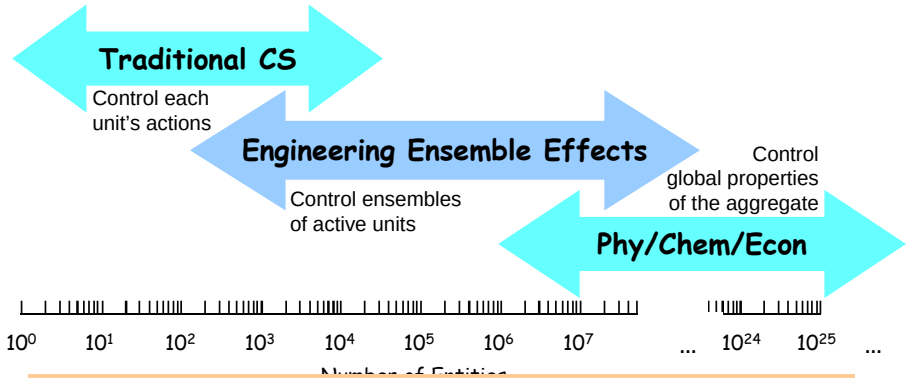


- Attributes:
  - Ensemble level thinking
  - Concise understandable program
  - Scalable
  - Amenable to proof
  - Robust to failure and environmental uncertainty

For movie see: www.cs.cmu.edu/~claytronics/movies/phototropic1.mpg

Thermodynamics for Computing

Aggregation fundamentally alters purpose and capabilities
⇒ causes a control barrier as systems scale



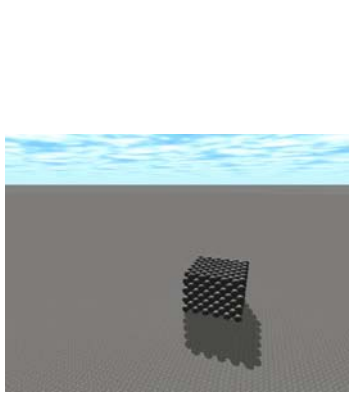
Goal: Understand methods for programming the ensemble as a whole.

Solution Attributes

- Programs must be:
  - Ensemble centric
  - Uncertainty tolerant
  - Concise
  - Support formal methods
- Tools must:
  - Compile ensemble-program into unit program
  - Harness distributed nature of problem and solution

Some Recent Work

- Programming languages
  - Oriented to the ensemble
  - 20x shorter programs
  - At least as efficient!
- Algorithms
  - For shape morphing
  - Finding out where you are
  - Deciding how to get where you want to be
- Tools
  - For debugging distributed systems
  - Visualizing massive numbers of particles



For these and other simulations,
see www.cs.cmu.edu/~claytronics/movies

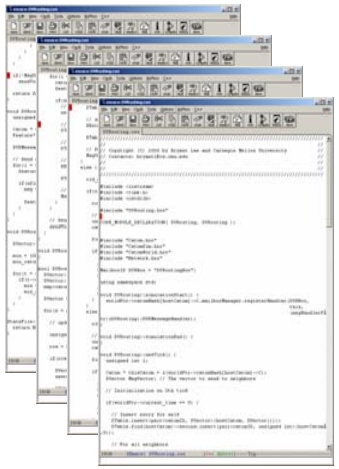
Something Concrete?

- What programming model?
- What language?
- How to measure effectiveness?

- Imperative approach currently in use
  - Must program each unit
  - Must handle messages, links
  - Changing topology creates compications
  - Focused on the unit

A simple "Walk"

C++ vs. Meld



```
dist(S, D) :-
        at(S, P),
        D = |P - destination()|.

farther(S, T) :-
        neighbor(S, T),
        dist(S, D),
        dist(T, D'),
        D >= D'.
moveAround(S,T,U) :-
        farther(S, T),
        farther(S, U),
        T != U.
```


Example execution & Base Facts

```
neighbor(b, a)
neighbor(b, c)
at(b, point2)
```

```
neighbor(a, b)
neighbor(a, c)
at(a, point1)
```

```
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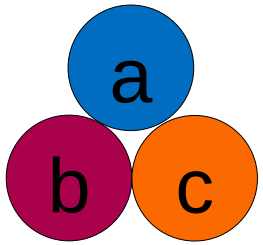


```
neighbor(c, a)
neighbor(c, b)
at(c, point3)
```


Example execution & Base Facts

```
~~neighbor(b, a)~~
neighbor(b, c)
at(b, point2)
```

```
~~neighbor(a, b)~~
neighbor(a, c)
~~at(a, point1)~~
at(a, point1)
```

```
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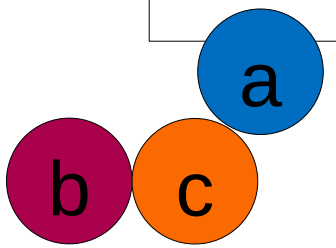
        T != U.
```




```
neighbor(c, a)
neighbor(c, b)
at(c, point3)
```

Some Details

- Automatic distribution of facts, rules

```
farther(S, T) :-
        neighbor(S, T),
        dist(S, D),
        dist(T, D'),
        D >= D'.
```

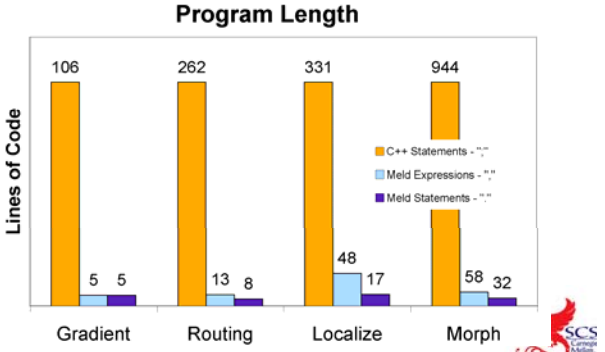
```
farther-remote(S, T, D') :-
        neighbor(T, S),
        dist(T, D').

farther(S, T) :-
        farther-remote(S, T,D'),
        dist(S, D),
        D >= D'.
```

- Handling deletion
- Messaging
- Side-effects

Can this possibly work?

- Amazingly:
  - Programs 20x smaller!
  - Message, bytes sent, memory used, and cpu used all scale at least as well as C++ program



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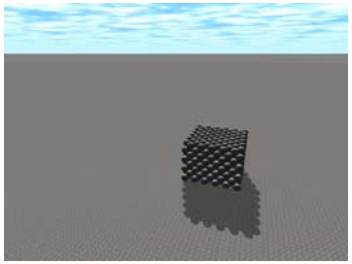
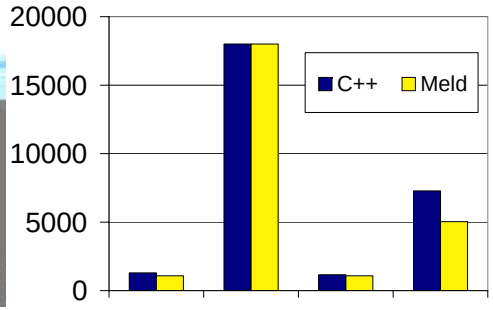
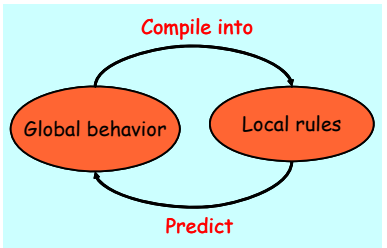




For movie see: www.cs.cmu.edu/~claytronics/movies/cube2man.mpg

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



My Vision for the future

- Imagine:
  - 3D Fax machines
  - Kinesthetic CAD tools
  - 3D TV
  - Surgical preparation
  - New drug design
  - Pario games
  - "In person" remote meetings
  - Doctors make house calls
  - Fire fighters out of harms way
  - …

My Vision for the future

- Imagine:
  - Imagination is the main limitation
- Not just Claytronics!

- Give the power of programming to matter!

Challenge Problem(s)

- Intermediate uses for two classes of programmable matter:
  - 1mm particles, not very cohesive
  - 1cm particles, sort of cohesive
- Suggestions?