Claytronics

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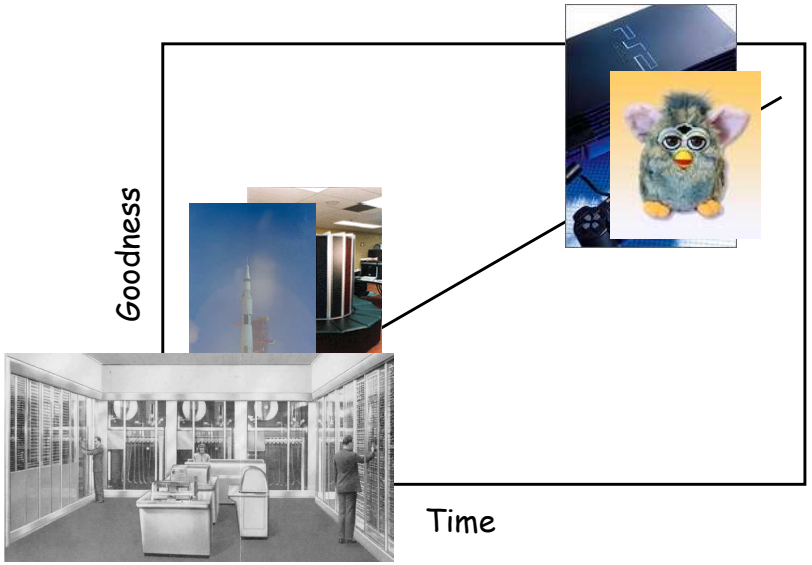
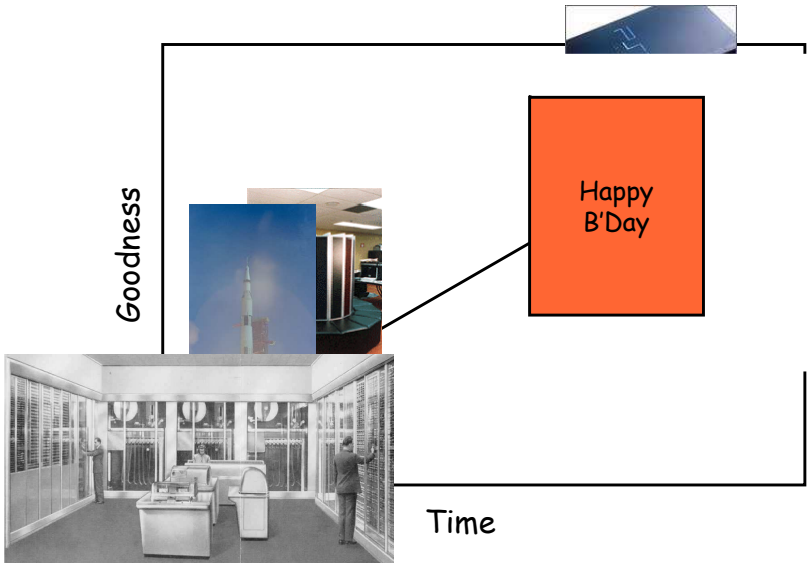
RSS – 6/11/05

Joint work with Todd Mowry
and
Baker, Campbell, Gibbons, Guestrin, Hoburg, Kufner,
Lee, Pillai, Seshan, Sitti, Sukthankar, Veloso,
Kirby, Aksak, Bhat, Bowers, DeRosa, Rister, Stanos

Moore's Law



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

audio

Encoding

...01110010...

mp3

video

Encoding

...01110010...

mpeg

pario

Latin: *to bear, bring forth, produce; create, make, get*

Encoding

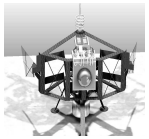
...01110010...

Science Fiction?

Science fiction?

Sensor Nets

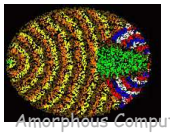
MEMS/Nanotech



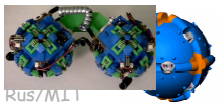
Fearing/UCB

Sitti/CMU

Amorphous Computing/ Emergent Behavior

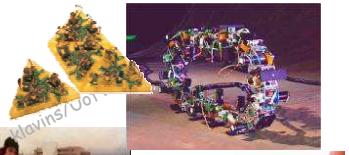


Amorphous Computing/MIT



Rus/MIT

Modular Robots



Yim/Parc

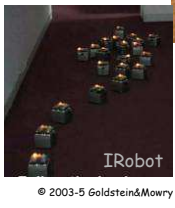
Materials

Flyn

Flynn/SRI

Multi-Robot Teams

Rabinett&BBC



IRobot

Veloso/CMU

Claytronics/CMU

Claytronics & Catoms

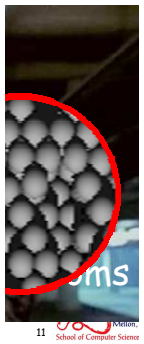
Not AI – Just the system to render 3D dynamic objects

Terminator 2: Judgment day trailer

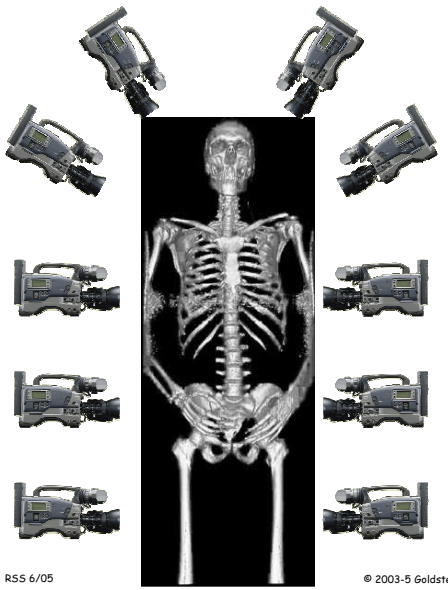
Claytronics & Catoms

Claytronics & Catoms

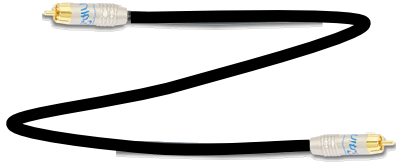
- Ensemble of elements which each contain
  - Processor
  - Communication
  - Power
  - Sensing
  - Display
  - Actuation
  - Programmable adhesive
- Can be programmed to form interesting dynamic shapes and configurations.
- A system for exploring the computer science of programmable matter



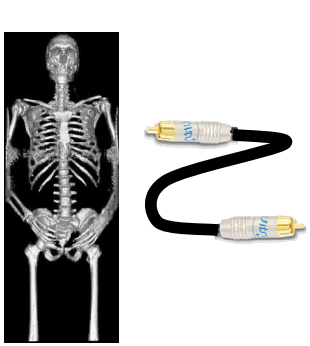
Capture

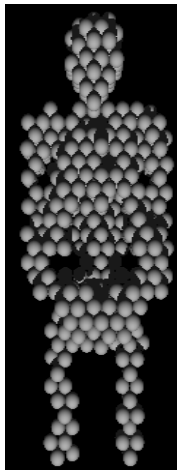


1. Capture 3D Object
2. Encode 3D model
3. Transmit data



Reproduce

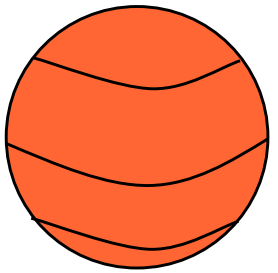




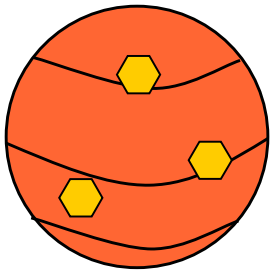
3-5 years

5+ years

A Claytronic Atom: Catom



A Claytronic Atom: Catom



The outside is studded with contacts

A Claytronic Atom: Catom

Each catom can display an image/pixel

Inside the Catom

Inside the Catom

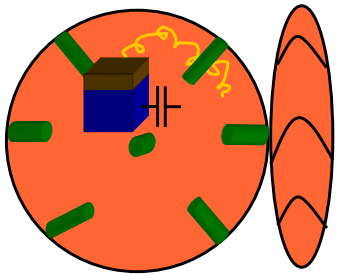
Inside the Catom

Communication

Antenna

SuperCap

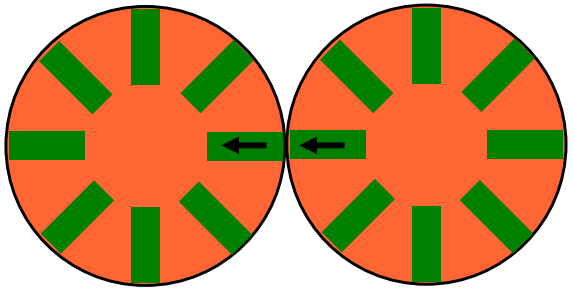
Computer



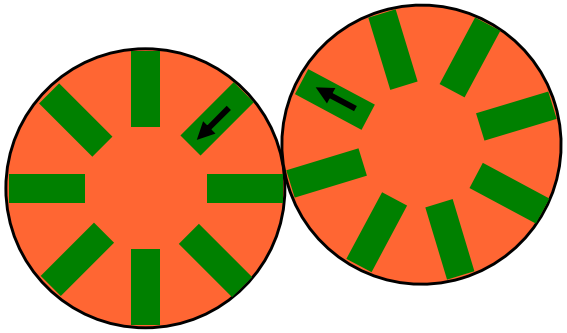
Programmable Magnets

We can buy these today!

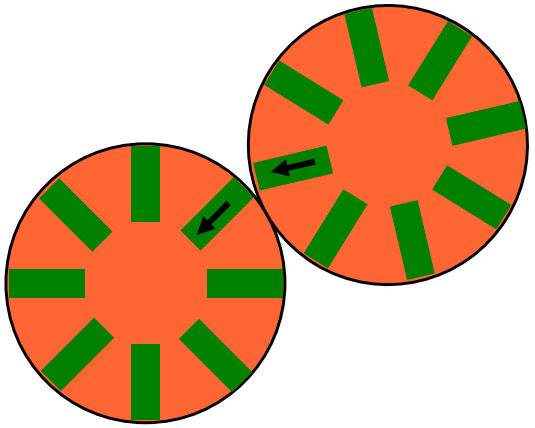
Moving the Catom



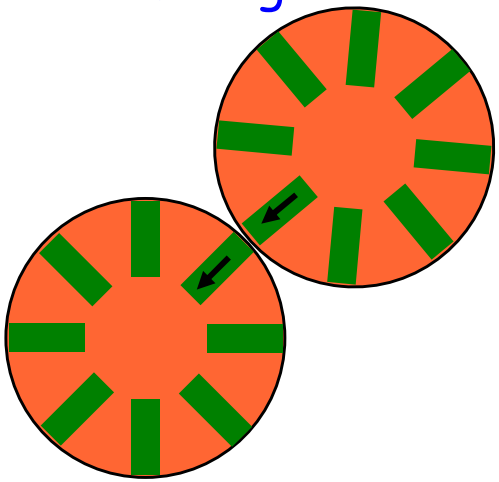
Moving the Catom



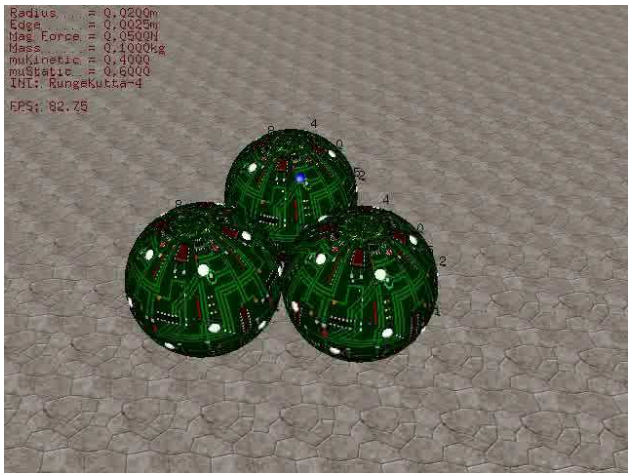
Moving the Catom



Moving the Catom

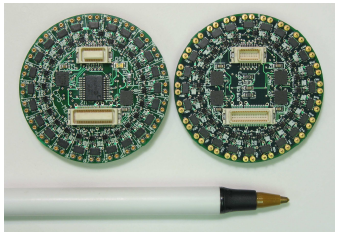


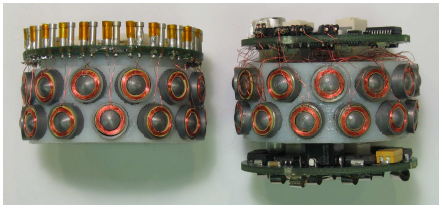
Simulation of Future Catoms

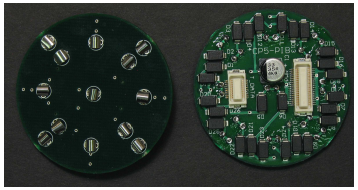


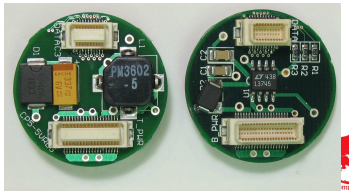
Claytronics REV4

- 2D system
- Modular design









REV3

Magnets For Locomotion

Design Principles

- Goal: Scaling
  - Up (in numbers)
  - down (in size)
- sub-goals:
  - simplicity
  - robustness
  - homogeneity
  - no static power
  - distributed, but catom local computation
  - low complexity algs

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Some consequences:

- No moving parts
- Genderless, unary connectors
- No self-contained power source
- New programming paradigm

The Ensemble Axiom

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  - Up (in numbers)
  - down (in size)
- Consequences:
  - No moving parts
  - Genderless, unary connectors
  - No self-contained power source
  - New programming paradigm

The Ensemble Axiom:

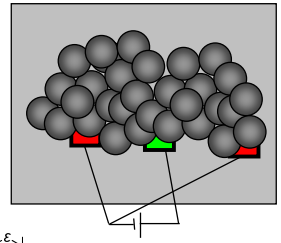
A catom should include only enough functionality to contribute to the desired functionality of the ensemble

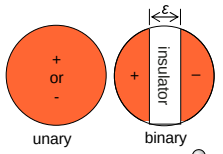
A day in the life of a catom

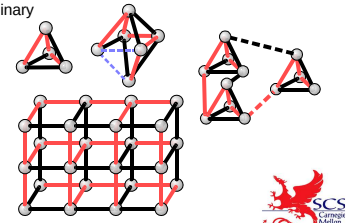
- Get power!
- Localize
- Establish a network
- Get to work
  - move to desired location
  - If on surface, display video, …

The Robot is the tether

- Catoms have no battery
- They cooperatively create a power grid
- Challenge:
  - connectors are
    - unary
    - genderless
  - Requires two indep sub-graphs
    - V_{dd}
    - Ground







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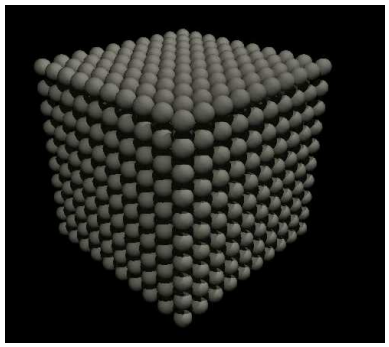
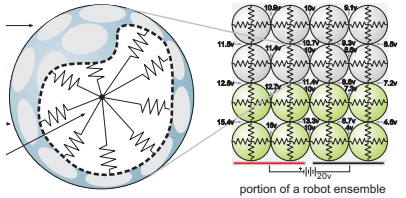


Multiphase Algorithm

- First, passive resister net
- Second, distributed environment/guid-oblivious algorithm
- Third, fix-up



portion of a robot ensemble

Multiphase Algorithm

- First, passive resister net
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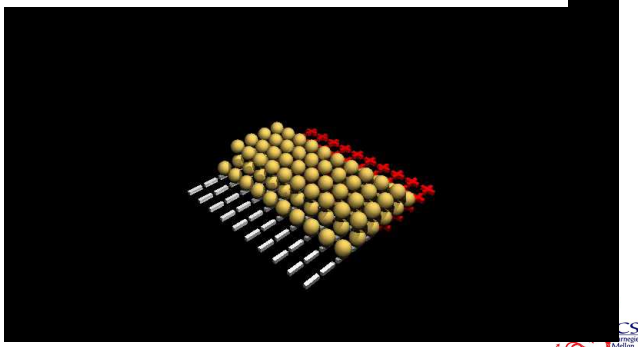

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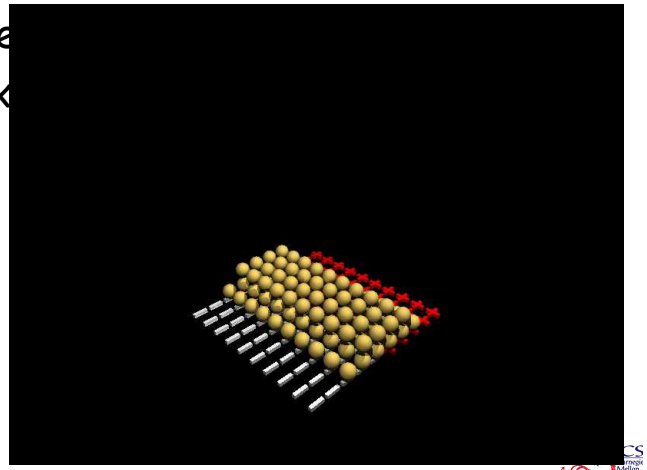


Algorithms Scale

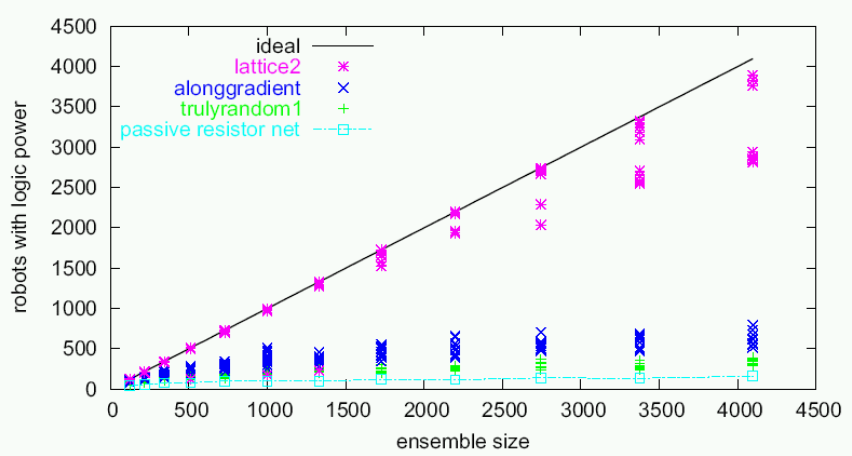
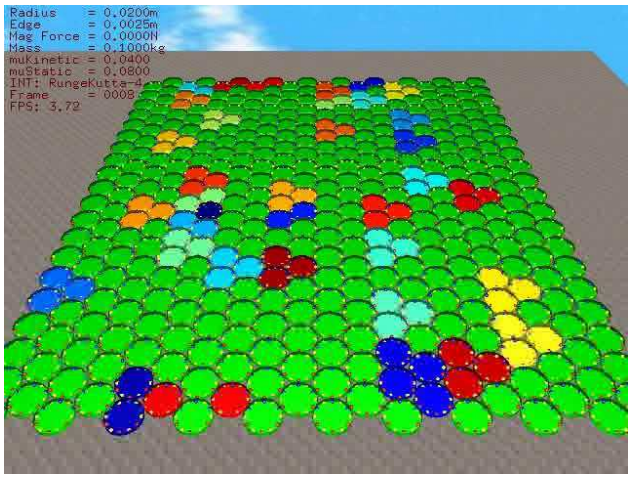


Fig. 11. *Robots energized (logic power) for three representative algorithms vs. ensemble size*

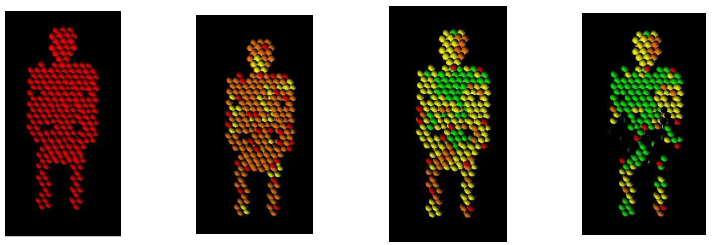
Distributed Localization



Scales sublinearly with diagonal of ensemble

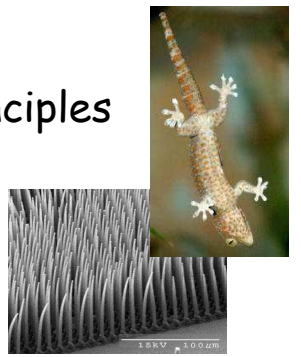
Next Step, Create Network

- Use simple local rules to form hierarchy
- 10 line program does this!
- Local only decisions → Global effect

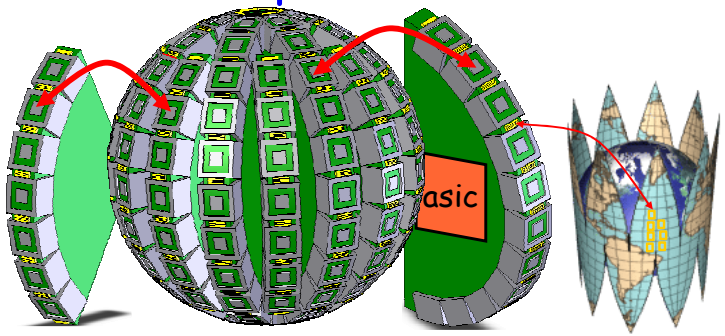


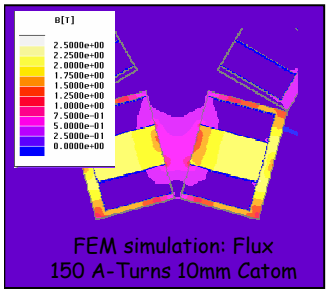
Getting There From Here

- Goal: Robust ensemble of millions of catoms
- Claytronics Design Principles
  - No Moving Parts
  - Local Control
  - No Static Power



Proposal for 3D





FEM simulation: Flux
150 A-Turns 10mm Catom

Catom diameter	Amp-Turns	Power (W)	Force (mN)	Weight (mN)
44mm	260	10	450	6420
20mm	150	3.3	78	192
10mm	250	6.6	50	24
10mm	150	2.8	33	24

Scaling of Claytronics

	Macro	Micro	Nano
Dimensions	>1 cm	>1 mm	<10 microns
Weight	10's gr	100's mg	<1 mg
power	<2 Watts	10's mW	10's nW
Locomotive mechanism	Programmable magnets / Electromagnets	Electrostatics	Aerosol
Adhesion mechanism	Nanofiber adhesives / Magnets	Programmable nanofiber adhesives	Molecular surface adhesion and covalent bonds
Manufacturing methods	Conventional manufacturing and assembly	Micro/Nano-fabrication and micro-assembly	Chemically directed self-assembly and fabrication
Resolution	Low	High	High
Cost	$$$/catom	$/catom	Millicents/catom

What about the software?

- Programming Models
- Distributed Planning
- Networking
- OS
- …

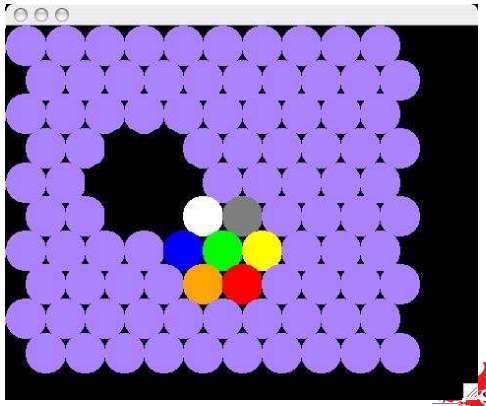
One example: Motion planning

Motion Planning Challenges

- Large Number of Catoms (~ 100k+)
- No central planner
- Physical Limitations
  - Maximum torque
  - Center of gravity
  - Structural stability
- Power/network connectivity
- Inaccuracies/failures

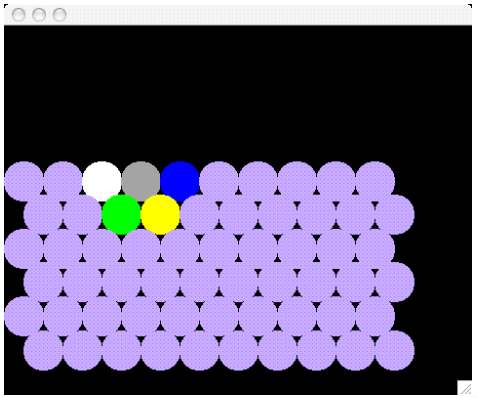
Hole Flow Methods

- Based on concept from moving tile puzzles or semiconductor physics
- Planning is scale-independent
- Three primitives
  - move
  - create
  - destroy



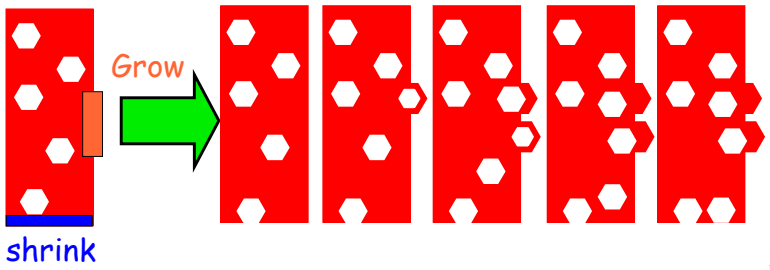
Motion Planning with Holes

- Create raises contour



Motion Planning with Holes

- Create raises contour
- Destroy lowers contour
- Holes circulate freely through structure (Brownian motion/gas molecules)



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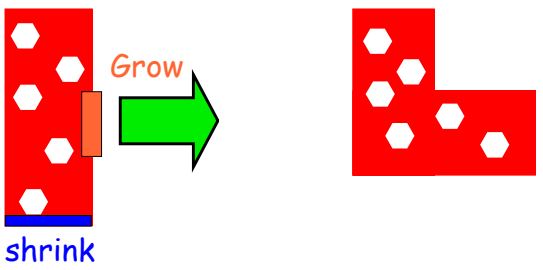
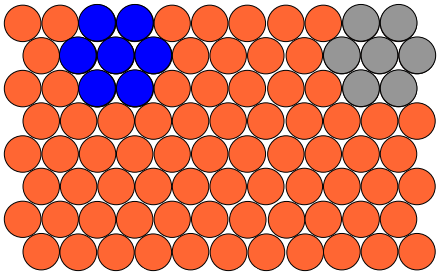


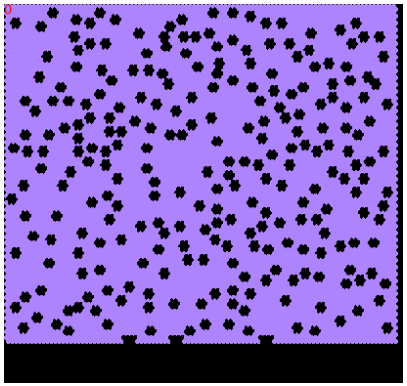
Keeping it local and smooth

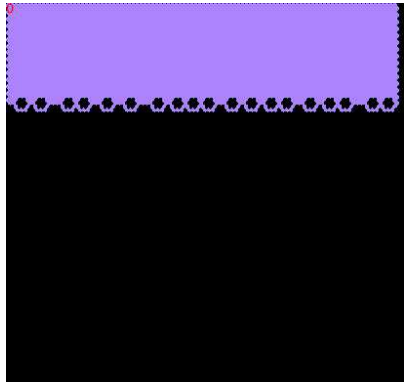
- Hole motion based on local rules
- How do we control the global effect?



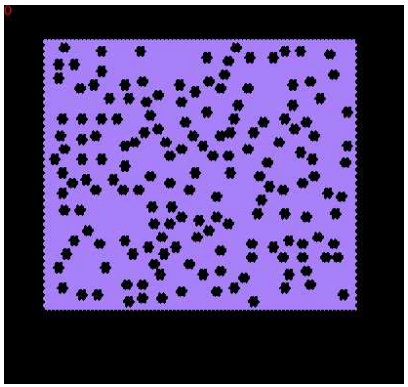
- Use ideas from self-organized criticality to do local Collapsing/smoothing

Effect of criticality smoothing





Making a shape



Claytronics & Pario

- Open up an entire new application space
  - Antennas (Programmable Antennas)
  - Design (100x protein model)
  - Entertainment (interactive clay)
  - Interaction (telepario)
  - Rescue (paramedic on demand)
  - Metal Man (fault tolerant robotics)
- Vehicle for studying CS problem of the future:

  How do you design, program, maintain, and use a billion component system?

Claytronics

- Open up an entire new application space
- Vehicle for studying CS problem of the future:

  How do you design, program, maintain, and use a billion component system?
- Our Approach:
  - The Ensemble Axiom
  - Make scaling work for us
  - Exploit scale invariance
  - Design for scalability in both number & size: Millions of Micron-scale catoms