Three-Dimensional Directed Construction

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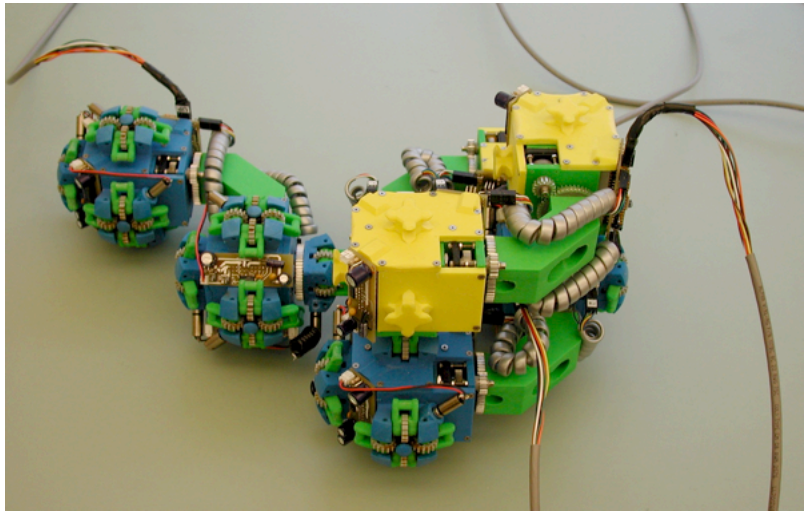
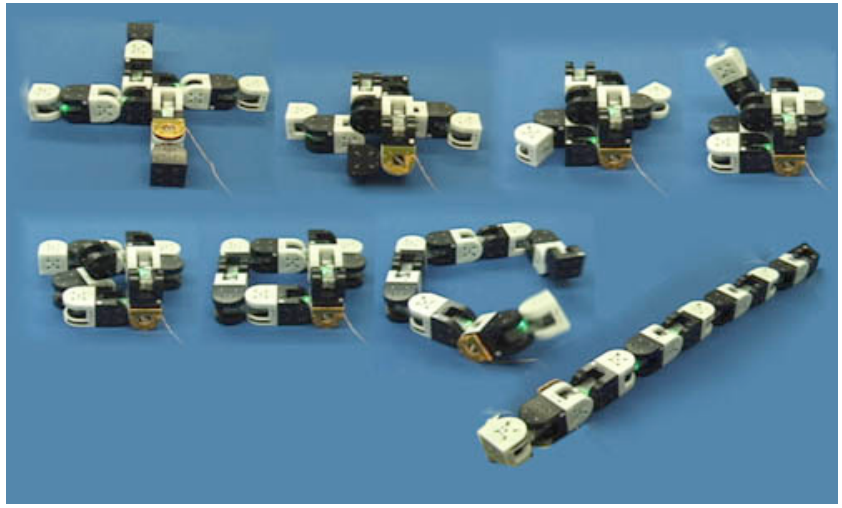
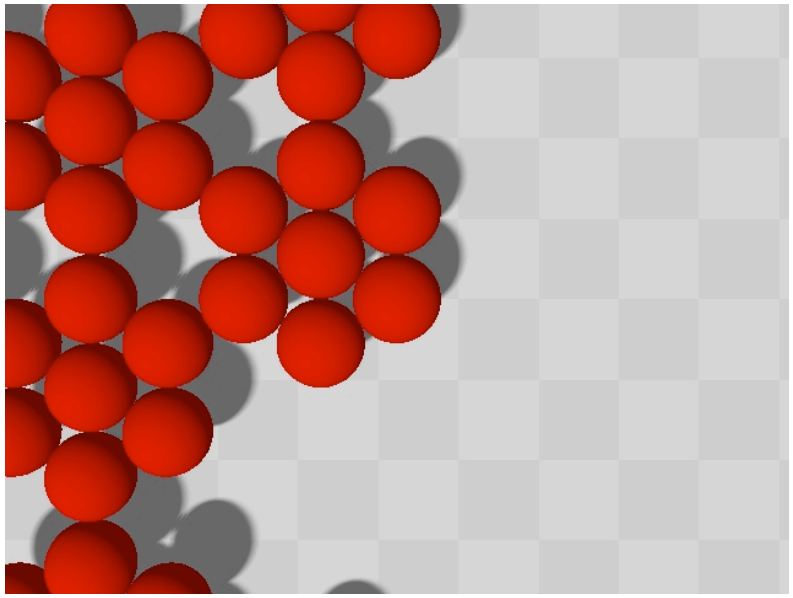


Molecule

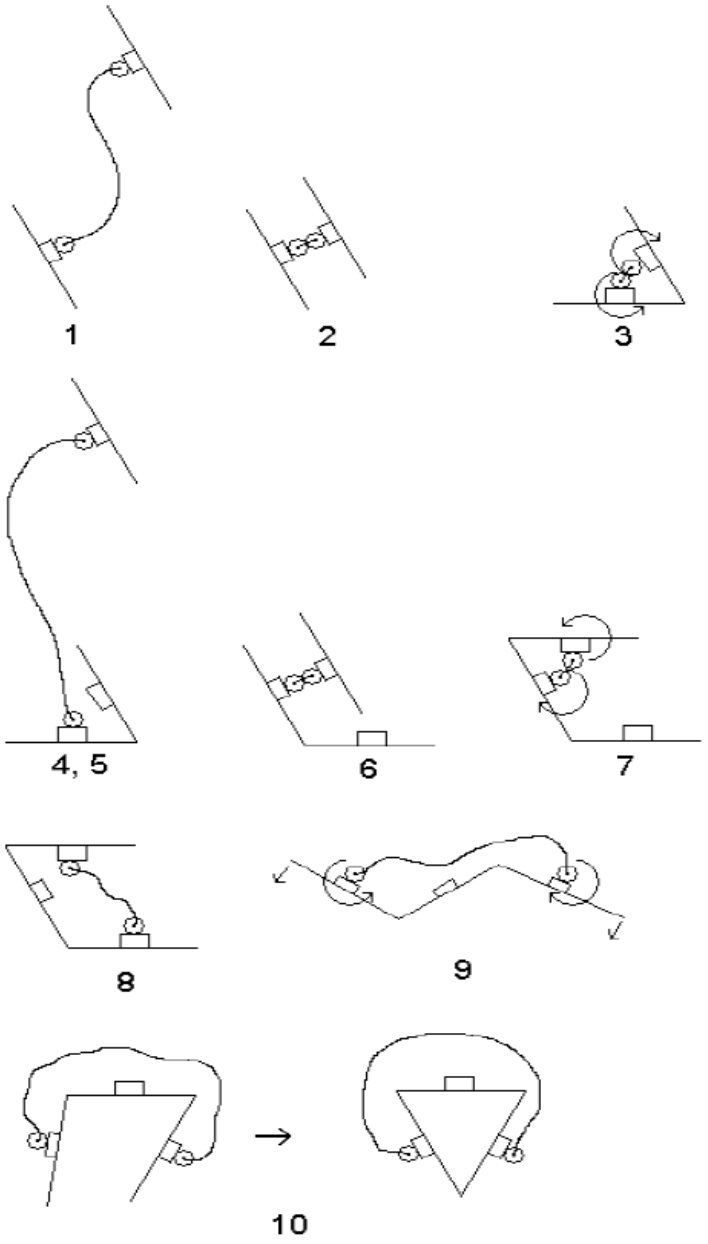


M-TRAN III



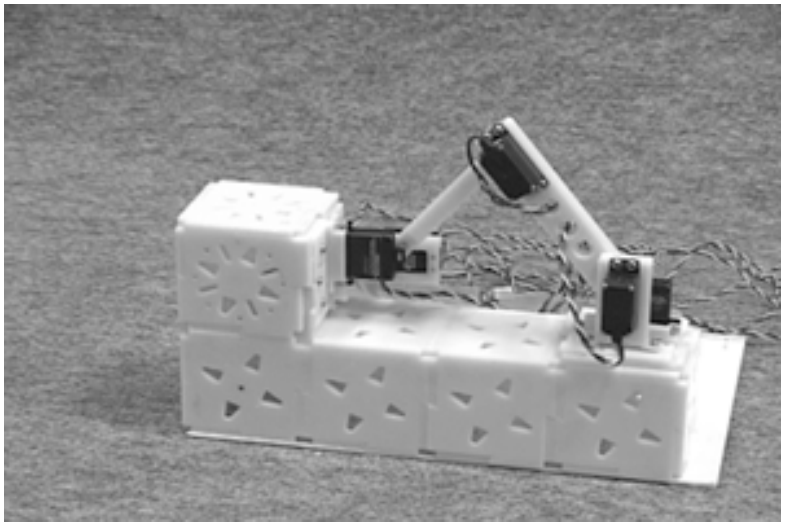
Claytronics


FOTOSEARCH

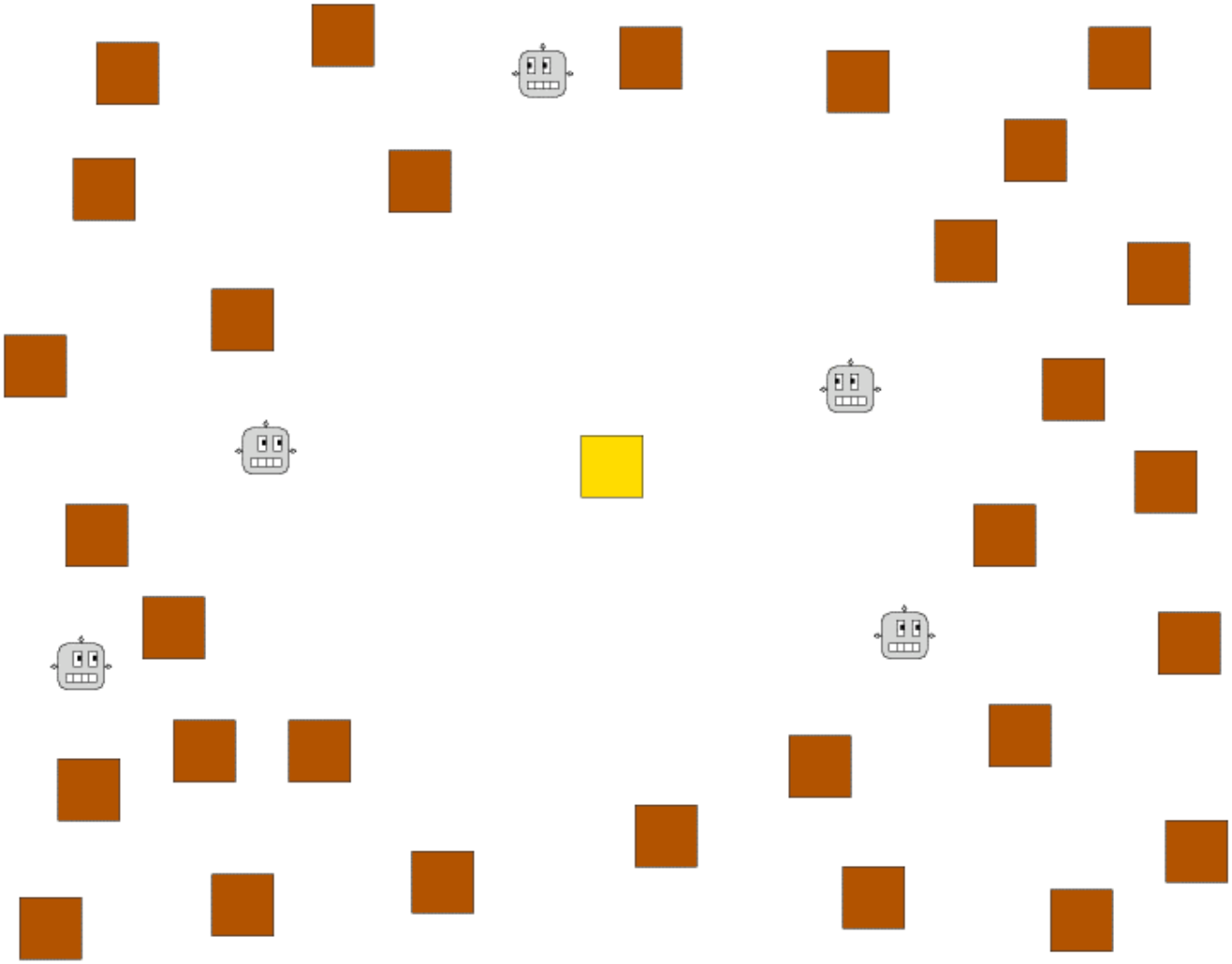


Everist, J., Mogharei, K., Suri, H., Ranasinghe, N., Khoshnevis, B., Will, P., & Shen, W. (2004). A system for in-space assembly. In *Proc. IROS 2004*, Sendai, Japan.

Terada, Y., & Murata, S. (2004). Automatic assembly system for a large-scale modular structure: hardware design of module and assembler robot. In *Proc. IROS 2004*, Sendai, Japan.



Focus on design of distributed algorithms



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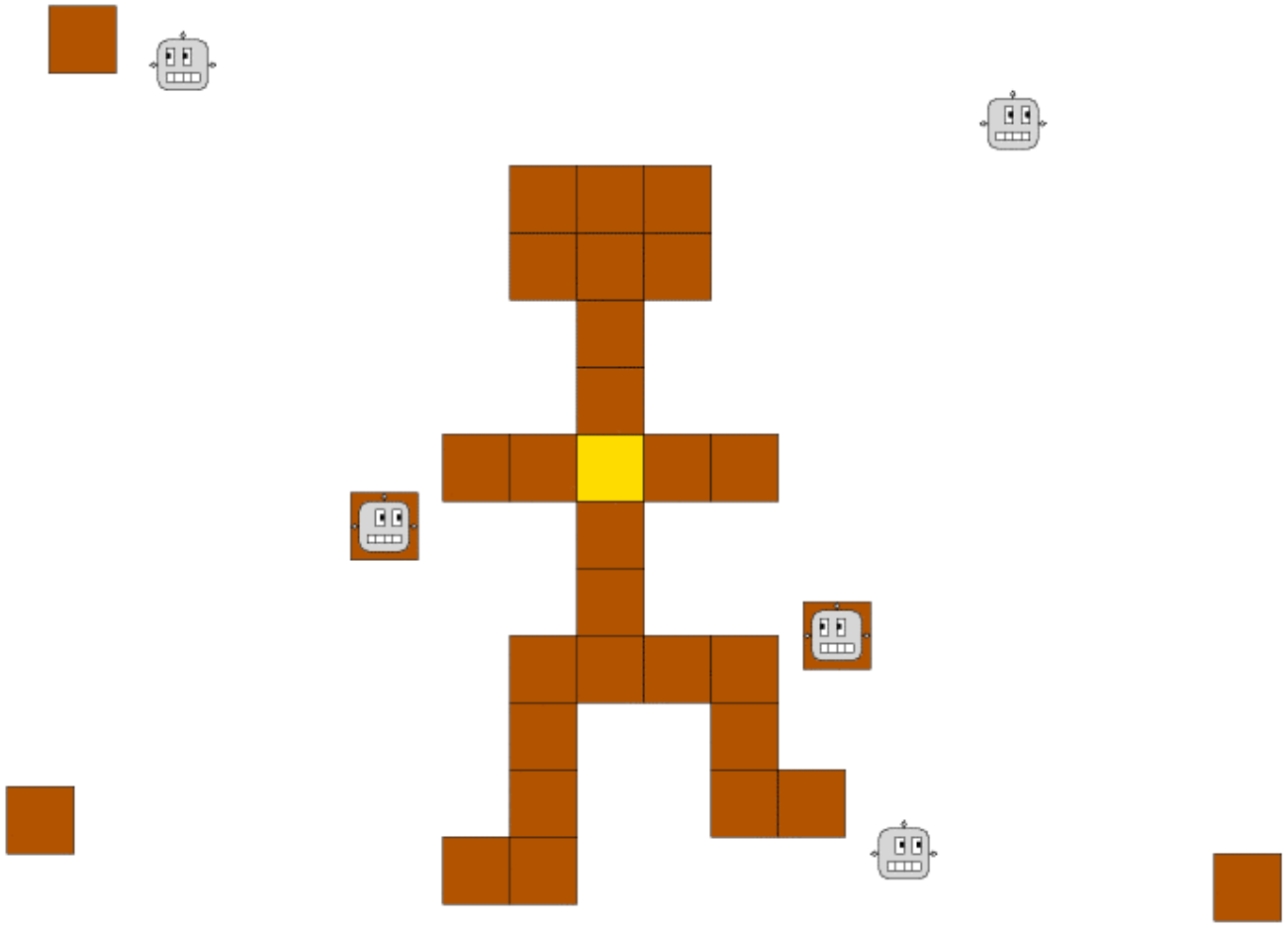
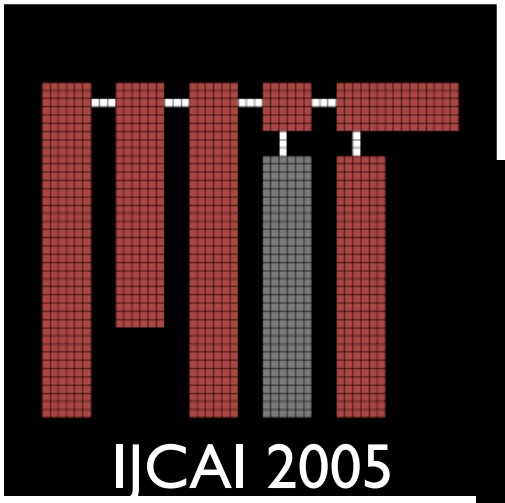
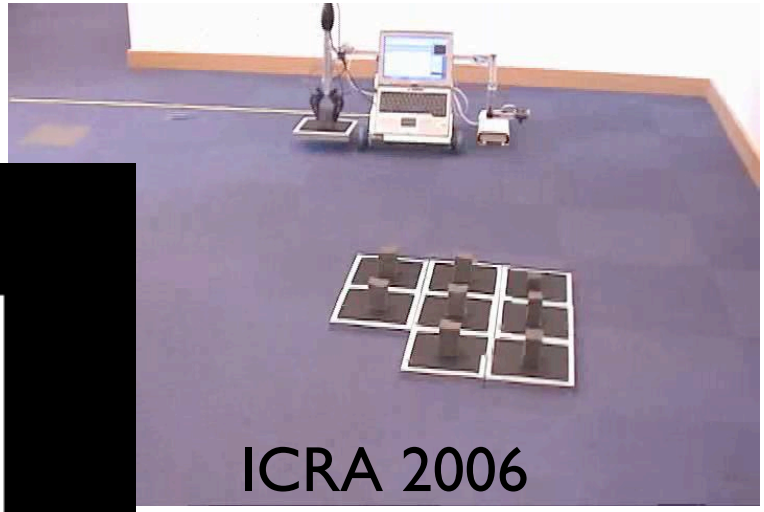


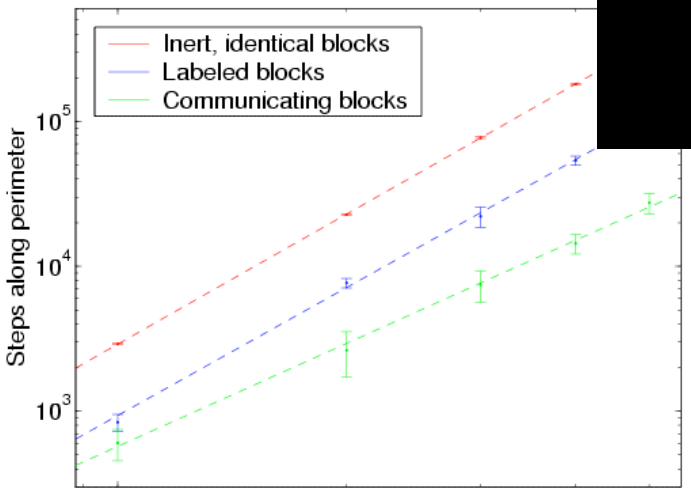
Focus on design of distributed algorithms



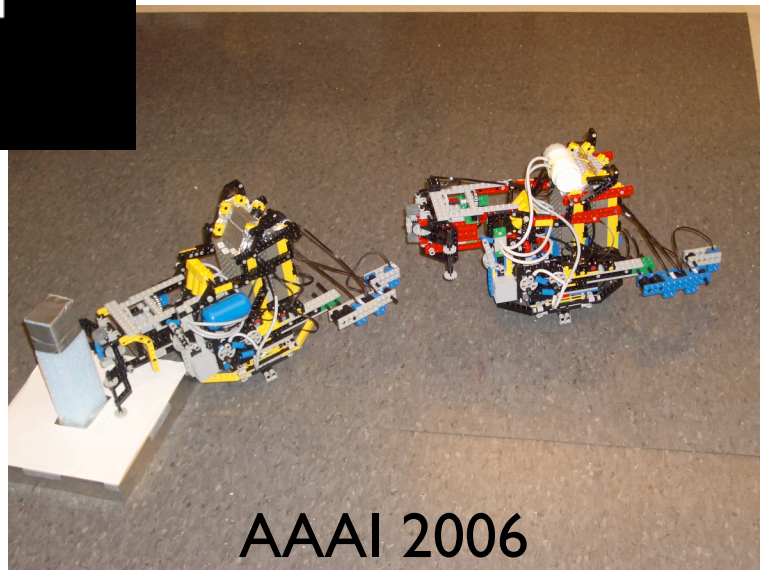
IJCAI 2005



ICRA 2006

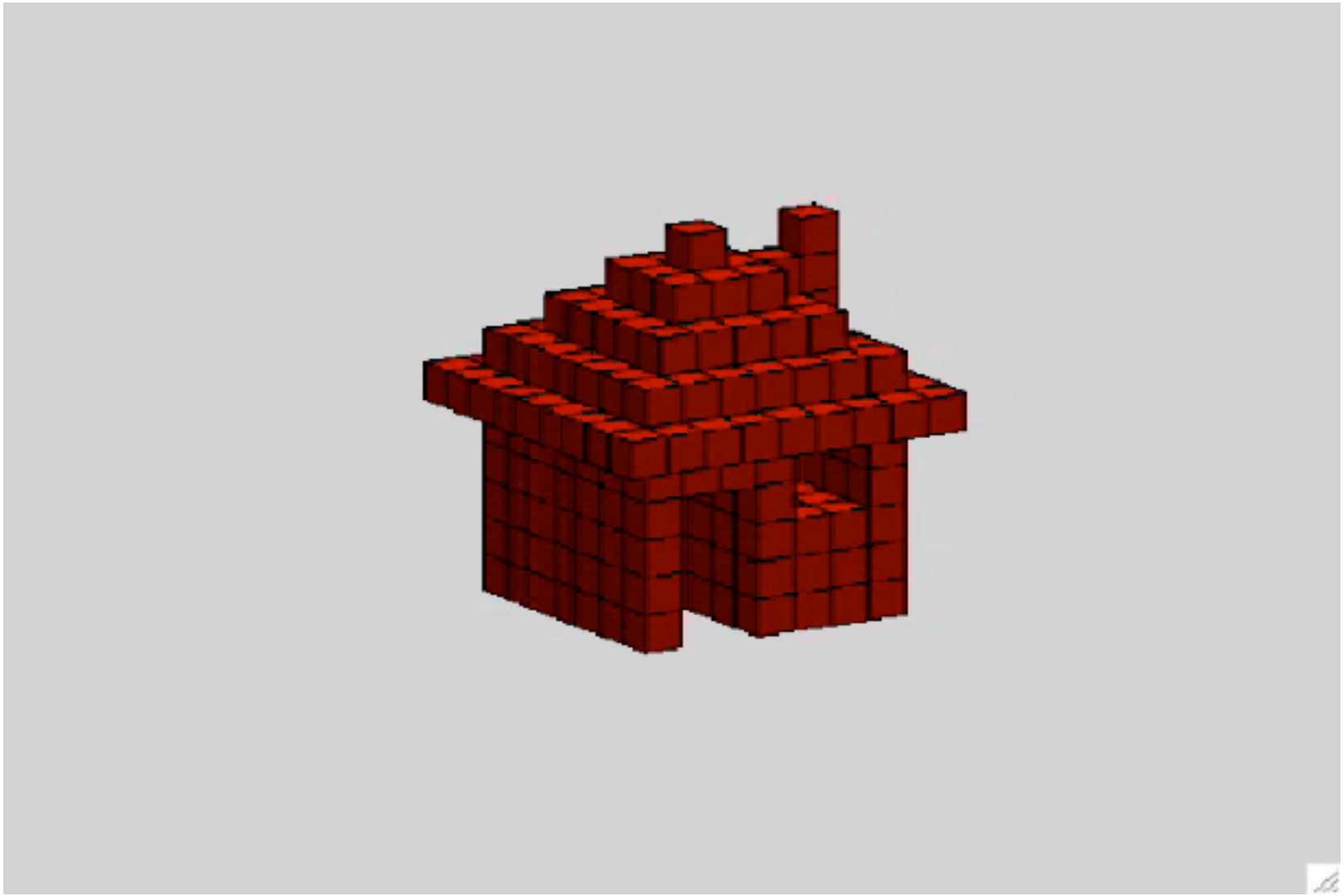


IEEE Intelligent Systems, 2006



AAAI 2006

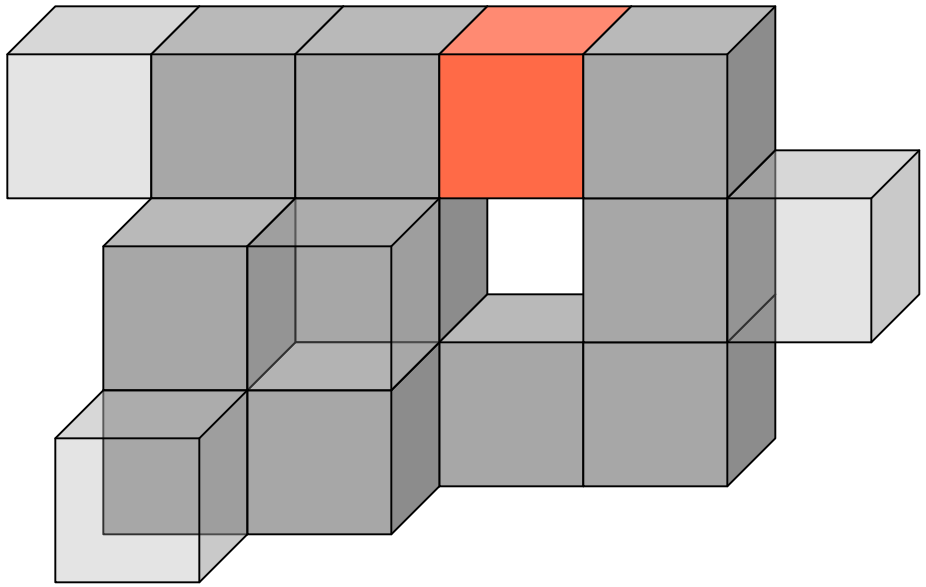
Focus on design of distributed algorithms



Assumptions

- Weightless environment
- Robots
  - Bring blocks to structure
  - Move in any direction along surface
- Blocks
  - Cubic
  - Physical movement restrictions

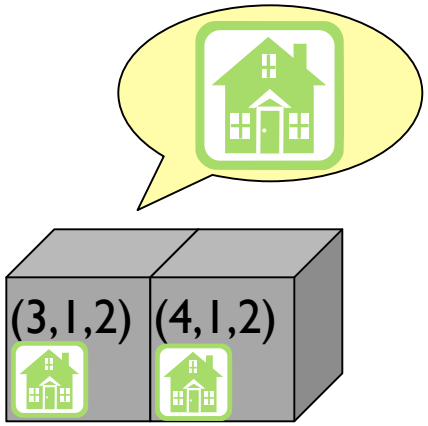
Movement constraints



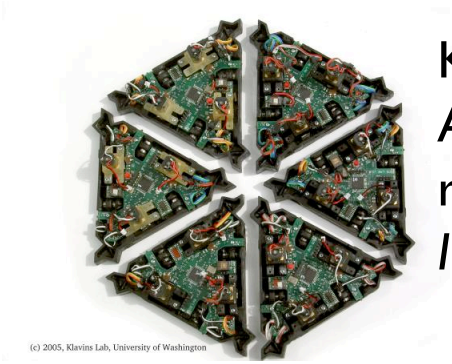
Building a desired structure

- Figure out where blocks go
  - Communicating blocks coordinate process
    - Shared coordinate system
    - Explicit representation of desired structure
    - Blocks tell robots where to attach

- Get them there

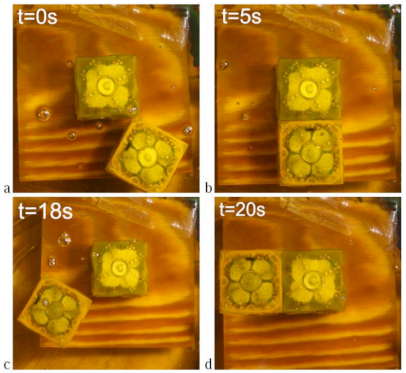


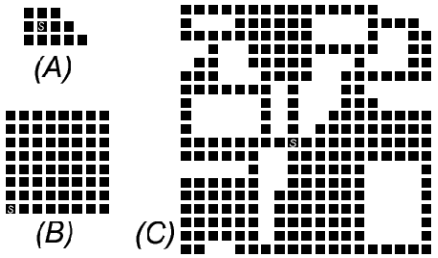
Programmed self-assembly



Klavins, E., Ghrist, R., & Lipsky, J. (2006). A grammatical approach to self-organizing robotic systems. *IEEE Transactions on Automatic Control*.

White, P., Zykov, V., Bongard, J., & Lipson, H. (2005). Three dimensional stochastic reconfiguration of modular robots. In *Proc. RSS 2005*, Cambridge, MA, USA.



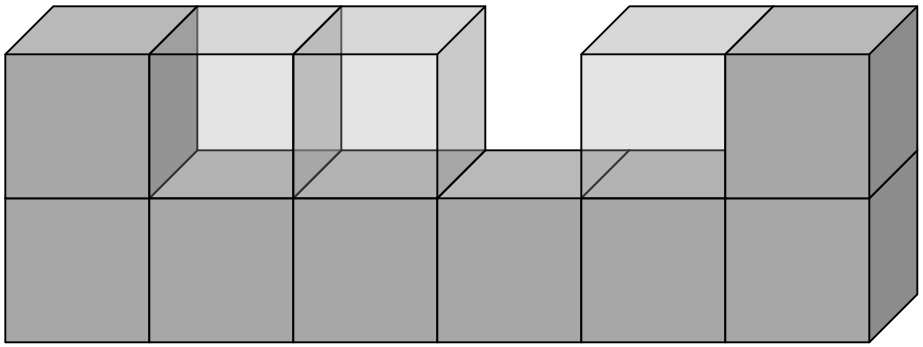


Jones, C. & Matarić, M. (2003). From local to global behavior in intelligent self-assembly. In *Proc. ICRA 2004*, Taipei, Taiwan.

Building a desired structure

- Figure out where blocks go
  - Communicating blocks coordinate process
    - Shared coordinate system
    - Explicit representation of desired structure
    - Blocks tell robots where to attach
  - Avoid dead ends
- Get them there

Restrictions on attachment



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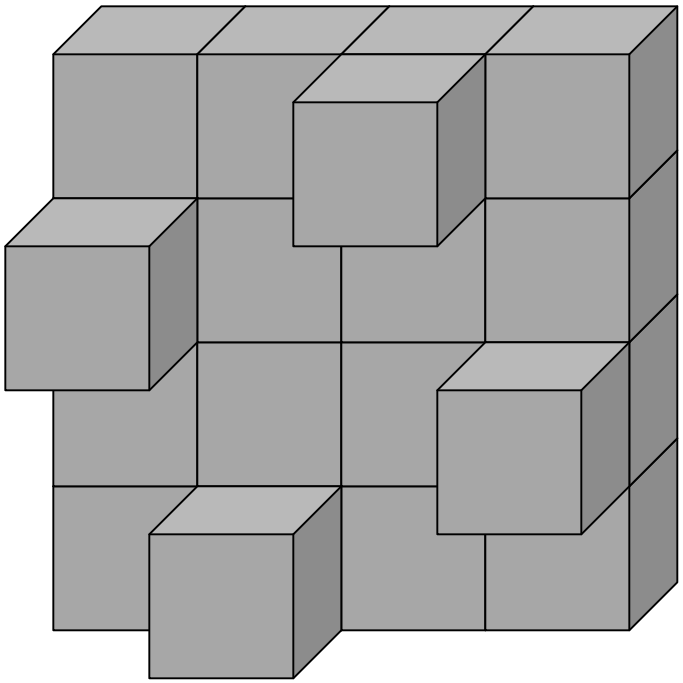

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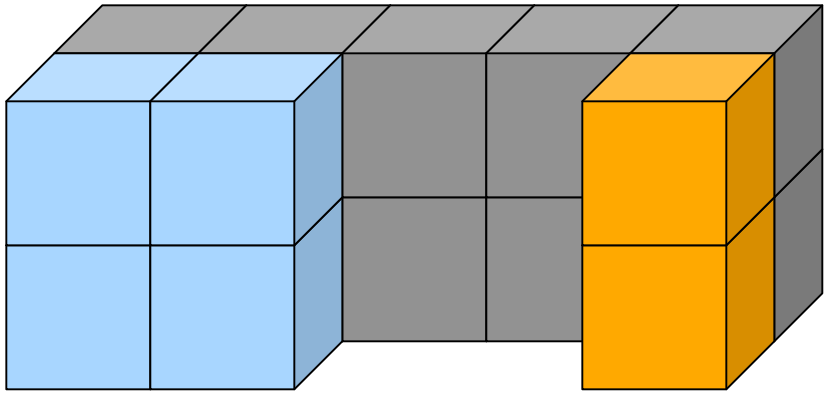

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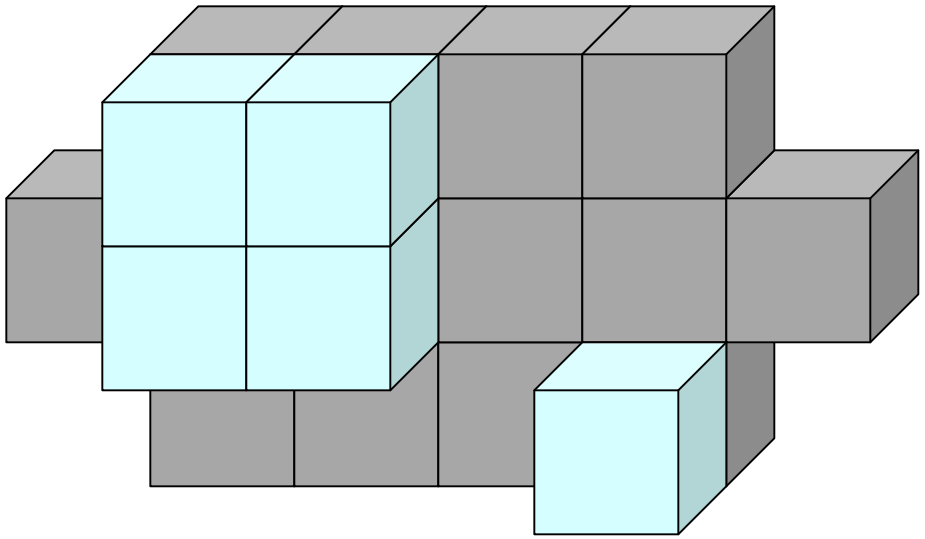
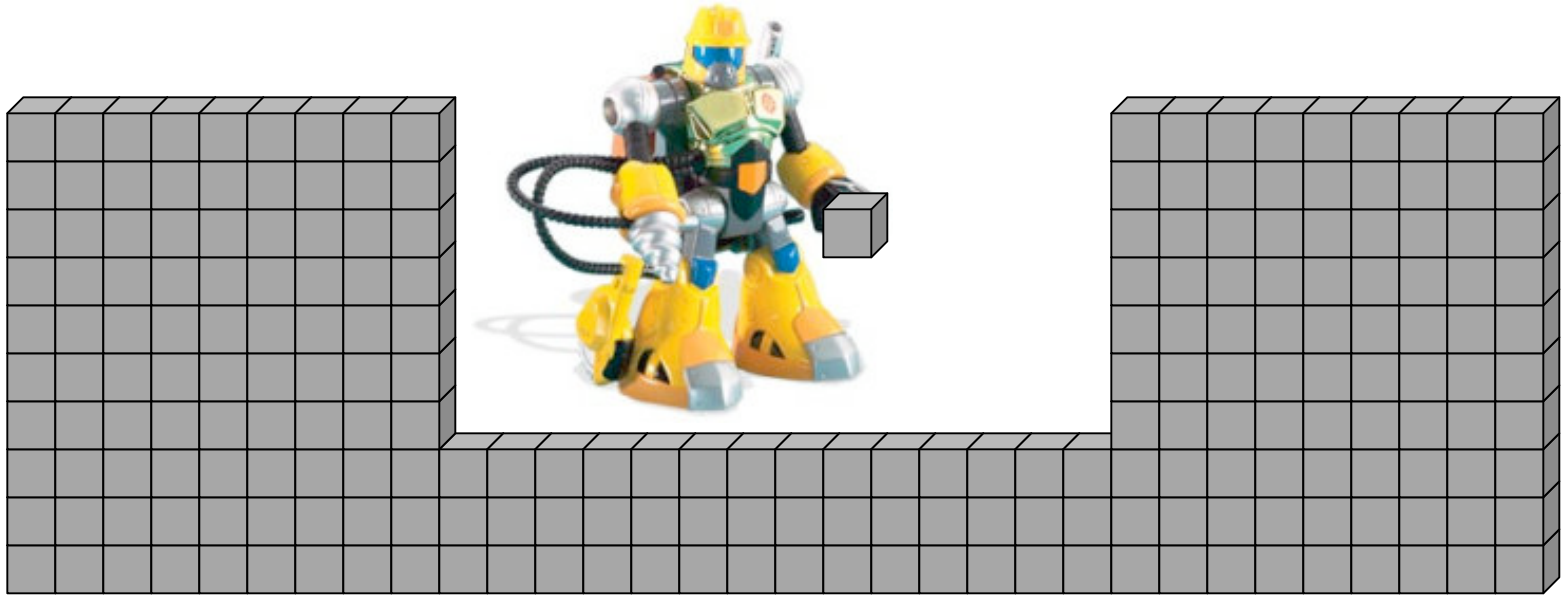


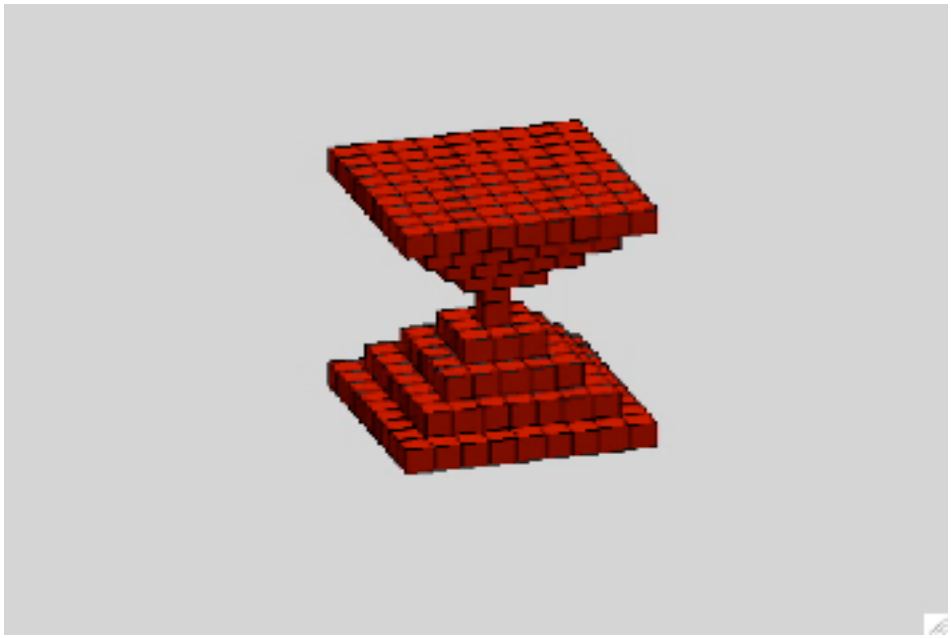
Block algorithm

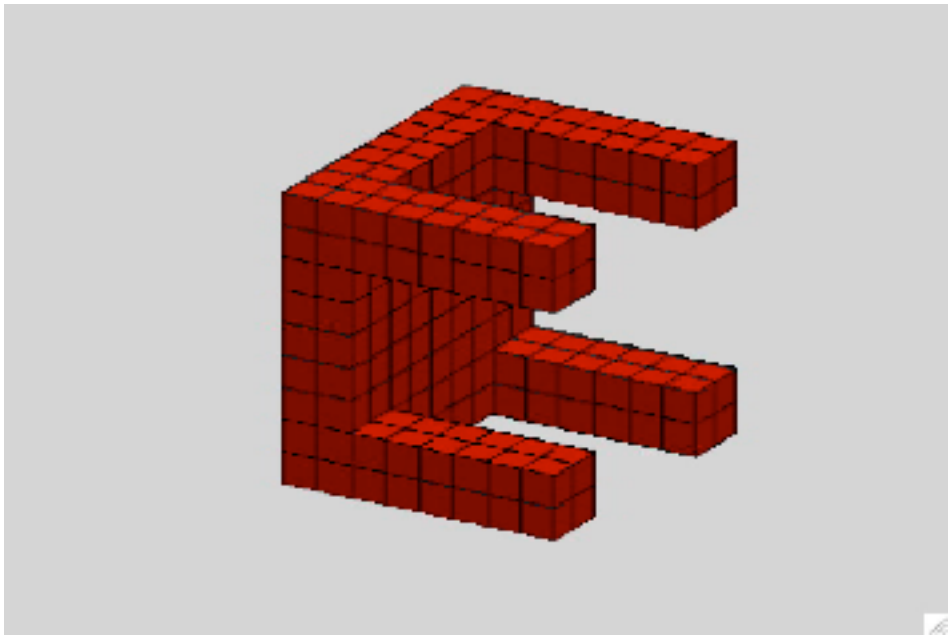
- From neighbors, get coordinates, blueprint, and info on previous attachment
- For site at each open face, check:
  1. Blueprint specifies block there
  2. No separated blocks in any row
  3. No separated blocks in any plane

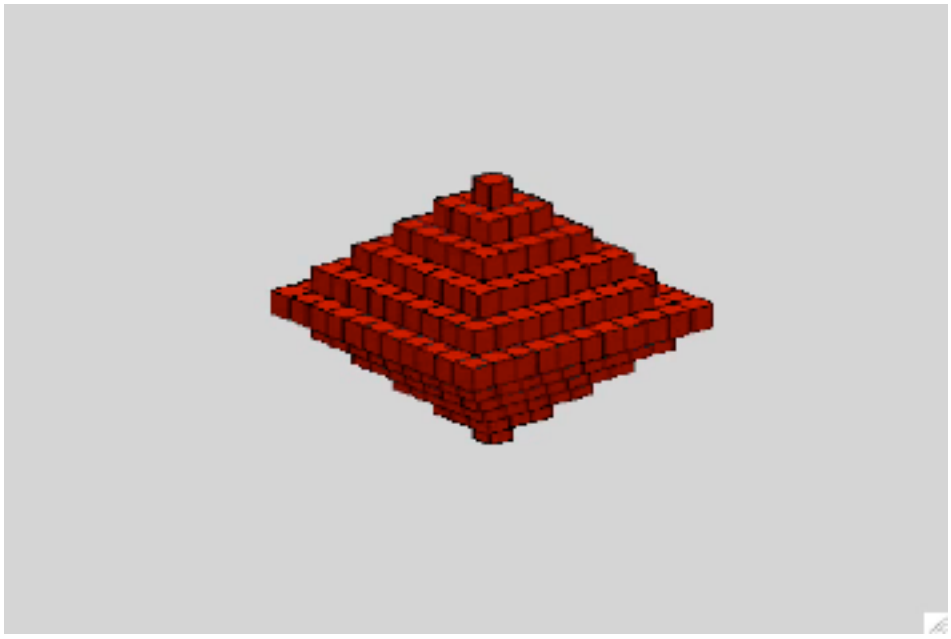
Block algorithm

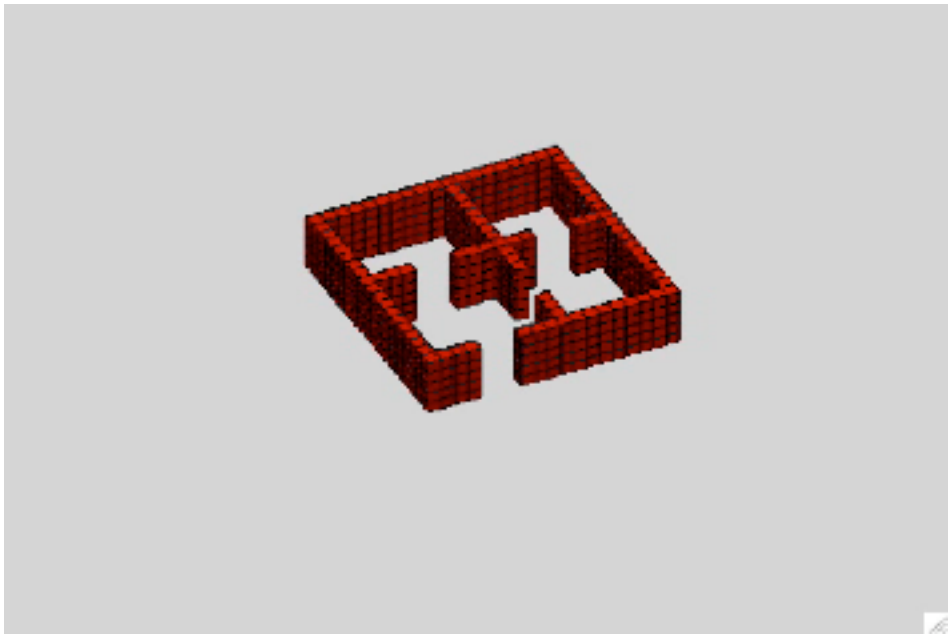
- Sufficient to build any desired solid structure, if intended concavities are wide enough to accommodate robots

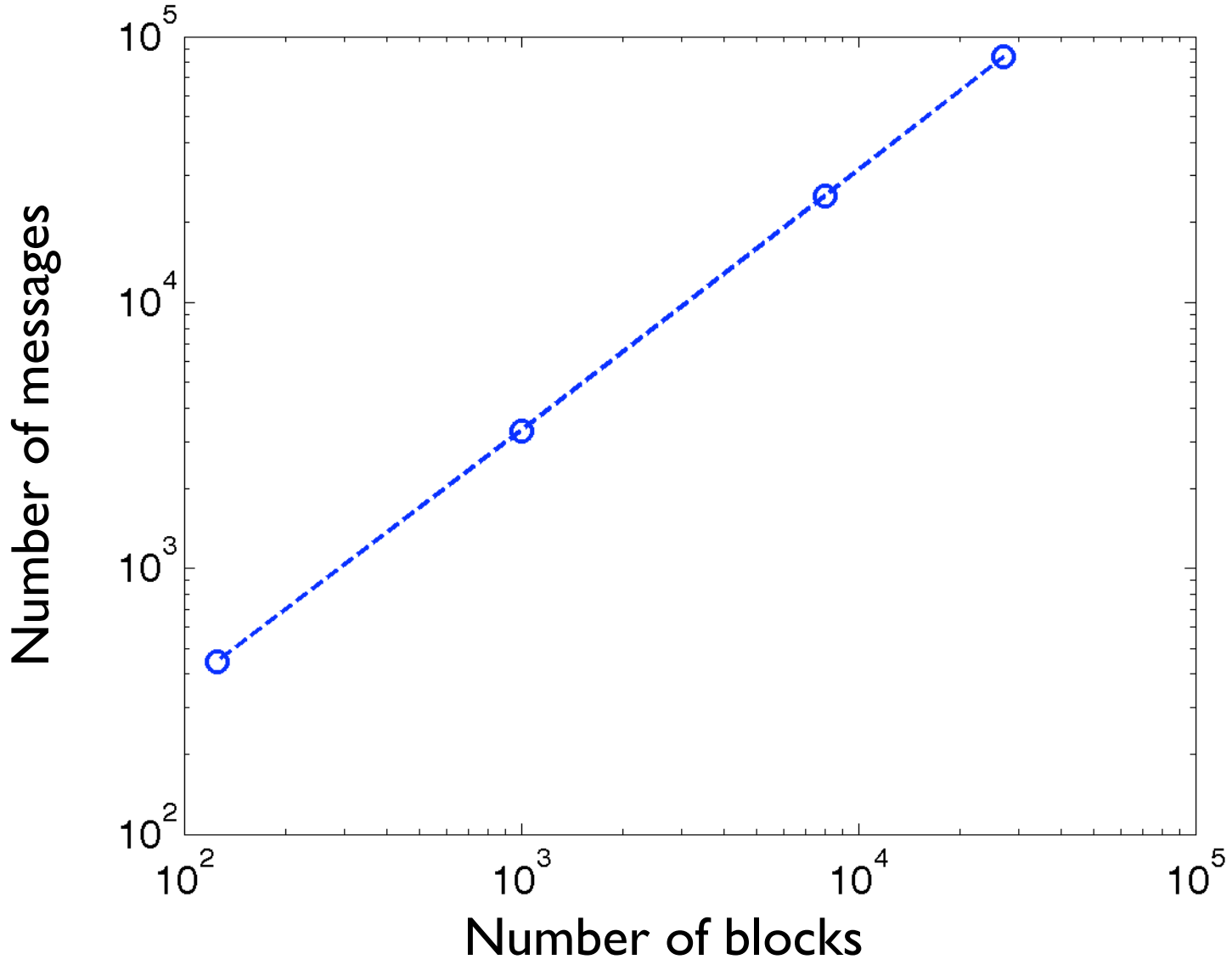


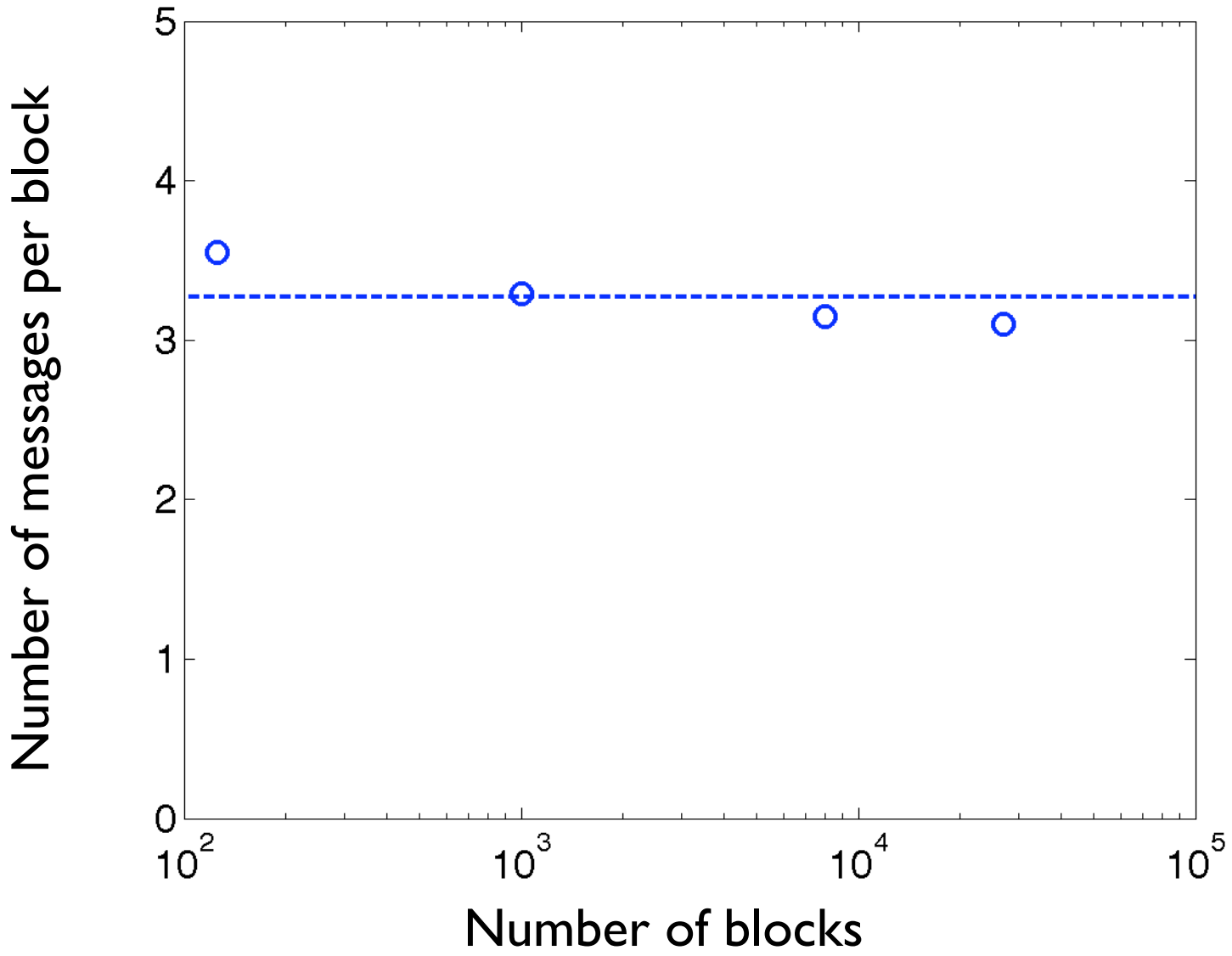









Number of messages
10^5
10^4
10^3
10^2
10^2
10^3
10^4
10^5
Number of blocks


Number of messages per block
5
4
3
2
1
0
10^2
10^3
10^4
10^5
Number of blocks

Building a desired structure

- Figure out where blocks go
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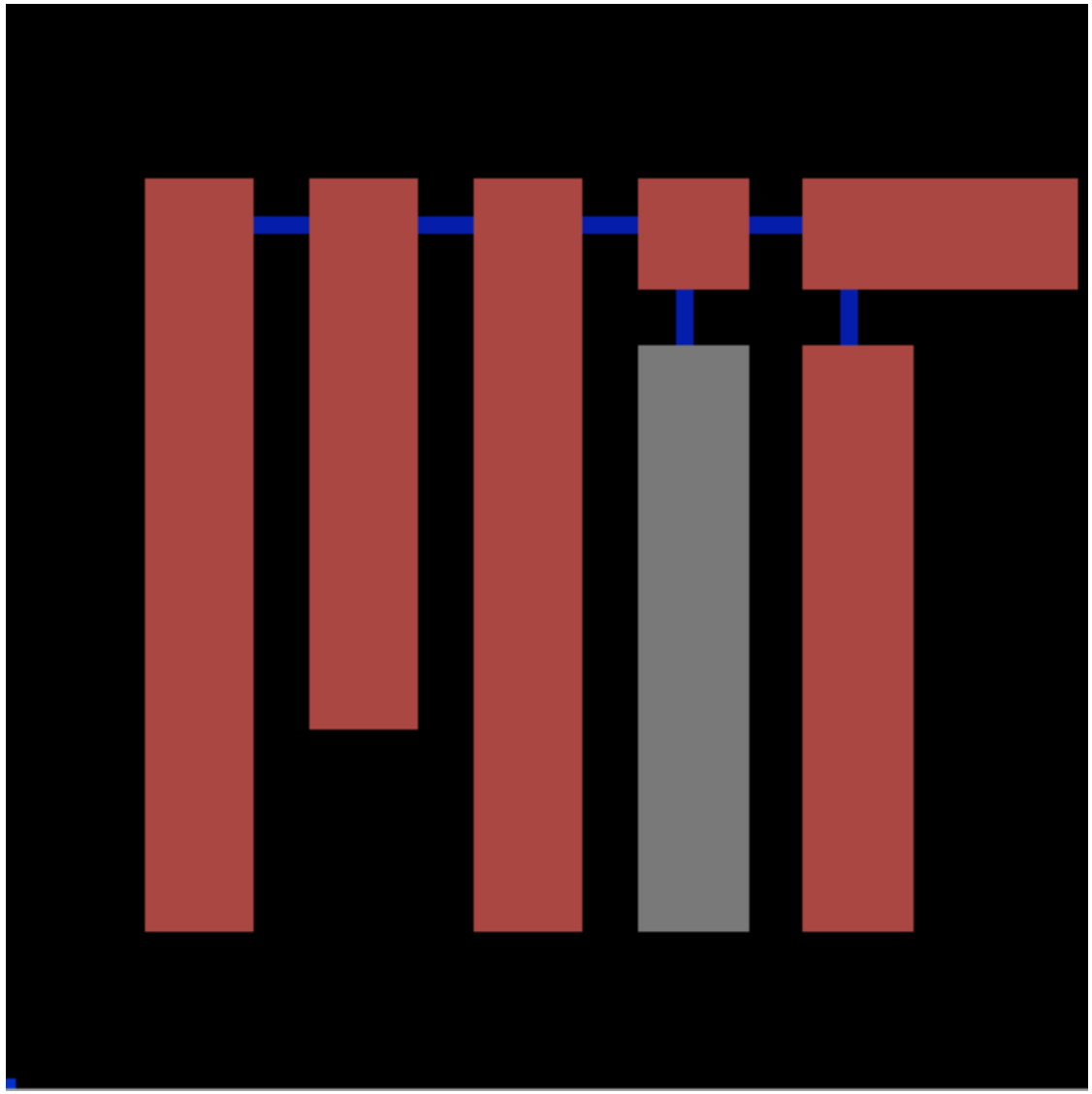
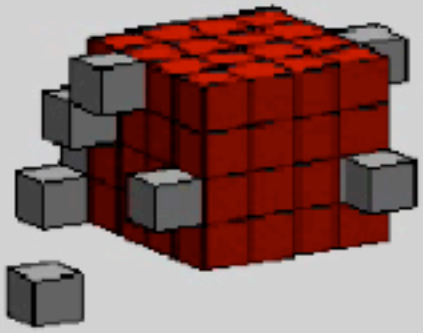
    - Explicit representation of desired structure
    - Blocks tell robots where to attach
  - Avoid dead ends
- Get them there
  - Comparison of three algorithms





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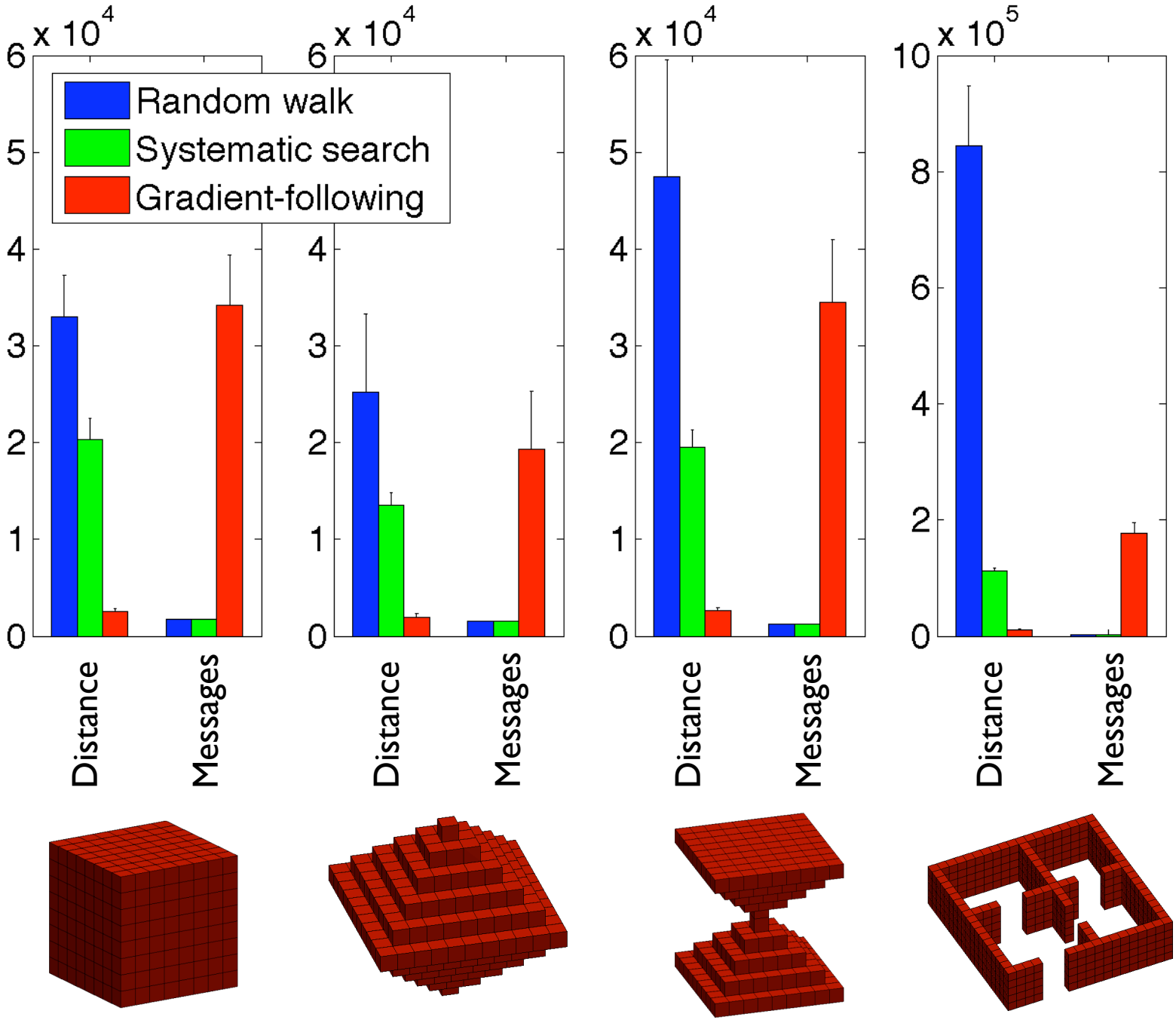
- Get them there
  - Comparison of three algorithms
    - Systematic search
    - Random walk
    - Gradient following


x 10^4
x 10^4
x 10^4
x 10^5
Random walk
Systematic search
Gradient-following
0
1
2
3
4
5
6
8
10
Distance
Messages

Summary

- Decentralized algorithmic approach to automatic construction of solid 3-D structures
- Relevant to existing hardware systems
  - Bipartite (robots + blocks)
  - Homogenous