Swarm Robotics
Part 4:

Collective Construction

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Collective Construction

* Social insects build physical structures (nests, hives, mounds) that are impressive in their size and intricate functionality
* Swarms of robots that could build structures autonomously might be useful in these situations:
  * Structures in hazardous environments (e.g. space, underwater)
  * Ad hoc structures for emergency needs

Stigmergy

The term **stigmergy** was coined by biologist Pierre-Paul Grassé who was an expert on termites. Stigmergy is indirect communication between agents that takes place through modifying the environment and perceiving the modifications made by other agents. Importantly, it is not that messages are left from one agent to others, but that a change is made to the environment that affects the behaviour of other agents somehow (Bonabeau et al., 1999).

Grassé developed his theory of stigmergy to explain the collective construction of termite mounds, which are massive complex, and take generations of termites to construct. He pictured the process like this...

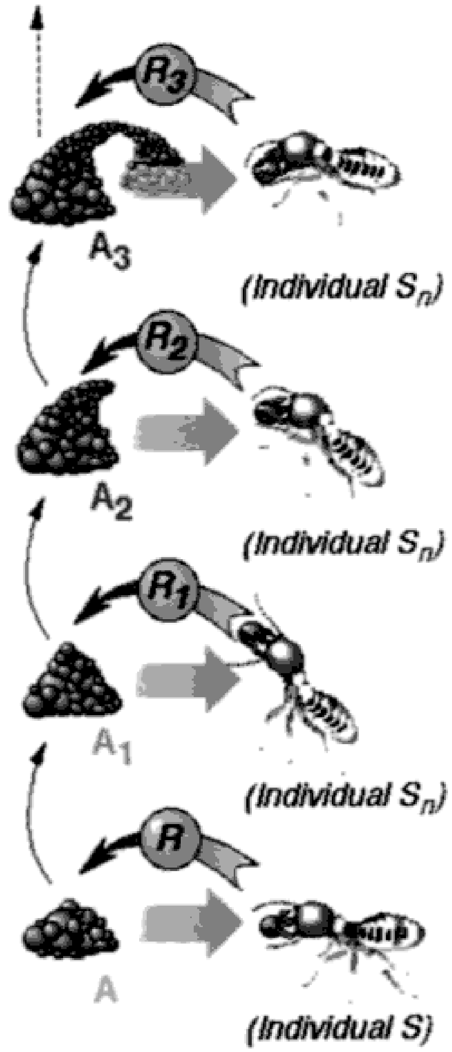
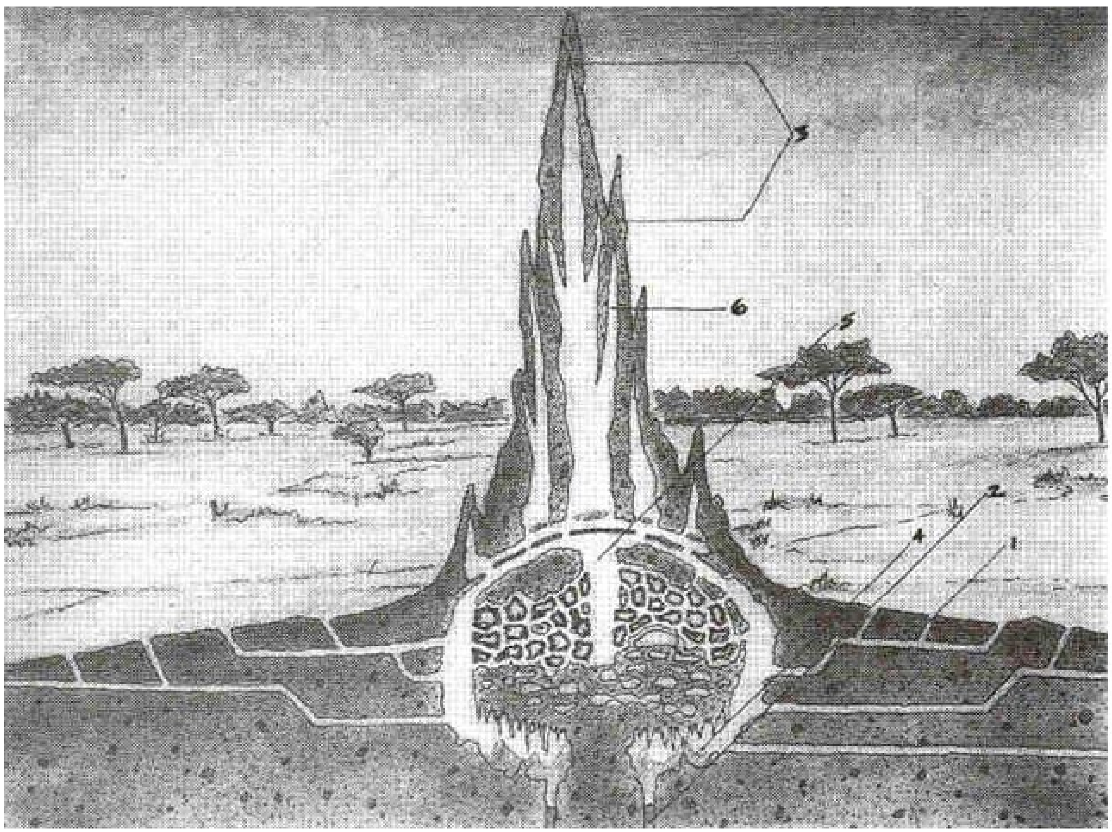


FIGURE 1.13 Assume that the architecture reaches state A, which triggers response R from worker S. A is modified by the action of S (for example, S may drop a soil pellet), and transformed into a new stimulating configuration A_1, that may in turn trigger a new response R_1 from S or any other worker S_n and so forth. The successive responses R_1, R_2, R_n may be produced by any worker carrying a soil pellet. Each worker creates new stimuli in response to existing stimulating configurations. These new stimuli then act on the same termite or any other worker in the colony. Such a process, where the only relevant interactions taking place among the agents are indirect, through the environment which is modified by the other agents, is also called *sematectonic* communication [329]. After Grassé [158]. Reprinted by permission © *Masson*.

An example of stigmergy that we have already seen is in the construction of cemetary clusters in ants. In Deneubourg et al.'s model for this behaviour, the ants react only to the local density of objects (i.e. dead ants), picking up isolated objects with high probability and depositing them with high probability when the density is high (in or near a cluster).

Example: Termite Nest Construction

As we saw in the very first lecture, some termite species build massive nests, which are intricately structured and detailed. It seems unlikely that any one ant can be directed the others and it is also difficult to understand how an individual termite's genetic blueprint can encode such complex structures.



1. night entrance and exit;
2. underground water supply for drinking and cooling nest;
3. "lungs" that expel rising hot air;
4. Cool air eventually sinks back to the cellar;
5. Warm air rises via central air duct;
6. Interior oxygen diffuses through the chimneys.

In (Ladley and Bullock, 2005) some of the models proposed for termite mound construction are summarized. In their own model Ladley and Bullock focus on the following features of termite mounds:

- The “royal chamber”, an open area surrounding the queen (an immobile termite, many times larger than any other termite)
- Tunnels that connect various chambers of the mound

Three different types of termite (a.k.a. castes) are involved: the queen, builders, trail-followers, and nursing termites. Except the queen, real termites can switch between these roles and others, but they are fixed in the model.

Ladley and Bullock proposed that three different kinds of pheremones are emitted:

- Queen pheremone emitted by the queen's body and detected by the builders and used to set the boundaries of the royal chamber
- Trail pheremone emitted by trail followers
- Cement pheremone emitted by newly placed pellets

The virtual termites in this model have the following behaviours:

Builders

Builders come into the world carrying a pellet of material, looking for a place to put it. Very similar to the cemetary cluster ants, they have a probability of depositing their pellet that is proportional to the amount of cement pheremone sensed. But they also sense queen/trail pheromone and will only place their pellet if the level of these other pheromones is in a certain range.
Once a builder places its pellet, it disappears and is replaced by a new builder. This models the notion of the builder now leaving the scene to obtain a new pellet of material.

Trail Followers

Trail followers represent termites that are engaged in non-building activities (e.g. foraging). They are attracted to trail pheromone and also lay new trail pheromone as they move. They move in a random but consistent direction across the world.

Nursing Termites

The nursing termites are very much like the trail followers except that they just move back and forth, away from the queen, then towards her. This models delivering food to the queen and taking her larvae.

In constructing the royal chamber, only builder ants are required.

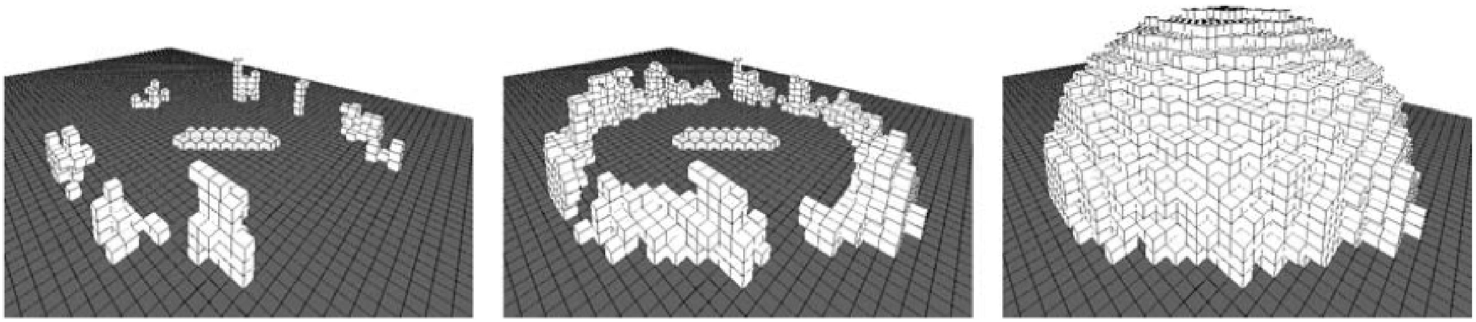


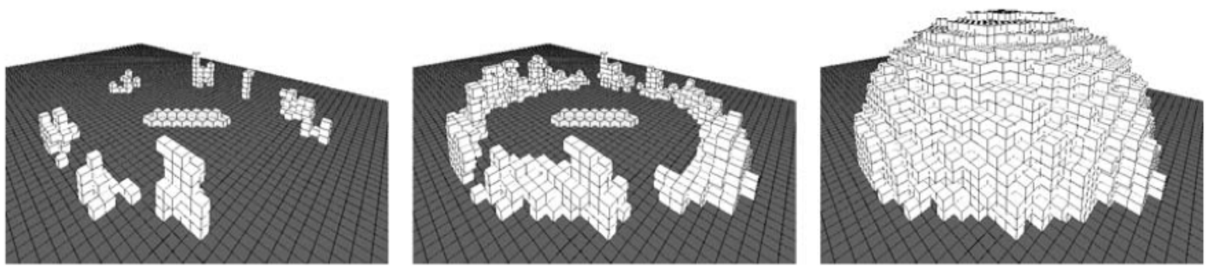
Fig. 3. A royal chamber being constructed. Parameters: $f = 400, r = 0.5, \alpha = \frac{1}{7}, v = 0.1, p = 0.1, n = 300, m = 5, s = 0.0$.

LEFT: The queen pheromone restricts placement only to a certain range of distances away from the queen (blob in centre). Initial random placements seed the formation of clusters.

CENTRE: The clusters join and grow vertically.

RIGHT: A roof is eventually formed.

Wind is modeled as a force that shifts the pheromone. The incorporation of wind simply elongages the structure.



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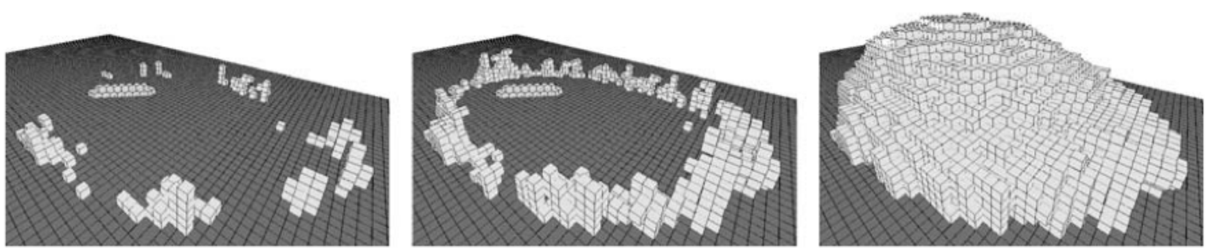


Fig. 4. A royal chamber being constructed under mildly windy conditions (wind emanates from the upper-left lattice edge). Parameters as Fig. 2, except: $s = 0.15$.

The swarm works well when there are many other agents acting on the environment, creating new oppourtunities for placement.

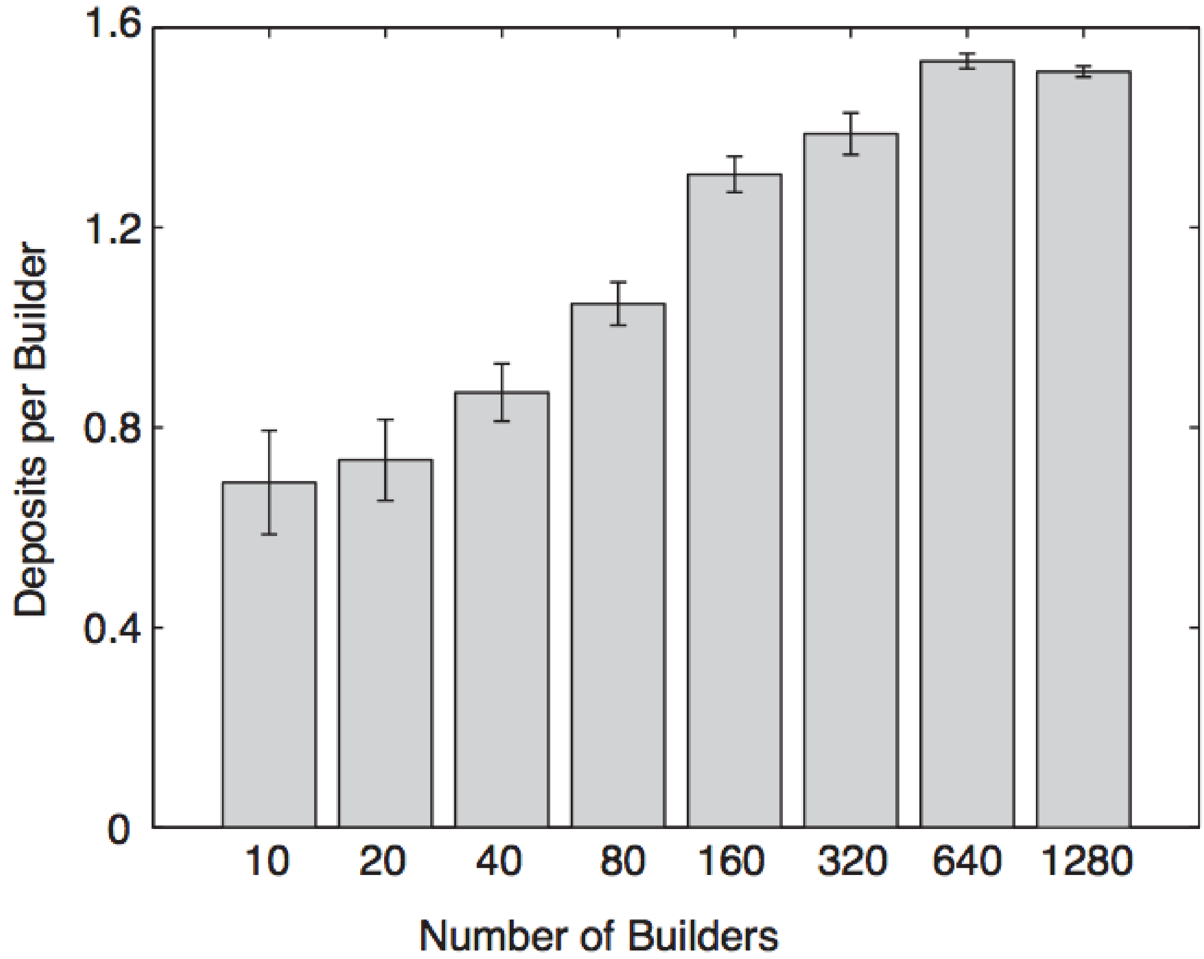


Fig. 5. A graph showing the amount of work done per termite versus the number of termites present in the simulation. Each error bar represents the standard error from the results of 10 replicates. Note the geometric scale on the abscissa. The sinusoidal shape is similar to that observed in real termites (Bruinsma, 1979).

The creation of tunnels is a combined (but uncoordinated) effort by the trail followers who establish the trail and the builders who surround it with material.

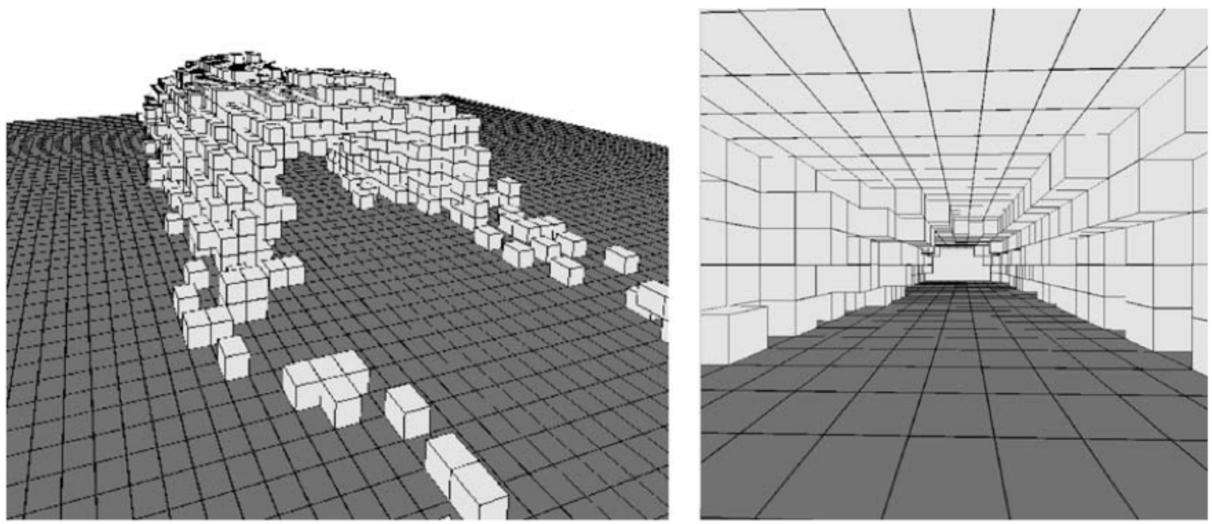


Fig. 6. A covered walkway is constructed. Parameters as Fig. 2, save that a flow of trail termites has been introduced: $t = 10, c = 0.5$. At each time step, between zero and 10 builder termites enter the lattice, with probability 0.5 per termite. The tunnel's interior is clear of obstructions, and the cross-section is quite regular.

Here is the result of combinging the queen, nursing termites, and builders. Multiple tunnels begin to radiate out from the royal chamber, but eventually the nursing termites converge to two tunnels and the others are closed in by the builders.

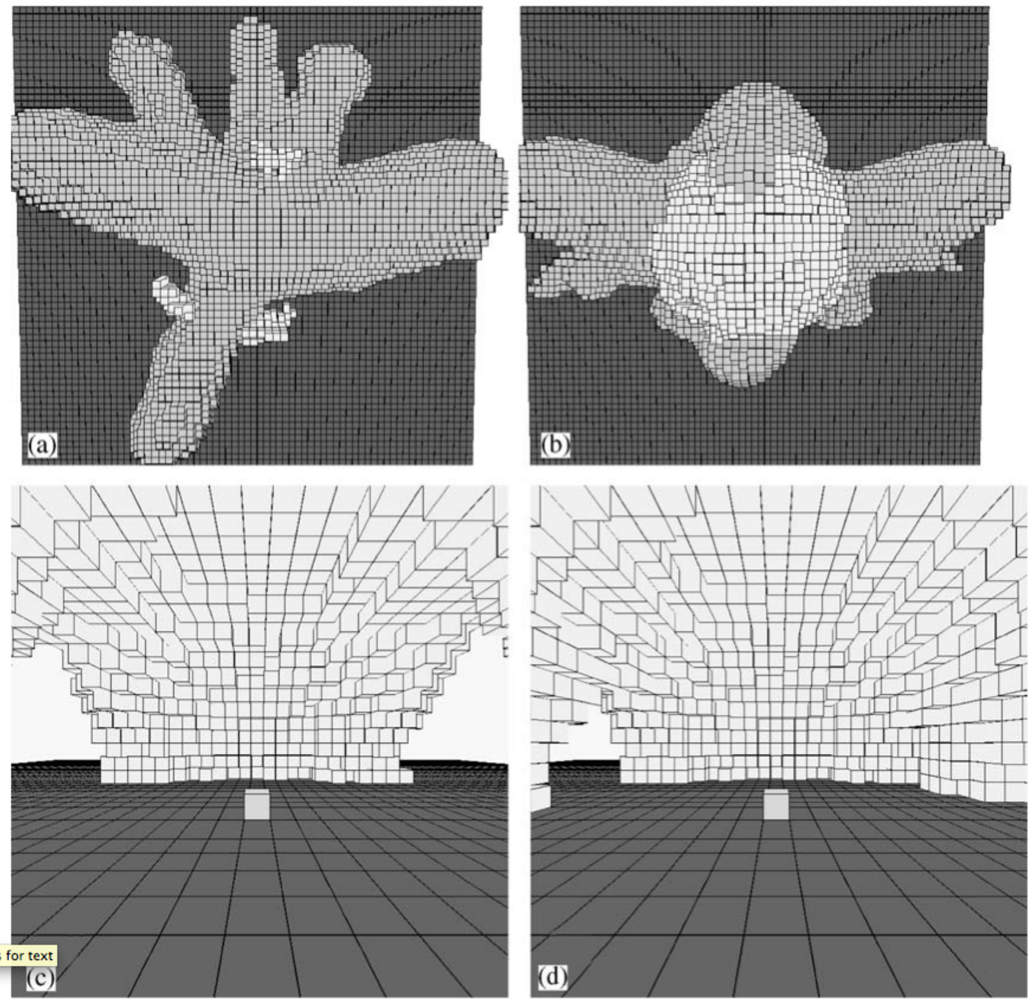


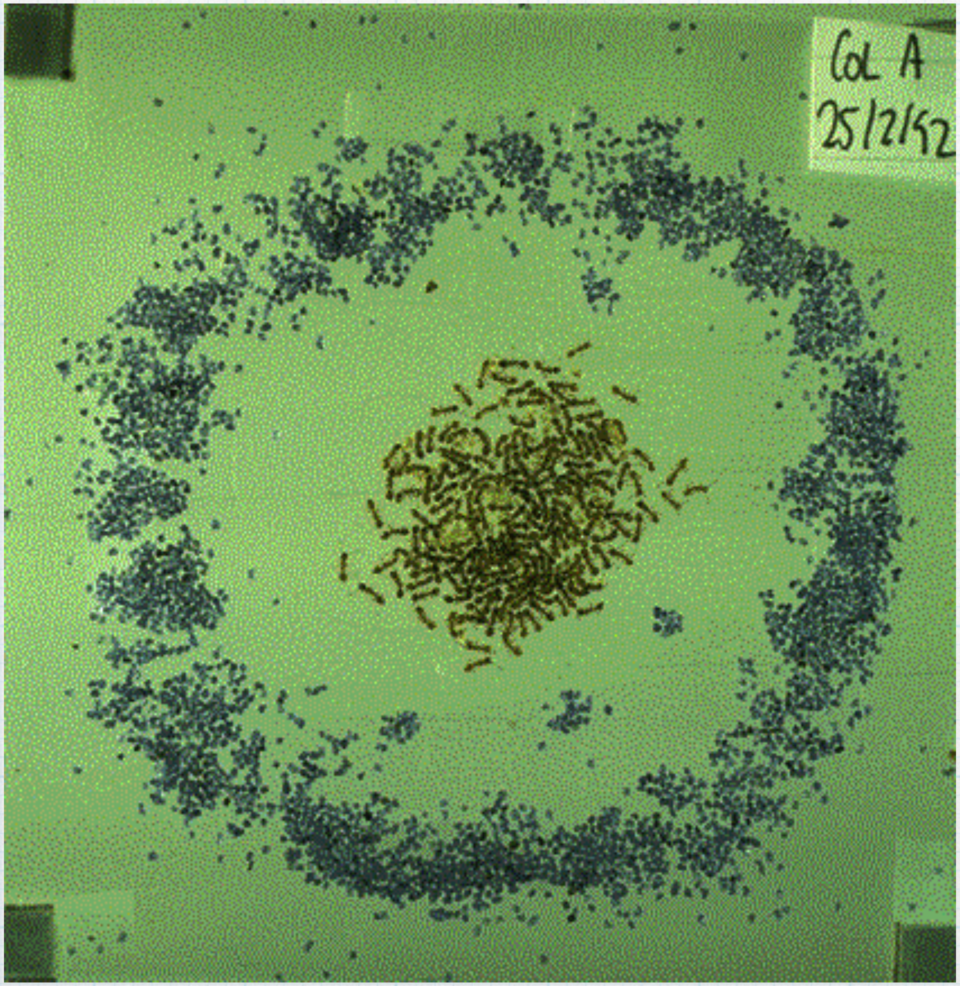
Fig. 10. An example of entrance formation. Parameters as Fig. 2, except $e = 300$ (300 nurse termites are added) (a) 50 time steps: several (medium tone) pheromone trails between a central queen and the lattice periphery have formed (shown from above). (b) 500 time steps: only two trails remain. (c) 500 time steps: A view from inside the dome. (d) 800 time steps: only one entrance remains.

Why Build with Swarms?

* Collective construction methods inherit the usual advantages of swarm robotics
  * Scalability: Larger structure? More robots!
  * Fault-tolerance: Individual robots can fail, but the rest continue
  * Robustness: Damage to the structure is repaired simply by continuing the construction process

Early Work: Blind Bulldozing

* Parker et al (2003) took inspiration from ants that build circular nets in flat cavities between rocks ("rock ants")



Early Work: Blind Bulldozing

* There is little light to guide the ants
* "Blind bulldozing":
  * An ant pushes granules of sand until the force of pushing the material is too great
  * The ant leaves what it was pushing (i.e. deposits it) then turns in a random direction

Blind Bulldozing Robots

* Parker et al. programmed their simple robots with two basic behaviours:
    * Move in a straight line, pushing whatever dirt lies ahead
    * If resistance exceeds a threshold then turn by a random angle and resume pushing
* Shape of the nest is unaffected by the number of robots

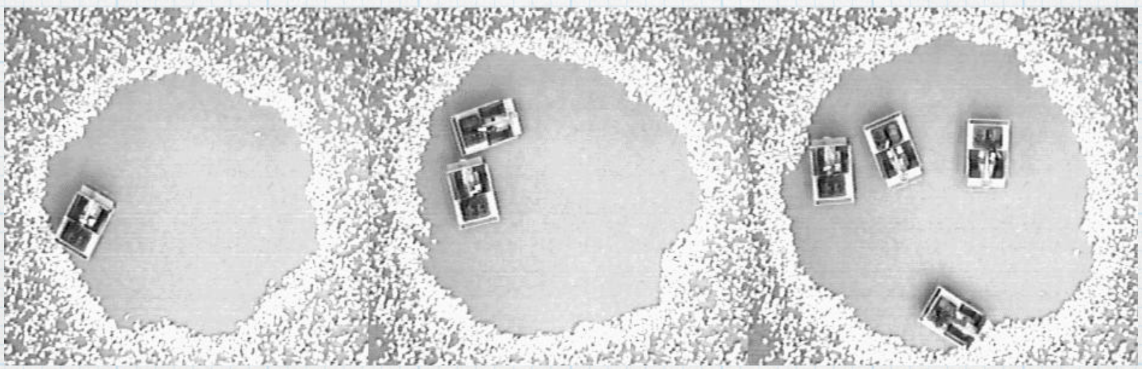
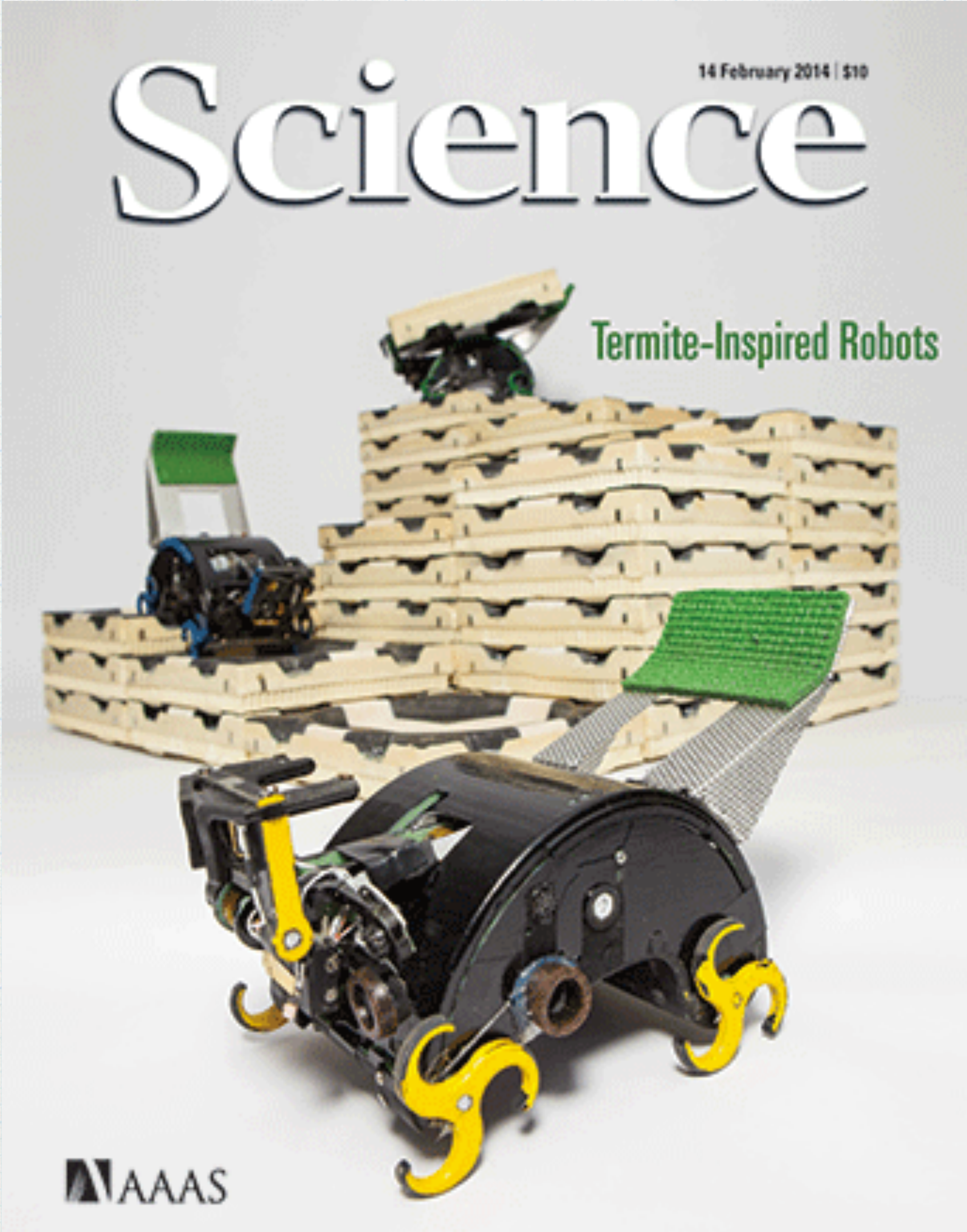


Fig. 7. Nests constructed by one, two and four robots after two hours. The nest retained its initial circular shape and has uniform walls because the blind bulldozers enlarge the nest by distributing their pushes against the nest wall along its entire length.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Science
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A Termite-Inspired Robot Construction Team

* Werfel et al (2014) have developed a technique allowing a group of robots to build any structure which satisfies these criteria:
  * Composed of identical rectangular bricks providing alignment cues and attachment points
  * Bricks stacked vertically
  * Paths exist on the growing structure to support the movement of construction robots

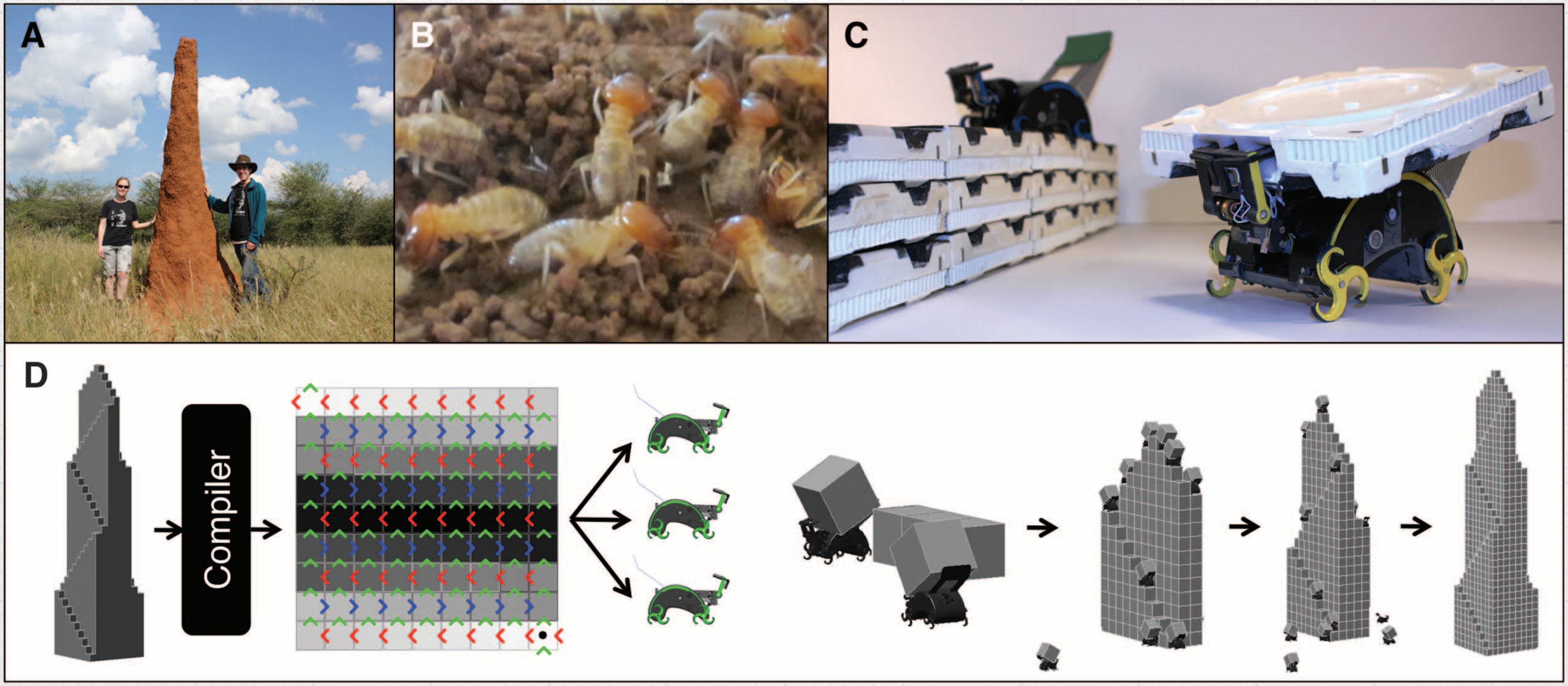

Fig. 1. Natural and artificial collective construction. (**A** and **B**) Complex meter-scale termite mounds (A) are built by millimeter-scale insects (B), which act independently with local sensing and limited information. (**C**) Physical implementation of our system, with independent climbing robots that build using specialized bricks. (**D**) System overview for building a specific predetermined result (Fig. 2, A and C): A user specifies a desired final structure; an offline compiler converts it to a "structpath" representation (Fig. 3), which is provided to all robots; robots follow local rules that guarantee correct completion of the target structure (movie S1).

The "structpath"

* Werfel et al's robots have the usual swarm characteristics:
  * Local sensing
  * No centralized control
* All robots follow the same rules
* To design a particular structure, the robots consult a special map called the structpath
* The structpath is compiled from a model of the desired structure

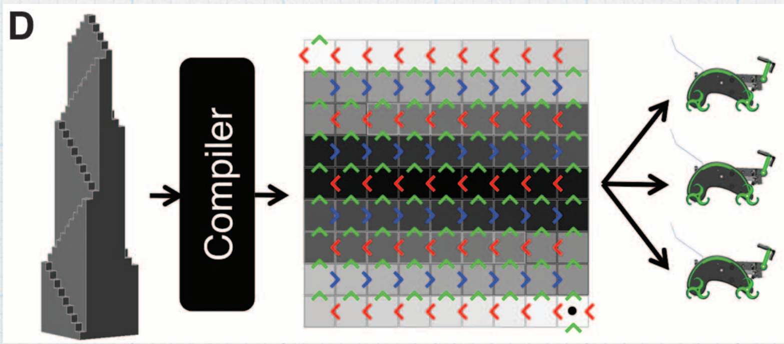

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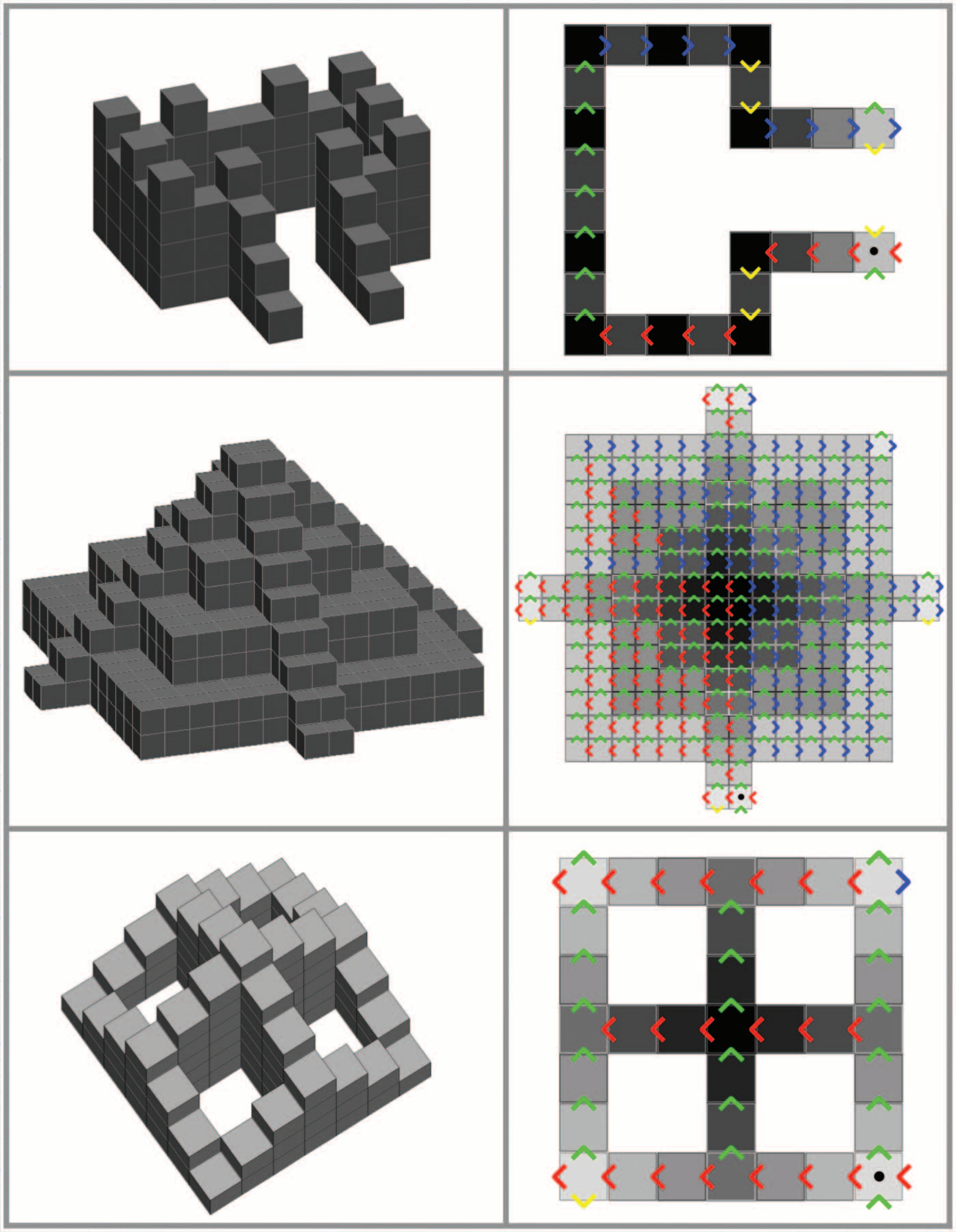
Fig. 3. Target structures and corresponding structpaths. For each predefined target structure at left, the corresponding structpath representation at right is generated by the offline compiler (*19*). From top to bottom: a simple structure with a unique structpath if the seed location is given; the temple of Fig. 2C, showing one of many possible structpaths; a structure enclosing internal courtyards. Sites in the structpath are shaded according to height (darker = higher); a dot marks the seed brick. Directions are color-coded to clarify flows (red, left; blue, right; green, up; yellow, down).



The seed block (dot shown) provides a landmark for the robots and is used to guide their building: any single row is built in order according to distance from the seed

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Is this Cheating? Is this SR?

* Option 1: Yes. This work is not true SR
  * This structpath sounds like a "master plan" that the robots carry out (i.e. instructions from above)
* Option 2: No. This work really belongs to SR
  * The structpath is given to all robots at the beginning, and does not change---similar to the genetic programming of an animal
  * It guides the robots much like traffic rules guide drivers, but it does not specify the exact behaviour of each robot

How Can We Tell?

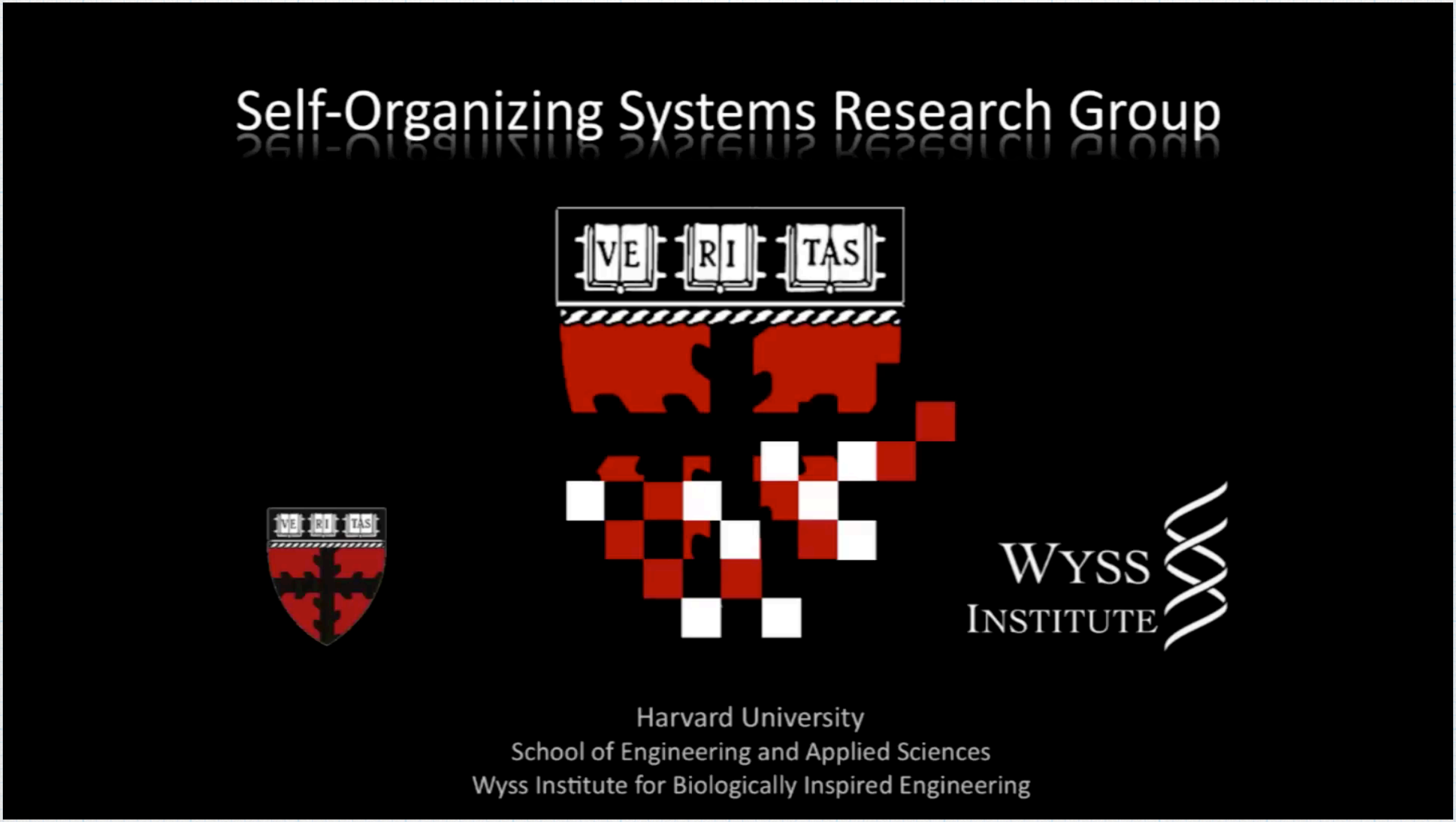
* If a collective construction system exhibits the desired properties of a swarm-based system, then we'll call it SR

* Scalability: Larger structure? More robots!
* Fault-tolerance: Individual robots can fail, but the rest continue
* Robustness: Damage to the structure is repaired simply by continuing the construction process

Yes

Partially (a broken robot could block construction)

Yes — At least to a degree (consider the movie that follows)



So... Yes, the swarm can repair a damaged structure (assuming the damage doesn't violate the construction constraints)

References

* Parker C, Zhang H, Kube C (2003) Blind bulldozing: Multiple robot nest construction. In: IEEE/RSJ International Conference on Robotics and Intelligent Systems (IROS)
* Werfel J, Petersen K, Nagpal R (2014) Designing Collective Behavior in a Termite-Inpsired Robot Construction Team. Science 343(6172): 754-758