Robots Acting Locally and Building Globally
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*Science* **343**, 742 (2014);
DOI: 10.1126/science.1250721
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Termites are among the most fascinating animal architects in nature; their mounds were first described in a scientific journal more than 200 years ago (1). How can such tiny insects, each less than 1 cm in size and equipped only with a simple brain, construct air-conditioned buildings up to 500 times their size? Termites’ construction principles differ fundamentally from those of human architecture. Humans build houses according to a blueprint, and the construction process is centrally guided by this plan. In contrast, social insects such as termites build in a decentralized, self-organized manner. Each individual works rather independently and follows a set of simple rules; the interactions among the workers and the interaction of each worker with its environment ensure an organized process without a central blueprint (2–4). On page 754 of this issue, Werfel et al. (5) describe the use of such insect principles to guide simple robots in constructing user-defined structures for human purposes.

Central to the work of Werfel et al. is the principle of stigmergy (6): Social insects use local information at the building site to coordinate building activity. As this information changes during the building process, the behavior is adjusted accordingly. An example in termites is the proposed deposition of chemical volatiles with the building particles that guide individuals to local construction sites. Similarly, Werfel et al.’s autonomous constructing robots move along a grid system and deposit building bricks next to other bricks. The robots are simple, even more so than termite workers. The robots can only sense bricks and the other robots next to them. They can move backward or forward, turn in place, and climb one step up or down; they can pick up, carry, and deposit bricks.

The robots adjust their behavior according to what they perceive locally when they move along the grid system; the possibilities include “nothing,” other robots, and bricks. The exact “traffic rules” depend upon the structure to be built, and these rules are derived by an offline compiler that transforms three-dimensional representations of a desired structure into two-dimensional

References and Notes

Acknowledgments: Supported by NSF Awards CBET 1154572 and 1158601.

10.1126/science.1250247
In both nature’s construction works and the structures created by the robots in the approach of Werfel et al., the properties of the final product are crucial. A termite mound’s architecture can determine the success of a colony (7). Mounds that are better adapted to local environments will, as a rule, have more offspring; thus, improved building rules that are genetically encoded will spread over time through a population. What is different in nature is that it starts with “mutations” in the building rules that are then tested in the evolutionary process. Over the millennia, evolution tested different rules, and what we observe today are those that worked. They might not be perfect, and the algorithms of Werfel et al. might also show us whether termites could still “learn” from humans.

References

10.1126/science.1250721

BIOCHEMISTRY

Protein Folding, Interrupted

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Globular proteins start their lives as linear chains of amino acids coming off the ribosome. Proteins must then fold into specific three-dimensional structures to be functional. In 1957, the first such structure, of myoglobin, was determined at atomic resolution (1). Fifty-six years and 90,000-plus protein structures later (2), we have a very good idea of the necessary requirements for a stable, specific structure. Key to these requirements is the formation of a well-packed, largely anhydrous core (3). Yet, on page 795 of this issue, Sun et al. (4) report an antifreeze protein with a core mostly consisting of water.

In globular proteins, the anhydrous protein core provides both structural specificity and energetic stabilization (see the figure, panel A). Burial of apolar amino acid side chains inside the core relieves their unfavorable interaction with water, a process known as the hydrophobic effect (5, 6). Even integral membrane proteins, which function in the nonaqueous lipid bilayer of the membrane and adopt structural motifs that are quite different from those of globular proteins, conform to this general principle. Here, the apolar side chains are on the outside of the structure, but by forming close contacts with the apolar lipid tails, they are still removed from water (7).

The remarkable structure of the antifreeze protein Maxi reported by Sun et al. flaunts its violation of the anhydrous-core principle. Maxi is a 145 Å–long four-helix bundle formed as a dimer of two-helix monomers. More than 400 highly organized water molecules form an integral part of Maxi’s structure. The water is interleaved as a roughly two-molecule-thick layer between both intra- and intermonomer helix inter-

Core questions. In a typical globular protein, the four-helix bundle Rop [Protein Data Bank code: 4D02 (10)] (A), water (blue) is excluded from the core because of efficient, interdigitated packing of apolar side chains (magenta), surrounded by polar side chains (green). By contrast, highly ordered water remains in the core in the antifreeze protein Maxi reported by Sun et al. (B). Secondary structure is rendered in orange. Slices through the van der Waals atomic surface taken through the core of the two proteins are shown in wire frame. Van der Waals surface slices produced by Pdb2DSlice and rendered in Pymol (11). In (B), the central third of the 145 Å–long Maxi protein is shown.