Self-reproducing machines

A set of modular robot cubes accomplish a feat fundamental to biological systems.

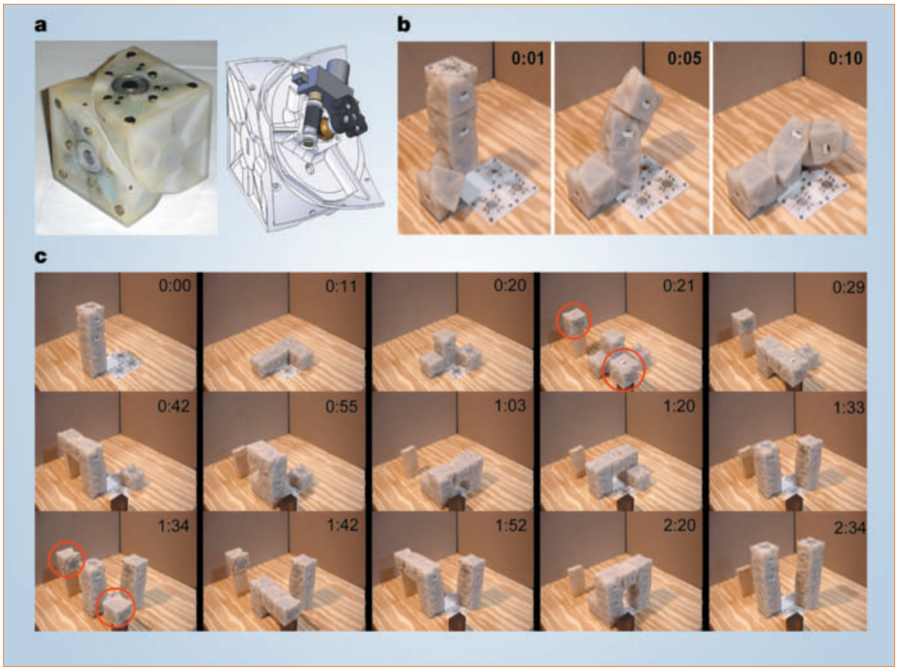

Figure 1 Self-reproduction of a four-module robot. **a,** Basic module, with an illustration of its internal actuation mechanism. **b,** Snapshots from the first 10 s showing how a four-module robot transforms when its modules swivel simultaneously. **c,** Sequence of frames showing the self-reproduction process, which spans about 2.5 min and runs continuously without human intervention, apart from the replenishing of building blocks at the two 'feeding' locations (circled in red). (For movie, see supplementary information.)

Self-reproduction is central to biological life for long-term sustainability and evolutionary adaptation. Although these traits would also be desirable in many engineered systems, the principles of self-reproduction have not been exploited in machine design[1]. Here we create simple machines that act as autonomous modular robots and are capable of physical self-reproduction using a set of cubes.

A physical system is self-reproducing if it can construct a detached, functional copy of itself — by definition, this will also be capable of self-reproduction. Self-reproduction differs from self-assembly[2], in which the resulting system is not able to make, catalyse or in some other way induce more copies of itself. These phenomena have been of interest since the early days of computation[3,4], but have been examined mostly in abstract[5,6] and simulated[7–9] systems.

The self-reproducing machines demonstrated here are essentially modular robots[10]. Their modules have electromagnets that selectively weaken and strengthen connections, determining where the structure breaks and joins. Each module is a 10-cm cube, split into two halves along the (111) plane (Fig. 1a). One half of the cube can swivel relative to the other half in increments of 120°, each time cycling three faces of the cube. Connected cubes can both form and change into arbitrary arrangements (Fig. 1b). The cubes are powered through the baseplate and transfer data and power through their faces. The control of the machine is distributed among the modules: a microcontroller in each module executes a motion schedule governed by time and contact events. (For details, see supplementary information.)

In order to self-reproduce, a machine requires a supply of material. We supplied the modular robots with cubes that were manually replenished at two 'feeding' locations. The four-module robot (Fig. 1c; for movie, see supplementary information) was able to construct a replica in 2.5 min by lifting and assembling cubes from the feeding locations. Because the replica is as large as the original, the replica reconfigures itself to assist in its own construction. A three-module robot is able to self-reproduce in just over 1 minute (see supplementary information). Other reproducing forms are also possible with these modules[8].

Self-reproduction of a physical machine has previously been achieved in two dimensions using tumbling wooden tiles[11] and a machine comprising four different components that are assembled by following tracks[12]. In neither case, however, was it clear how to scale the process to more complex systems, short of redesigning the 'atomic' components.

In our demonstration, we use a modular substrate in which arbitrarily complex self-reproducing machines can be constructed. We circumvent the long-standing hurdle of what counts as self-replication by suggesting that self-replicability is not a binary property that a system either possesses or not, but is a continuum dependent on the amount of information being copied. This factor can be measured by comparing the log probability of a machine spontaneously appearing in an environment to the log probability of it appearing, given that one instance already exists. This factor can be computed precisely for some well-defined formal systems[13] and approximated for others. For example, an abstraction of Penrose's replicating tiles[11] yields a factor between zero (not self-replicating) and log 2.

Even without calculating absolute numbers, systems can be ranked by comparing properties that affect this factor, such as the number of basic building blocks used compared with the number of building-block types and their complexity. This factor is exceedingly high for animals, which have about 10^{20} amino-acid combinations of roughly 20 amino-acid types, but is very low for our robots (four modules of one complex type). This view allows us to quantify, compare and systematically improve the processes of self-reproduction. It is possible, for example, that self-reproducing machines composed of many identical microscale modules would improve this factor.

Although the machines we have created are still simple compared with biological systems, they demonstrate that mechanical self-reproduction is possible and not unique to biology. This design concept could be useful for long-term, self-sustaining robotic systems in emerging areas such as space exploration and operation in hazardous environments, where conventional approaches to maintenance are impractical.

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Botany

A record-breaking pollen catapult

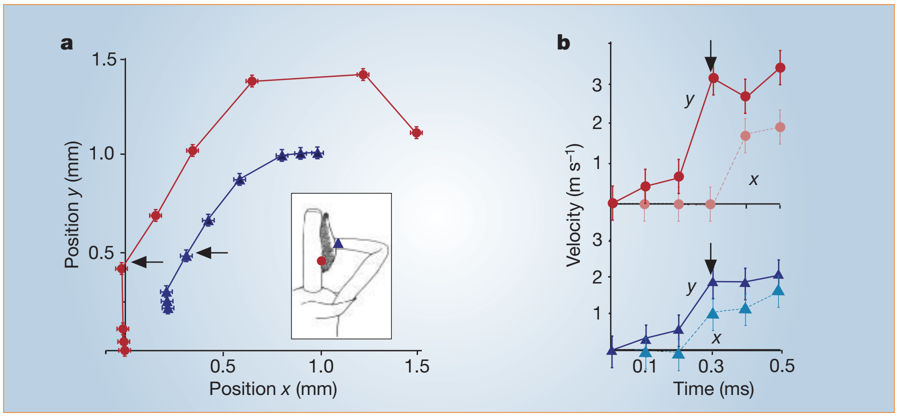

Figure 2 Dynamics of floral explosion. **a,** Coordinates *x* and *y* of positions of the filament tip (blue triangles) and anther tip (red circles), plotted at 0.1-ms intervals. Inset, a single stamen; points used to plot positions are indicated. Arrows, stamen positions just before pollen release. **b,** Coordinates *x* and *y* of velocity components of the anther (top) and filament (bottom) as a function of time, derived from the first six points in **a**. Arrows, velocity just before pollen release. Error bars represent uncertainty in measurements from **a**, propagated as random errors.

The release of stored elastic energy often drives rapid movements in animal systems[1,2], and plant components employing this mechanism should be able to move with similar speed. Here we describe how the flower stamens of the bunchberry dogwood (*Cornus canadensis*) rely on this principle to catapult pollen into the air as the flower opens explosively[3–5]. Our high-speed video observations show that the flower opens in less than 0.5 ms — to our knowledge, the fastest movement so far recorded in a plant.

Cornus canadensis grows in dense carpets in the vast spruce-fir forests of the North American taiga. As bunchberry flowers burst open, their petals rapidly separate and flip back to release the stamens (Fig. 1). During the first 0.3 ms, the stamens accelerate at up to 24,000 ± 6,000 m s^{-2} (2,400g), reaching the high speed (3.1 ± 0.5 m s^{-1}) necessary to propel pollen, which is light and rapidly decelerated by air resistance (terminal velocity, 0.12 ± 0.03 m s^{-1} (mean ± s.e.m.); $n=7$). The pollen granules are launched to an impressive height of 2.5 cm (range, 2.2–2.7 cm; $n=5$), which is more than ten times the height of the flower: from this height, they can be carried away by the wind. (For methods and movies, see supplementary information.)

Petals open independently of stamen activity, moving out of their way within the first 0.2 ms (Fig. 1). Petals attain a maximum speed of 6.7 ± 0.5 m s^{-1}, accelerating at up to 22,000 ± 6,000 m s^{-2} (or 2,200g). The process of petal opening and pollen launch in bunchberry plants occurs faster than the opening of *Impatiens pallida* fruits (2.8–5.8 ms, $n=3$, see supplementary information); the snap of venus flytraps (*Dionaea muscipula*; 100 ms)[6]; the leap of froghoppers (*Philaenus spumarius*; 0.5–1.0 ms)[1]; or the strike of the mantis shrimp (*Odontodactylus scyllarus*; 2.7 ms)[2].

As in these other organisms[1,2,6], rapid movements in bunchberry flowers rely on stored mechanical energy. Physiological processes, which take about a millisecond for each enzymatic reaction[7], are not required for the explosion itself. We find that the flowers will open even when the stamen filaments have been crippled by treatment with sodium azide. But the flowers do not open if their turgor is reduced: dehydration of flowers with sucrose decreases the extent of opening, although subsequent rehydration allows them to open fully (results not shown). Turgor pressure is therefore required in the production of mechanical energy for explosive flower opening.

Bunchberry stamens are designed like miniature medieval trebuchets — specialized catapults that maximize throwing distance by having the payload (pollen in the anther) attached to the throwing arm (filament) by a hinge or flexible strap (thin vascular strand connecting the anther to the filament tip). This floral trebuchet enables stamens to propel pollen upwards faster than would a simple catapult. After the petals open, the bent filaments unfold, releasing elastic energy. The tip of the filament follows an arc, but the rotation of the anther about the filament tip allows it to accelerate pollen upwards to its maximum vertical speed, and the pollen is released only as it starts to accelerate horizontally (Fig. 2).

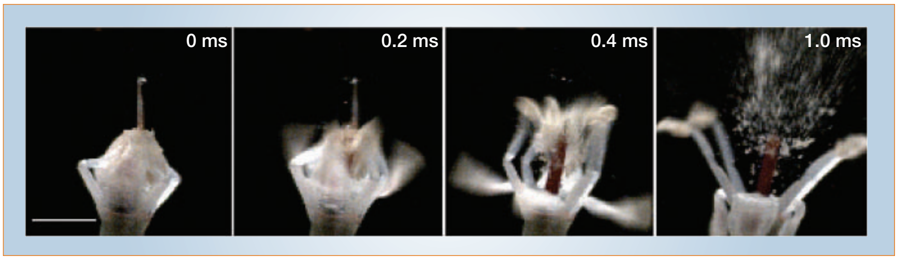

Figure 1 Bunchberry flower opening, recorded on video at 10,000 frames per second. Time elapsed is indicated. First frame shows a closed flower with four petals fused at the tip, restraining the stamens. Blur represents the distance moved in 0.1 ms. Scale bar, 1mm.

The rapid opening of the self-incompatible[8] bunchberry may enhance cross-pollination in two ways. First, when insects trigger flower opening, the pollen released sticks to their body hairs until it is transferred to an adhesive stigma. The force required to open flowers (0.1–0.5 mN) favours large pollinators (bumblebees, for example) that move rapidly between inflorescences; it effectively excludes smaller, less mobile visitors such as ants. Second, pollen from flowers that open by themselves may be carried by wind currents. Indoors, pollen is transported over 22 cm (more than 100 times the size of the flower) and outdoors, in the presence of a steady wind, pollen can move farther than a metre. Exploding flowers enhance insect pollination and may allow wind pollination, adding to growing evidence that flowers often use multiple pollination mechanisms[9,10].

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