Abstractions

LAST AUTHOR

Conventional mass production of silicon-based electronics requires many expensive steps. Making electronic circuits from organic molecules that assemble themselves, an idea first proposed in the 1970s, is a major goal of engineering. On page 956, Dago de Leeuw of Philips Research Laboratories in Eindhoven, the Netherlands, and a multidisciplinary team from industrial and academic centres across Europe describe how they achieved self-assembled-monolayer transistors and integrated circuits. de Leeuw tells *Nature* how they achieved this without dedicated funding.

How is this approach different from traditional circuit fabrication?

We want to be able to throw molecules into a beaker and let them organize into the desired structure without human intervention. Some well known examples of self-assembling entities are DNA or liquid crystals. Our approach required a molecule that could conduct electricity, self-assemble and chemically bind to a physical platform. Through trial and error, we designed a liquid-crystal organic semiconducting molecule and gradually fine-tuned the electrical transport through it — the most demanding aspect of the transistor. To demonstrate their quality and performance, we combined hundreds of these transistors into fully integrated circuits to produce a code generator.

How was this project possible without a dedicated budget?

This project was considered too risky for dedicated funding, but my colleagues and I felt it was crucial to our broader work. Everyone chipped in resources and spare time to get it done. It wouldn't have been possible without industry support or the input of many dedicated colleagues. Philips Research Laboratories provided the technical infrastructure to design, process and model the circuit.

What are the potential applications?

Self-assembled transistors will make good sensors because the semiconductor can be only one molecule thick. One application will be in detecting biomarkers in air and in exhaled breath, part of Philips' health-care strategy. Another planned application is fully self-assembled electronic devices, such as flexible television screens. Imagine that you could put the molecules in your printer at home and get a customized, functional MP3 player 'printed' on paper.

How important is this work?

This is just a first step but we know it will pay off. Sensors are now within reach. Commercial, fully self-assembled organic integrated circuits will come, but much later. ■

MAKING THE PAPER

Redouan Bshary & Olof Leimar

In the cleaning business, two fish are better than one.

Redouan Bshary (left) and Olof Leimar.

Cooperative behaviours, which often involve an exchange of goods or services between two types of 'trader', have intrigued researchers for decades. The bluestreak cleaner wrasse fish (*Labroides dimidiatus*) cleans parasites off the skins of other coral-reef fishes, reaping a satisfying meal in return. But is that all there is to the arrangement? After observing that 'client' fish seem to preferentially visit 'cleaning stations' serviced by pairs rather than by a single cleaner fish, Redouan Bshary, a behavioural ecologist at the University of Neuchâtel in Switzerland, set out to investigate how the quality of service provided by pairs of bluestreak cleaner wrasses might differ from that of individuals.

Although cleaners make a meal of their clients' parasites, they prefer to steal 'cheat' bites of the tastier protective coating of mucus that covers the fish itself. However, this nibble carries the risk that the bitten client will swim away. When Bshary's team first observed that, in the lab, pairs of bluestreak cleaner wrasse cheat less than individuals, they were perplexed. From game theory — a field that explains behaviour through mathematical models — they expected that the pairs would at best be equally cooperative with their clients and provide a cleaning service comparable to that of individual cleaners. Instead, "we found that they are more cooperative and give better service when they clean together than if they clean alone," says Bshary. "This was a big surprise to us."

So when he presented the findings at a behavioural ecology conference in France in 2006, he invited theoreticians in the audience to offer up an explanation. Olof Leimar of Stockholm University proposed a solution on the spot, and subsequently developed a new model of game theory to explain how pairs provide more efficient cleaning (see page 964).

Leimar began with a widely known scenario in game theory called the 'prisoner's dilemma'. The idea behind this is that two partners in crime have a choice: cooperate with one another, remain silent and each face a minor sentence; or testify against the other, go free and commit the other to a long sentence. Although in the short term behaving selfishly is advantageous to one prisoner, cooperation tends to reap greater benefits in the long term.

Leimar applied a version of this theory that incorporated the exact time course of the interaction between cleaner pairs and clients based on field observations. With this model, he showed that if the cleaner fish coordinate efficiently, they remove more parasites from the clients per session. Increased cooperation leads to longer interactions with the client fish, more clients, and more parasite meals for the cleaners. The cleaner fish pairs "are like two partners in business," says Leimar. "They want to have a big line of clients, and the clients like to go to pairs more than singletons because they provide better service. So there is this market effect."

Bshary's team also wanted to know what role cheating might have in the increased cooperation of cleaner pairs. The researchers observed cleaner–client relations among coral reefs in the Red Sea at Ras Mohammed National Park, Egypt. They also performed lab experiments in which cleaners ate from a plexiglass plate 'client' adorned with fish flakes and prawns. If the cleaners ate the tastier prawns, the plate was immediately removed. By counting the number of fish flakes eaten before the removal of prawns, the team measured the willingness of the cleaner fish to cooperate against the preference to cheat.

> **"It's not clear what keeps the males in line."**

Cheating is risky for the cleaner fish because it often results in the client fish terminating the cleaning process. "So cleaners have to find ways to prolong the interaction," says Bshary. "Their only means of doing that is to reduce their cheating." In their field observations and experiments, the researchers found that, although both sexes performed similarly when cleaning alone, within cleaner fish pairs — which always consist of a male and a female — females contribute more to the increase in service quality than the males. Males are larger than females, and often chase their female partner aggressively if she cheats.

This indicates that the male in a pair increases the female's cooperation by punishing her for the cheating behaviour. In other words, in a pair of fish, the unpleasantness of a male's punishment appears to outweigh the female's temptation to sneak a mucus snack and thus increases cleaning efficiency. But the researchers caution that the behavioural interactions between males and females need further exploration, because it's not clear what keeps the males in line. "So punishment may be part of the explanation, but not the whole explanation," says Leimar. ■

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