How Beetles Developed Their Own Biochemical Lab to Take Over the Earth

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Courtesy of SynEvol
Credit: J. Parker

Some groups of species remained very limited—or even vanished entirely—while others were extraordinarily diversified as life on Earth progressed. For scientists researching the origins of life, one of the most important questions has been why evolution favored some groupings over others.

One of the best examples of evolutionary success is the beetle. Their diversity is unparalleled, with over 400,000 species known to exist—nearly a fifth of all recorded life forms—and countless more that are probably undiscovered. Both co-discoverers of natural selection, Charles Darwin and Alfred Russell Wallace, were enthralled by their beauty and diversity when they were younger.

However, why are beetles so common? Their evolution of elytra, which are toughened, shield-like structures that protect their delicate flight wings, is one widely accepted theory. Because of this adaption, beetles may flourish in settings that many other insects cannot reach. According to a different view, beetles and flowering plants co-evolved, diversifying as the insects adapted to consume the plants.

The rove beetles (Staphylinidae), a vast radiation of over 66,000 species, are not only the largest family of beetles but also the largest family in the entire animal kingdom. Nevertheless, neither of these theories can adequately explain the largest beetle group of all. They appear to have both abandoned, highly defensive elytra and are mostly predatory rather than plant-eating, which makes roving beetles a mystery. However, within the last 200 million years, they have exploded throughout the biosphere of Earth, occupying every conceivable terrestrial niche.

Researchers in the lab of Joe Parker, an assistant professor of biology and biological engineering, Chen Scholar, and director of Caltech's Center for Evolutionary Science, have conducted a new study that aims to determine what caused this extraordinary result. The study, which was led by former postdoctoral scholar Sheila Kitchen and published online on June 17 in the journal Cell, identifies the evolution of two cell types that form a chemical defense gland within the bodies of these beetles as the driving force behind their worldwide radiation.

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The "tergal gland," a feature at the tip of rove beetles' flexible abdomens, was the subject of a 2021 study by Parker lab researchers. Using two distinct cell types, the scientists demonstrated how the tergal gland produces toxic substances called benzoquinones and a liquid combination (or solvent) into which the benzoquinones dissolve to form a powerful cocktail that the beetle releases at predators.

In the new study, Kitchen, Parker, and their colleagues compiled whole genomes from a wide range of species across the evolutionary tree of rove beetles and examined the genes expressed by the two cell types of the gland. By doing this, they were able to discover an old genetic toolbox that gave these insects their potent chemical defenses and evolved more than 100 million years ago.

"We were astounded by how similar the gland's genetic architecture was across this enormous group of beetles when we were piecing together the genomes," says Kitchen, who is currently an assistant professor at Texas A&M University. When we began examining particular gene families, we discovered a small but crucial group of evolutionarily new genes in addition to hundreds of ancient genes that had discovered new roles within the gland. The remarkable chemistry of roving beetles evolved thanks in large part to these new genes. Our outstanding multidisciplinary team of evolutionary biologists, chemical ecologists, protein biochemists, and microscopists enabled us to tell this story.

The team discovered a significant evolutionary breakthrough in the way the beetles developed to safely produce the toxic benzoquinones by retracing the molecular stages in gland evolution. The method of poison secretion that rove beetles discovered is remarkably similar to how plants regulate the release of chemical compounds that discourage herbivores. Only until the chemical is safely released outside of the beetle's own cells do they break the toxin from the sugar after binding it to the sugar molecule and making it inactive.

Parker says, "It's pretty amazing that chemically defended beetles put together essentially the same cellular mechanism as plants to prevent themselves from poisoning themselves with their own nasty chemicals."

The beetles began to spread out into tens or perhaps hundreds of thousands of species when they developed this technique in the Early Cretaceous. "It is the quintessential key innovation." Evolutionarily speaking, they advanced significantly once they discovered this solution, according to Parker. With few tens to hundreds of species, related rove beetle lineages lacking the gland have not undergone the same evolutionary diversification.

Through examining the chemistries of several species, the researchers discovered that, astonishingly, although the two cell types that make up the gland have remained mostly unchanged, the chemicals they produce can change significantly, allowing rove beetles to adapt to various ecological niches. A beetle species can create the chemicals it needs to survive in new surroundings by using the gland as a sort of chemical laboratory. In order to live symbiotically with and even prey on worker ants, one group of rove beetles evolved to prey on mites and repurposed the gland to secrete mite sex pheromones. Another group of beetles lives inside ant colonies and produces chemicals that calm the otherwise extremely aggressive worker ants.

"This amazing, reprogrammable mechanism for creating new chemistries and developing new interactions is the rove beetle tergal gland," adds Parker. These beetles were able to attain tremendous ecological specialization because of it. The strange and amazing niches that these beetles have found themselves in would not have been accessible without the gland.

Paradoxically, the team discovered that the gland was overproduced in one set of beetles. "Apparently, you no longer need the gland once you have lived inside an army ant colony of millions of aggressive ants for a sufficient amount of time," Kitchen said. We discovered that beetles that have successfully enticed ants to accept them into their communities had evolved without glands. Many inactivating mutations had accumulated in their gland toolkit genes. Most animals would find an ant colony threatening, but these beetles see it as a safe haven because they have tricked the ants into defending them.

The new study demonstrates how cellular evolutionary changes can have significant, long-term effects on ecological and evolutionary diversification. In this instance, helping to the excessive love of bugs in nature.
