Coevolution

By Tim Stephens

JIM MACKENZIE

UC Santa Cruz biologist John Thompson's research explores how species evolve together in the web of life

In the creeks and woodlands around San Francisco Bay, garter snakes and newts are engaged in a biological arms race—the snakes eat newts, the newts produce a potent neurotoxin in their skin, the snakes evolve resistance to the toxin, the newts evolve to produce more toxin, and so on. While the newts still fall prey to toxin-resistant snakes, even a resistant garter snake may be incapacitated for hours after eating a highly toxic newt.

This situation has evolved over time as a result of "tit for tat" evolutionary changes driven by natural selection—a classic example of the coevolution of two interacting species.

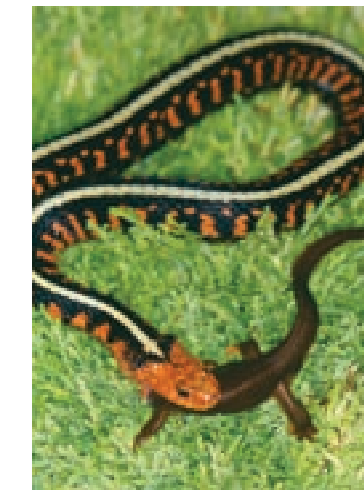
Coevolution shapes all kinds of interactions between species—not only the antagonistic interactions of predators and prey or parasites and their hosts, but also mutually beneficial partnerships like those of flowering plants and their pollinators. In fact, most plants and animals depend on coevolved interactions with other species in order to survive, says John Thompson, an internationally recognized authority on the subject.

"Much of evolution turns out to be coevolution, and ecological communities are based on these deeply coevolved relationships between species," says Thompson, a professor of ecology and evolutionary biology at UC Santa Cruz.

Thompson's research explores the role of coevolution in organizing the web of life on Earth. The potential applications extend from medicine and agriculture to conservation of the Earth's biodiversity. "It turns out that many of the major societal problems we face in biology are problems involving coevolution," he says.

Thompson, who published his third book on coevolution last year, has been a leading player in the field's rapid growth over the past decade. One of his major accomplishments has been to establish a coherent

The snake and the newt:
Trapped in a biological arms race



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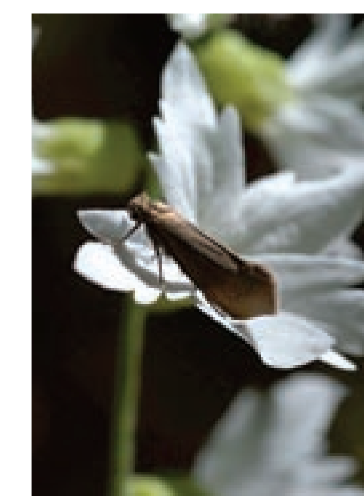
The moth and the flower:
Mutually beneficial, but not always



OLLE PELLMYR

theoretical framework for studying and understanding coevolution.

"He has been instrumental in pushing the field forward," says Indiana University biologist Edmund Brodie, whose research on the interactions between the newts and garter snakes illustrates a central concept in Thompson's work: the geographic mosaic of coevolution.

This idea explains how the coevolution of two species can lead to different ecological outcomes in different environments. In the case of newts and garter snakes, their evolutionary arms race has escalated around San Francisco Bay and in one area on the Oregon coast, but not in other places where the same species coexist.

Thompson's book, *The Geographic Mosaic of Coevolution,* includes many similar examples, some from his own research and others, like the snakes and newts, from the work of other researchers. His geographic mosaic theory builds on a key insight about the genetic structure of species: Every species is made up of many different populations, each adapted to its local environment and therefore genetically distinct from other populations of the same species.

"Different populations of the same species are connected to each other to various degrees across landscapes, but each population evolves different adaptations to its local environment," Thompson says.

He notes that the local environment for any given population includes locally adapted populations of *other* species. Coevolution is the dynamic process that occurs as each local population evolves in response to evolutionary changes in the populations of other species with which it interacts.

The result is a complex geographic mosaic of species interactions. Some of these local interactions become coevolutionary "hotspots," where natural selection drives reciprocal evolutionary changes in the two species to an extreme degree. Why the San Francisco Bay Area is a hotspot in the coevolution of newts and garter snakes is still unclear.

JIM MACKENZIE

Coevolution in the lab: Postdoc Samantha Forde creates a microcosm of bacteria and viruses that coevolve as the viruses infect the bacteria, the bacteria build resistance to the viruses, the viruses overcome the resistance, and so on.

"The challenge is to understand how coevolution occurs within all the conflicting pressures that are pulling populations one way and another," Thompson says.

Much of Thompson's own research has focused on the relationship between a small grayish-brown moth and a common wildflower called woodland star. The moth is both a pollinator of the wildflower and a consumer of its seeds, and their interactions have evolved in different locations to cover the full range of possibilities, from mutually beneficial to antagonistic. For example, in locations where there are other pollinators for the flower, the plants have evolved defenses against the moth that are not present in populations that depend on the moth for pollination.

Thompson also uses laboratory experiments involving common bacteria infected with viruses to test the predictions of his theory. By working with microbes that reproduce rapidly (ten generations per day in the laboratory), he and his collaborators are able to track genetic changes over time as the bacteria and viruses coevolve, with bacteria evolving resistance to the viruses, the viruses overcoming that resistance, and so on. These studies have shown that the pattern of adaptations depends on both the environment in which the organisms are growing and the spread of genes between different populations.

"We could not really probe these things well until the rise of molecular biology and the development of sophisticated tools for genetic analysis," Thompson says.

The geographic mosaic itself is constantly shifting. Each local interaction between species is like a coevolutionary experiment. Over time, some of those local experiments fail and populations go extinct. Other populations, however, prosper and spread their genes across landscapes.

"It's this process of ongoing coevolution across landscapes that keeps interacting species in the evolutionary game over thousands or millions of years," says Thompson, who is increasingly concerned about how the coevolutionary processes that organize ecosystems can be maintained in the face of rapid changes driven by human activities.

"One of the things we may be losing as development causes increasing fragmentation of natural landscapes is the luxury of occasional extinctions of populations," he says. "It's like having a diversified stock portfolio that allows you to win some and lose some and still stay in the game."

Conservation strategies have tended to be based on the idea that the ecosystems that people want to protect exist in a fairly static state. But scientists are now realizing that populations can evolve and coevolve more rapidly than was once thought possible. As a result, conservation organizations are beginning to see the need to consider dynamic coevolutionary processes in their planning, Thompson says.

Biomedical researchers are also starting to recognize the importance of coevolution in understanding the dynamics of infectious diseases. In 2003, for example, Thompson was invited to speak at an international conference on malaria at Harvard University.

"Malaria is a good example of a disease that we know is geographically variable and has coevolved with its host species over thousands of years," he says.

Human populations differ in their genetic defenses against malaria, and the mosquitoes that transmit the disease also show geographic variability. Rapid evolutionary changes have occurred in both the malaria parasite and the mosquitoes in response to the drugs and insecticides that have been deployed to fight the disease.

"The question is, how can we use what we know from evolutionary biology to develop better therapies and devise strategies that will minimize the evolution of resistance when we come up with new therapies," Thompson says. "We are just beginning the conversations between disciplines that will help us answer those questions."

Humans have, in fact, been manipulating the coevolutionary process for thousands of years. The story of agriculture involves a long history of human-induced coevolution between crop plants and rapidly evolving parasites and pathogens, Thompson says.

This game of surrogate coevolution continues, going back and forth between plant breeders, who are constantly producing new disease-resistant crops, and the fungi, bacteria, and viruses that are constantly evolving to become more virulent. A current example is the emergence in East Africa of a new strain of wheat rust that, according to biologists who raised the alarm in September, could wipe out 10 percent of the world's wheat production. Of course, work is already under way to breed and disseminate new resistant varieties of wheat to combat this new strain of rust fungus.

As researchers learn more about how the coevolutionary process works and the factors that create hotspots and coldspots, they may find new ways of manipulating that process.

"We should be able to take the results from studying coevolution in the wild and start applying them to practical problems," Thompson says.

Controlled environment: Thompson inspects glass tubes used to conduct experiments with coevolving flowers and moths.

JIM MACKENZIE

JOHN THOMPSON

Taking STEPS to advance environmental research

The theme of connectedness runs throughout the work of John Thompson, professor of ecology and evolutionary biology, and through the activities of the institute he directs at UC Santa Cruz—the STEPS Institute for Innovation in Environmental Research. The STEPS Institute encompasses science, technology, engineering, policy, and society in its approach to environmental research, which it supports through a variety of initiatives, workshops, fellowships, and grants.

An interdisciplinary approach to environmental research comes naturally to a scientist concerned with the interactions between species, the interconnected web of interactions within ecosystems, and the connections between human activities, ecosystem functions, and the global environment.

"Humans are creating changes in the environment that amount to a set of intertwined global experiments whose long-term effects are unknown. We don't really know what's going to happen down the road," Thompson says.

The STEPS Institute fosters research and policy efforts that address these potential effects. Its efforts have coalesced into two initiatives—the Genes to Ecoregions Initiative and the Regional Climate Change and Water Initiative. Through these initiatives, the institute is forging new collaborations among faculty researchers, policy makers, and environmental managers.

Part of the Genes to Ecoregions Initiative, for example, is the Santa Lucia Gradient Study, which focuses on a region of California that is rich in both biological diversity and jurisdictional complexity. STEPS has hosted workshops at UCSC that brought together representatives of the many governmental and nongovernmental agencies, private groups, and university researchers studying the remarkable landscape of the Santa Lucia Range, which rises steeply from the Big Sur coast. The institute has developed a "meta-database" of biodiversity research in this region—a comprehensive resource to give researchers access to the results of decades of past work by researchers and managers working for different organizations.

The STEPS Institute was established in 2002 with a $500,000 gift from UCSC alumnus Gordon Ringold and his wife, Tanya Zarucki. Since then, it has provided fellowships for interdisciplinary graduate research and research grants to faculty, graduate students, and undergraduate students. Most of the funds are for research projects that either link multiple research laboratories at UCSC or link UCSC laboratories with outside agencies or policy makers.

Thompson's current focus for the institute is to increase support for graduate students interested in environmental research problems that span traditional disciplines. "We need to train the next generation of environmental scientists to think about problems in a more interdisciplinary way," he says.