



# the Evolution of Individuality and Sex

BY DON MONROE

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**“As far as we know, life began once, four**

and a half billion years ago, and since then has been passed down like a family heirloom from parent to offspring,” says Richard Michod, head of the Department of Ecology and Evolutionary Biology at the University of Arizona. Along the way, life has repeatedly devised novel ways to organize and reproduce itself as it evolved from primitive self-replicating molecules to complex societies of multicellular organisms.

The persistence and enhancement of our genetic legacy is all

the more striking when contrasted with our frail and mortal bodies. In fact, eliminating inferior individuals is crucial to the biological evolution that drives new innovations. As an evolutionary biologist, Michod has explored this process both theoretically and experimentally.

At a September SFI Business Network meeting in Washington, D.C., Michod spoke about “Cooperation and Conflict during the Evolution of Individuality and Sex.” The talk came within the larger theme of the meeting: “Conflict, Cooperation and Creativity in Complex

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SEM (Scanning Electron Microscope) of a single sperm penetrating an egg at the point of fertilization: Researchers are finding that sex has important biological purposes beyond procreation.

Systems.” Organized by SFI Research Fellow Jessica Flack, and William Glenney, Chief of the Naval Operations Strategic Studies Group, the meeting focused on identifying the types of conflict that lead to creative new solutions.

Michod described a continuing cycle—more accurately a spiral—of cooperation leading to new types of conflict, which in turn lead to higher levels of cooperation and the emergence of novel traits. “Basic properties of the living world emerge out of this cycle of cooperation and conflict,” he said.

He described several stages along this spiral, starting with the innovation of the cell. Drawing on his own experiments in colony-forming algae,

some of which catalyze the replication of DNA, but in the beginning there was probably only a single molecule. The prime suspect is RNA, which can both replicate its internal structure and act as a catalyst.

Simply replicating is not enough, however, because some errors always happen during copying. Some three decades ago, theoretical biologists suggested that cooperative networks of genes (presumably RNA at first) that promote each other’s production could keep errors from accumulating. As long as the error rate is below some threshold, Michod said, such networks, known as heterocycles, “maintain themselves stably through time.”

Although free-floating genes can cooperate in this way, “it’s a poorly

fates of its constituents, Michod said, “it enforces cooperation on them,” because cells with selfish mutants do worse than cells with cooperative genes. “The cell is the perfect example of a conflict mediator.”

Michod only briefly mentioned another milestone, the appearance of eukaryotic cells that comprise all multicellular organisms as well as many single-celled organisms. Biologists widely agree that the DNA-containing mitochondria—the structures in animal cells that provide energy—and chloroplasts—which perform photosynthesis in plants—were once separate species. Even the nucleus, the defining feature of eukaryotic cells, may have arisen from such interspecies cooperation.

to devote resources to every aspect of survival, and addressing one task can impede another.

“There are often tradeoffs between the effects of a trait on different necessary components of fitness,” Michod observed. In the alga *Volvox carteri*, for example, cells cannot reproduce while they maintain the hair-like flagella that let them move in response to their environment. An individual cell cannot benefit from having flagella without sacrificing reproduction.

“Division of labor in the group is a way to break through this tradeoff that governs the life of single cells,” Michod explained. In fact, many *Volvox* species form colonies with a few germ cells dedicated to reproduction while other “soma” cells retain the flagella that let the entire colony move.

Although specialization clearly benefits the colony as a whole, Michod pointed out, the soma cells must act altruistically, because they forgo the chance to reproduce themselves. “Altruism is widely appreciated to be the central problem of social behavior, and it’s also fundamental to the evolutionary transition to multicellularity. It takes fitness from one level and gives it to another, from the cell to the colony.”

One evolutionary explanation of altruism, known for decades, is based on kin selection: it makes sense for an individual to sacrifice its life for others, as long as those others share enough of its genetic heritage. The genetically identical algae cells clearly meet this requirement. However, Michod’s team is still clarifying why only some *Volvox* species—generally

those that form larger colonies—display this altruistic behavior.

The researchers also identified the molecular mechanism by which *Volvox* cells specialize. They found that the genetic “switch” that determines whether a cell becomes a germ or soma cell is adapted from a mechanism that already existed in single-cell algae. That mechanism—like the calorie-restriction response that extends life in many animal species—acts to delay reproduction in favor of extended survival when resources are limited.

There are limits to this strategy for resolving conflict between cells, Michod noted. Since the soma cells do not divide at all, they can never go on to make larger structures. The way in which conflicts are mediated, he noted, “can have effects on the future evolvability of the lineage.” In contrast, our own cells continue to divide. Even when they are not destined to become reproductive cells, they continue to specialize, forming the various complex tissues in our bodies.

#### Sex: Evolution’s Raw Material

Finally, Michod discussed the evolutionary role of sexual reproduction. In many species, such as humans, sex is

tied to reproduction. But other species, including large animals like some lizards, reproduce asexually, while other species exchange genetic material independently of reproduction, Michod noted. “The idea that sex is necessary for reproduction doesn’t hold up.”

From an evolutionary perspective, Michod said, “the most obvious thing about sex is its cost.” Extravagant displays like those of the male peacock appear to be unnecessary and wasteful, but help meet the challenge of finding a choosy mate. Sex also exposes the body to the risk of infection.

“What are the benefits that offset all these costs?” Michod asked.



Sex has an evolutionary cost, as evidenced in the extravagant display of the male peacock

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he clarified the conflicts leading to multicellular life and to sexual reproduction. This cycle of innovation illuminates not only the nature of life on Earth, but more general principles of how conflict and cooperation can foster innovative approaches to problems.

#### Cells as Conflict Mediators

In the primordial chemical soup, Michod said, “the first individuals were things like molecules and genes replicating through some kind of prebiotic chemistry.” Current organisms use DNA to specify proteins,

defined life, these cycles of genes,” Michod observed. “Cheating was rampant.” A gene that undergoes a “selfish” mutation, so that it propagates at the expense of its partners, will eventually take over. “Pretty soon there’s only taking, no giving, and the whole cycle goes extinct.”

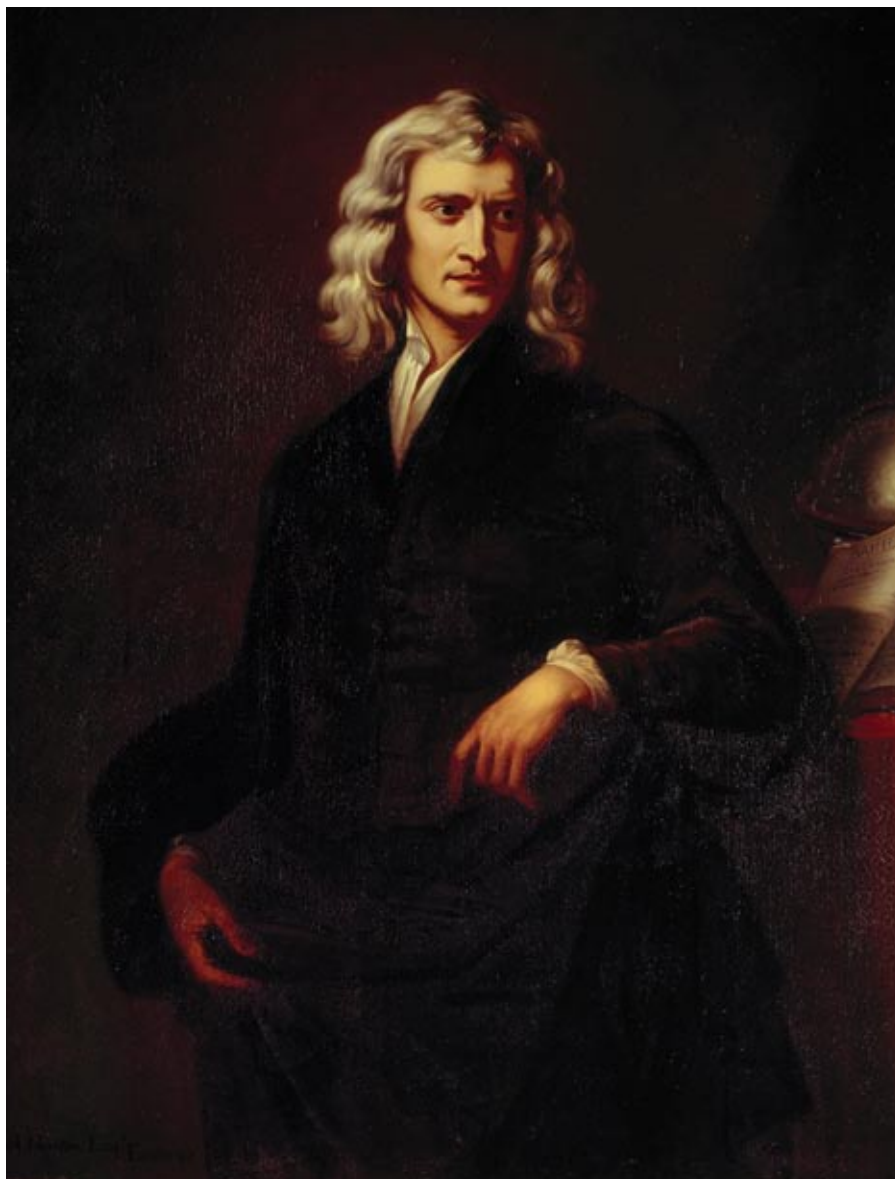
Faced with this conflict between its constituents, Michod said, “there’s a need for some kind of conflict mediation.” The membrane-enclosed cell solved this problem. “What the cell does is align the interests of all the members inside.” By linking the

#### Altruistic Cells

In the laboratory, Michod recapitulates the more recent development of multicellularity by studying colony-forming algae. Poised at the crossroads between a single-cell and multicellular lifestyle, these primitive plants illustrate the conflicts that push life one way or the other.

“A single cell has immediate and effective interaction with its environment,” Michod said, making it easy to get resources and get rid of wastes. “The problem is simply that a single cell has to do everything.” A cell has





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Curiously, creative people, such as Isaac Newton (1642–1727), are often misfits who don’t reproduce, raising questions about their repeated appearance in the population.

“Biologists differ strongly on what they think are the major benefits of sex, and there’s no real agreement on the whole problem.” They agree, however, that the mixture of traits between individuals provides raw material for evolutionary change. Like altruism, this explanation involves a transfer of fitness between levels, in this case between individuals and their species.

Sex also corrects genetic damage, Michod said. Damage to the DNA of one partner can be repaired by undamaged DNA from the other partner. In this way, sex recovers an error-correcting feature that had been present in early genetic networks. This feature was lost somewhat when life began forming cells, because “damages and mutations get trapped on the inside,” Michod observed.

“Sex repairs DNA,” he said, helping to explain how “the cells in our body get old and die, but our germ line goes on forever.”

Further insight into sex comes from species that can reproduce either sexually or asexually. There is general agreement, Michod said, that “in such organisms sex is induced by stress.” He suggested that the stress acts by affecting the balance between the oxidation and reduction reactions that fuel life. “Stress universally upsets this balance,” he said, resulting in a buildup of reactive oxygen species that can damage DNA. “Sex is a way of coping with this damage,” Michod commented, because it repairs DNA. Indeed, he and collaborator Aurora Nedelcu of the University of New Brunswick found that exposing algae to antioxidants prevents their sexual response to heat stress.

Like other evolutionary changes, sex helps to solve problems introduced by earlier innovations, but it introduces new problems. These include biological and behavioral manipulation of the mating process, such as genes that limit the resources that males devote to offspring. “There are all kinds of conflicts that are set up because of sex,” Michod observed. “You solve one set of conflicts but then create other sets of conflicts. It’s the raw material that leads to continued evolution.”

### Harnessing Social Conflict

Other presenters at the meeting identified the types of conflict that lead to creative new solutions. Flack set the stage by describing conflict-mediation mechanisms in three very

different arenas: policing of conflict by dominant chimpanzees, elaborate election procedures in Renaissance Venice, and co-option of “jumping genes” to build the adaptive immune system. In each case, she said, “either the arms race between the components or the implementation of the robustness mechanisms, resulted in new problems, which in turn generated the evolution of new solutions to maintain stability. So we get this ratcheting up of complexity in all of these systems.”

In the context of the whole meeting, Michod’s research provides intriguing examples of innovative mechanisms for mediating conflicts, which could also apply to human situations. Good managers, for example, well know the value of aligning the interests of individuals with those of the whole team, as the cell does for its genetic networks. Similarly, division of labor was applied in manufacturing long before it was recognized in *Volvox*. Enlightened managers have also encouraged (non-sexual) “cross-fertilization” between teams to stimulate new ways of thinking.

Still, there are risks to using evolutionary conflicts as a metaphor for human behavior. For one thing, biological evolution acts only through the persistence of genetic changes in offspring, while cultural evolution transmits new ideas rapidly between unrelated individuals and organizations. Perhaps more sobering, biological evolution works only because

*Volvox alga*, a kind of green algae, reproduces both asexually and sexually. Such behavior raises questions about the purpose of sex.

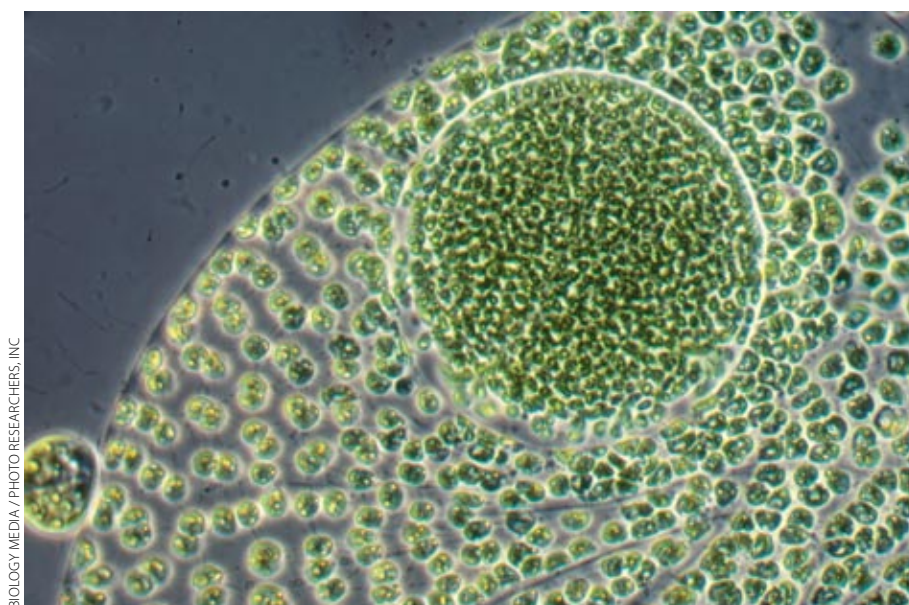
individuals or species that use inferior strategies are killed off. Hopefully, directly adopting the best practices of others can help organizations avoid this fate.

The other speakers at the meeting offered highly varied insights into the roles of conflict at the social level. Dean Simonton, Distinguished Professor and Vice Chair of the Department of Psychology at the University of California at Davis, for example, extended evolutionary ideas to individual creativity in two distinct ways. Creative geniuses are often misfits who do not reproduce, he said, so their repeated appearance in the population demands an evolutionary explanation, perhaps like those that Michod described for altruism. Simonton also described “secondary Darwinism,” the social and personal influences that encourage susceptible individuals to generate the wide-ranging ideas that underlie creativity.

Uniquely creative individuals were clearly critical in the development

of both atomic and thermonuclear weapons. Richard Rhodes, author of the Pulitzer Prize winning *The Making of the Atomic Bomb* and many other books, contrasted these two mega-projects, saying that, although external conflict was a primary driver for both, conflict within the project was much more destructive for the hydrogen bomb. Aaron Clauset, a postdoctoral fellow at SFI, discussed more modern conflicts, analyzing patterns in terrorist attacks. He concluded that although the attacks of September 11, 2001 were unusually large, they are best seen as part of the “long tail” of a power-law distribution of event sizes, rather than as historically unique events.

The tension between conflict and cooperation leads to innovation in a variety of situations, and researchers are still struggling to describe the many ways this happens. One day, perhaps, they may be able to systematically analyze and even predict this evolution. —Don Monroe ◀



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