Electronic Ecosystem

Evolving 'life' flourishes and surprises in a novel electronic world

By JOHN TRAVIS

"I created them, I can destroy them, and I can bring them back," Thomas S. Ray says playfully.

Ray, a decidedly ungodlike evolutionary biologist, has created an intriguing electronic world named Tierra, populated with self-replicating digital "organisms" that evolve as they compete for computer time and memory.

Tierra (Spanish for Earth) is a diverse world, home to helpful neighbors and a variety of liars, cheaters and freeloaders. According to Ray, this digital domain provides a unique laboratory for studying ecological and evolutionary theories that are otherwise difficult to test.

His work advances a relatively new and fast-growing field called artificial life. In this somewhat nebulous discipline, scientists seek to simulate and synthesize lifelike behaviors within computers, chemical mixtures and other media. Their creations have included ant colonies and flowering plants that flourish within computers and on digital display screens, and computer-animated birds that develop a classic V-shaped flocking pattern on their own (SN: 5/19/90, p.312).

Ray's Tierra organisms do not actually "live," as we define the word; they are merely computer programs that constantly make copies of themselves. Nonetheless, he says, their "evolution" may help us understand what living is all about. Moreover, he says, "it's extremely exciting to create 'life.'"

Ray, like his creations, is a mixture of biology and computer science. After earning a doctorate in biology, he built his own laboratory to study evolution and ecology on 40 acres of Costa Rican rain forest, which he had purchased with money borrowed from his father. Two years ago, after receiving tenure at the University of Delaware in Newark, he immersed himself in computers and shifted his focus from the tropical ecosystem to an electronic one.

His interest in synthetic life goes back to 1980, when he was a doctoral student at Harvard. Ray had started playing an ancient Chinese board game called Go, and one night he met a player from MIT's artificial intelligence laboratory who explained the game in lifelike metaphors. The MIT player also told him that computer programs could self-replicate. Though Ray was extremely excited by that thought, it lay dormant in his mind for nearly a decade, he says.

Last year, he gave birth to Tierra – a world where life, death, competition and reproduction are represented in computer terms. He can observe this world in a variety of ways, the most visual being ALmond (short for Artificial Life Monitor), developed by Delaware graduate student Marc Cygnus. In ALmond's shifting patterns of colored rods, Ray watches his organisms evolve and compete with each other. A single short computer program whose only task is to replicate itself will quickly populate the screen with its progeny, he says.

To create Tierra, Ray used a "virtual computer," a software program within his computer that simulates a second computer. This prevents his fledgling creatures from getting loose and wreaking havoc like computer viruses. His artificial life scenarios are therefore no more dangerous than the text files on a word processor, he explains.

The virtual computer includes a block of memory that Ray calls the "soup" – a reference to the primordial mix of chemicals from which Earth's life apparently emerged. Into this soup, he unleashes the computer programs he calls organisms. Ray developed his own computer language to write these self-replicating programs. Whereas most computer languages require huge numbers of machine instructions, Ray sought to create a much smaller instruction set to mimic the size of the human genetic code. Eventually, he pared down to 32 the number of distinct instructions needed to control all operations within Tierra.

Another vital feature of Tierra borrowed from molecular biology is the concept of "address by template." This phenomenon enables real-life proteins to interact within a cell. Protein A may not know exactly where protein B is, but it presents a surface template that is complementary to B. Eventually, diffusion brings the two proteins in contact with each other; their templates interlock, and the proteins interact.

Many Tierran instructions, such as those directing an organism's self-replicating process, have templates. The electronic template is actually a series of four computer instructions, each representing a 1 or 0. Thus, a digital organism cannot replicate itself until its copy template (1100, for example) finds a complement (0011) nearby in the computer memory. In effect, says Ray, Tierran templates act as sensory apparatuses, allowing organisms to explore the soup and interact with each other.

"I think this feature is one of the most important things I did," he says, because a Tierran creature can still function if its template undergoes mutations. As long as the organism's important instructions are left unharmed, it need only search for a different complement template to execute those instructions.

Mutations are what allowed Ray's original creature – a self-replicating program 80 instructions long – to evolve and diversify.

Tierran mutations arise in two ways. In one type – Tierra's equivalent to mutagenic cosmic rays – bits in the memory soup randomly flip from 1 to 0 or vice versa about once in every 10,000 executed instructions. All in all, the creatures in the memory pool hold more than 60,000 instructions consisting of 300,000 bits.

The other type of mutation occurs during reproduction. Tierran creatures mimic the asexual reproduction of bacteria and viruses: Each program produces a daughter "cell" that should be an exact copy of itself. However, replication errors do occur. About one bit flips per every 1,000 to 2,500 instructions copied, adding variation to the daughter cell.

Ray's creatures also add variations through what he calls "sloppy reproduction." In effect, this is a primitive sexuality similar to a bacterium's absorption of DNA fragments from dead bacteria nearby. The organism's instructions are "being scrambled, which is what sex is about," says Ray. "It results in genetic recombination, even though it is not organized, as it is in higher organisms."

Death also exists in Tierra, in the form of the "reaper." This monitoring program eliminates the oldest creatures and the most defective ones – those that erred most often in executing their computer instructions. When the "population" of the memory soup reaches a specific level, such as 80 percent, the reaper starts killing. This measure became necessary, Ray says, because self-replicating creatures would quickly fill up the soup and lock up the system. With the reaper, there is no immortality on Tierra. An organism eventually ages or mutates to death.

The reaper maintains a prioritized "hit list," adding new organisms in the order of their birth. As an organism ages, it moves up the queue. Errors in execution also move an organism up the queue, in a process resembling the Darwinian elimination of the "weak" before the "strong," Ray says.

Tierra even contains a temporary Fountain of Youth, consisting of two difficult computer instructions. If an organism executes these instructions successfully, it moves down a spot on the hit list, staving off death a bit longer.

During Tierra's first working run, in January 1990, Ray experienced a pleasant surprise. His lone, 80-instruction organism, the "ancestor," quickly reproduced and diversified into a variety of different creatures.

"I sincerely thought it would take years of hard work," he recalls, "but everything I've described in my papers occurred in the very first run. It was that easy."

Ray, who programmed the ancestor himself, had expected its offspring to show a slight increase in efficiency, and had even guessed at the possibility of a self-replicating program involving as few as 76 instructions. But overnight, Tierran evolution produced a speedy creature that was only 22 instructions long and could reproduce six times as rapidly as the ancestor.

"That really floored me," Ray says. In fact, after seeing the pint-sized speed demon, he was slightly embarrassed by the amateurish nature of the ancestor program. To add sophistication to future programs, he has recruited the expertise of Dan Pirone, a computer scientist from the University of Delaware.

Large creatures – including a mammoth one with 23,000 instructions – also emerged in Tierra, but these behemoths could not compete with the smaller, faster-reproducing organisms. Like the dinosaurs, they went extinct.

Although Ray expected to see size variations, some denizens of his digital planet also evolved a surprising amount of functional diversity. Benign parasites emerged, along with immune hosts, "hyperparasites" and "cheaters."

Tierra's parasites cannot replicate without help from a host. Ray compares these harmless freeloaders to real-life viruses that invade a cell and use its ribosomes to make copies of themselves. "My parasites don't have the 'genes' for the copy procedure," he says, so they follow the instructions programmed into surrounding organisms. Their small size gives the parasites a distinct competitive advantage, since they require less computer time to copy themselves.

One parasite, 45 instructions long, quickly emerged in the memory soup and entered into a benign relationship in which it used an ancestor organism's copying instructions to replicate. Later, a 79-instruction creature, more efficient than the ancestor, proved immune to most parasites and came to dominate Tierra.

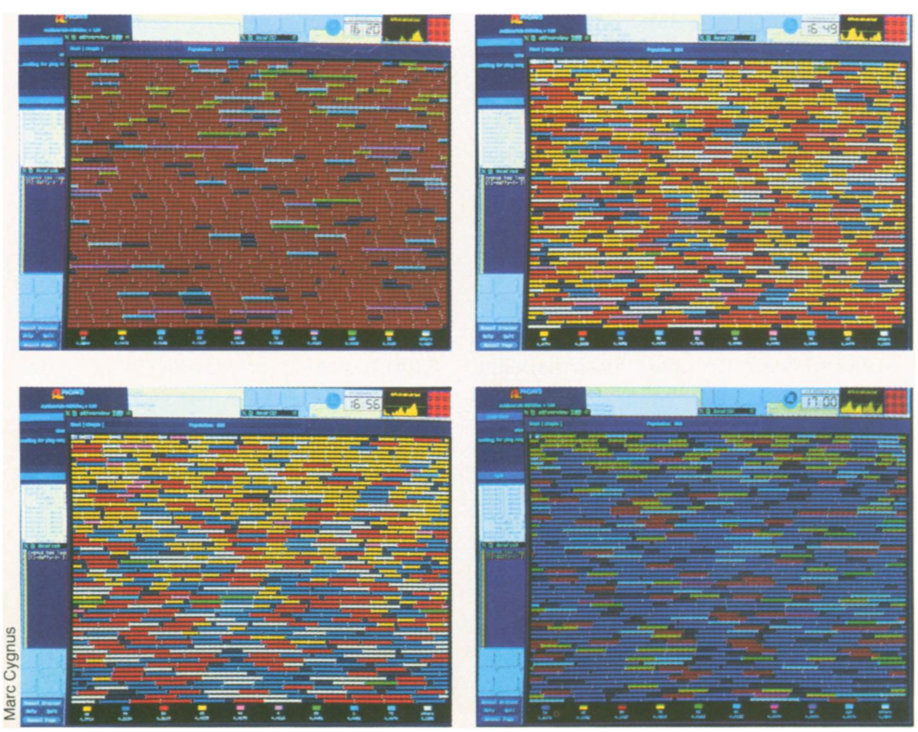
But Tierran evolution eventually produced a parasite capable of bypassing that immunity. This organism, 51 instructions long, could successfully invade the "resistant" host to copy itself.

These tricks were simple compared with those of the bizarre entities Ray describes as "hyperparasites." Tierran organisms normally "compete" for space in the soup, yet "they invented innovations for competing for time," Ray says. Computer time, the Tierran equivalent of energy, is doled out equally to each program by a "slicer" that determines when an organism can execute instructions. But some creatures developed an ability to steal extra time for reproducing.

When a normal parasite invades one of these hyperparasites and attempts to reproduce using the host's copy procedure, the hyperparasite substitutes its own code for the unsuspecting organism to copy throughout its life. In this way, the hyperparasite manages to reproduce more often but without using any extra energy. It's like a neighbor stealing your electric line and running his appliances, says Ray. You sit in the dark, and you still pay the electric bill.

Despite their nasty ways toward parasites, hyperparasites can be downright sociable with one another, he adds. After driving the parasites to extinction, the hyperparasites can form a community where they cooperate in copying each other. In order to reproduce, "they need to be with their own kind or others that look like them," says Ray, emphasizing their interdependency.

This type of trusting community is vulnerable to outsiders, and other creatures evolve to take advantage of hyperparasitic naivete. A "hyper-hyperparasite," known more simply as the "cheater," sneaks into the placid community and steals the energy source that the hyperparasites pass among each other. The extra energy does not make it immortal, but Tierran cheaters do prosper, accomplishing more and reproducing more of-



Marc Cygnus

Shifting patterns on an Artificial Life Monitor depict evolution and competition among Tierran "organisms." At first, Tierra is dominated by red rods representing the ancestor organism – the original, 80-instruction computer program (upper left). Smaller, faster-reproducing "parasites," shown in yellow, soon emerge and dominate the electronic world (upper right). However, evolution then produces parasite-resistant hosts (blue rods at lower left), which quickly take over the display screen (lower right).

ten over a lifetime.

Lying, too, can pay off on Tierra. When the slicer doled out time on the basis of size, some organisms "told" it they contained more instructions than they actually did, garnering more computer time, Ray says.

Another organism developed an odd habit of sometimes executing three instructions in a row instead of the normal one. Perplexed by this development, Ray turned to computer science friends, who immediately recognized the phenomenon as a computer programming trick that increases efficiency, called "unrolling the loop."

This evolution from a single, simple ancestor into a wide variety of creatures is important, says Ray, since none of the offspring organisms were built into Tierra. He argues, therefore, that Tierra depicts a synthesis of life, not a simulation as in other such projects. For example, the digital birds mentioned earlier developed their flocking patterns because of preset rules governing how close to each other they could fly and other aspects of flight. And in the simulated ant colonies, the ants came equipped with "genes" that controlled their insect-like behavior and sensory input.

"Others [in the field of artificial life] define in advance what the genes are," says Ray.

Because Tierra has no such preconditions, Ray says, its inhabitants can truly evolve strategies that are not predefined in the system. "It's like I've defined an underlying chemistry and thrown in a self-replicating molecule to see where it goes. They [the organisms] keep coming up with innovations," he says.

The individual creatures intrigue Ray, but it is their interaction and the emerging population patterns that fascinate the ecological scholar in him. "One of the biggest questions in ecology is: To what extent does competition structure community?" he notes.

Tierra, which demonstrates the two important concepts of competitive exclusion and coexistence, can help with the answers, he contends.

Exclusion occurs when two species compete for a limited amount of space — such as Tierra's memory soup — and the stronger one drives the weaker near extinction. Coexistence is less clearly understood, says Ray, but in tests pitting a 79-instruction program against larger creatures, both outcomes have resulted. For example, a size-79 organism quickly excludes a size-93 competitor but develops stable communities with programs such as the 80-instruction ancestor.

Another ecological concept that Ray has explored in Tierra is the "keystone predator" effect, in which the addition of a new predator stimulates diversity by suppressing the prey organism that was once the dominant competitor in the ecosystem. Testing this theory in the real world has been difficult, he says, because collecting the needed information is a time-consuming, delicate task. Furthermore, environmentalists often protest such tampering with actual ecosystems, Ray notes.

But Tierra has no environmental regulations, and new organisms can be added or removed at will. "Tierra is the best model we have of natural evolution," Ray argues, "and I can extract unlimited amounts of information from the system without disturbing it. It's so hard to get data in real systems."

Sure enough, when he inserted certain parasites into Tierra, he observed an effect similar to that of a keystone predator. "In my [Tierran] community, we got the same result: more species coexisting," says Ray, who labels this result the "keystone parasite" effect. Surprisingly, the effect appears to operate by a mechanism different from that theorized for the keystone predator.

In the standard theory, the new predator creates diversity by targeting the dominant competitor more often than others, although field experiments have not yet confirmed this preference, Ray says. But Tierra's keystone parasite apparently invades hosts at random, showing no preference for the dominant host — and yet it still spurs diversity.

"Maybe this result should cause us to question the phenomenon," says Ray, who suggests that ecologists look for other mechanisms. "It may be that the theoretical conclusion is wrong."

Tierran evolution is also marked by punctuated equilibrium, lending credence to the controversial theory that periods of stability are interrupted by times of rapid evolutionary change, he says.

In addition, the electronic world displayed a phenomenon known as population cycling: Hosts and parasites developed a cycle in which one peaked and then declined, allowing the other to rebound, Ray explains.

Tierra has impressed a number of scientists in Europe and the United States — once they got over their initial disbelief. "The claims at the outset were grandiose to say the least," says Stephen P. Hubbell, a tropical ecologist at Princeton University. But a seminar on Tierra converted Hubbell and his colleagues from "total skepticism" to "amused contemplation of where this could lead," he says. Ray "captured a lot of the critical evolutionary issues in a very simple model," says Hubbell, but he also cautions that the "spectacular" results are preliminary and need to be confirmed in more runs of the program.

British evolutionary theorist William D. Hamilton offers high praise for Ray's work. "I've not seen anything like it. It's quite an original piece of work," he says. "Some very fascinating ideas about the origin of life may come out of it."

Hubbell agrees. "We can now run evolution in the lab over and over," he says.

What looms in Tierra's future? Sex, predators and multicellularity, says Ray. Indeed, he notes, a Danish researcher has extended the program to include a suicide instruction in some self-replicating organisms. The instruction is not meant for self-termination, but rather to trick unsuspecting parasites into executing the deadly code of such hosts. If this deception works, the host in effect will kill the parasite.

To motivate the evolution of this predatory development, the Danish researcher removed the reaper, whose absence allowed the memory to fill up and created a population crunch. In order to reproduce, an organism would have to free up memory by killing another creature.

Perhaps another way to spur the evolution of predators, suggests Ray, is to somehow make the instructions in each creature valuable, as food is to the body. "It would then become worthwhile to kill other creatures to get their instructions," theorizes Ray.

Multicellularity might be achieved by allowing the mother cell to retain control over the daughter cell it creates. Daughter cells might then evolve to carry out specific tasks for the mother cell, in a scenario perhaps similar to the emergence of flagella in real microorganisms. "That's the essence of multicellularity — to force differentiation on the daughter cell," says Ray.

By combining this multicellularity with "sexual" reproduction — in which progeny are created by two organisms mixing their instructions — Ray hopes to mimic what he describes as "the Cambrian explosion of diversity." During the Cambrian era, roughly 570 million years ago, single-cell organisms evolved into incredibly complex multicellular creatures, he explains.

Tierra can also serve as a teaching tool about evolution. It offers skeptics dramatic proof, contends Hamilton, that random chance can produce systems of great complexity. "It's very impressive and educational," he says.

Perhaps most important, Ray adds, is that Tierra is "creating something that would call into question our definition of life." People may one day have to confront philosophical questions about whether such creatures are alive, sentient and deserving of rights, he suggests.

Ray admits to being slightly awed by his creative computer screen. "Life is a very powerful force," he muses. "You can just set up the conditions and it will go." □