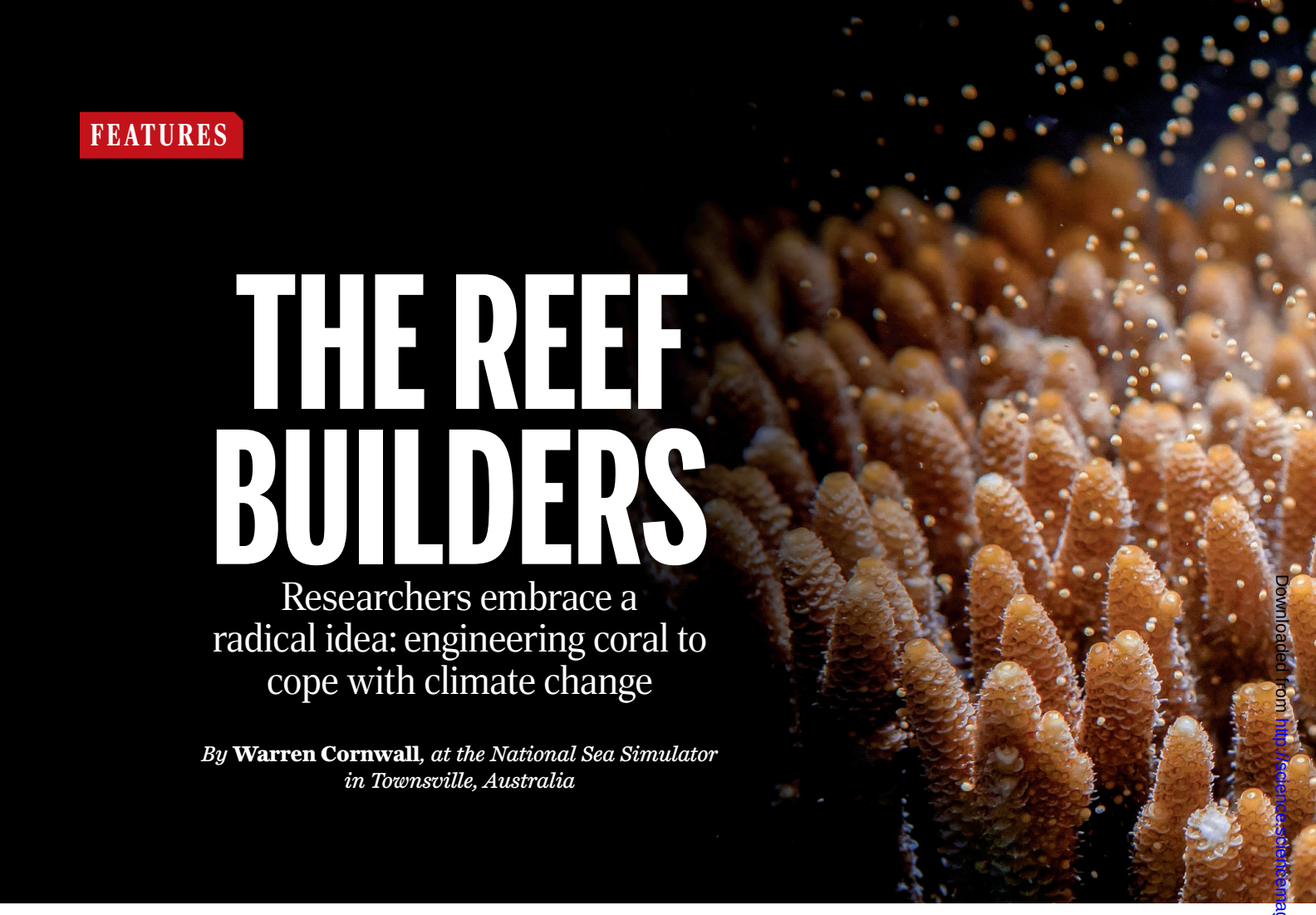
THE REEF BUILDERS

Researchers embrace a radical idea: engineering coral to cope with climate change

By **Warren Cornwall**, *at the National Sea Simulator in Townsville, Australia*



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The rush starts at sunset, just before the first tiny pearls of egg and sperm rise from chunks of coral resting in tanks here at this sprawling marine science center. Figures scurry past in the fading light, their red headlamps casting a lurid glow. The thrum of pumps and gurgle of water drown out the cicadas trilling on a sweltering November evening. Researchers huddle around the tanks, their lights turning the pools into pink lanterns as they watch for signs of spawning.

Amid the controlled chaos, coral geneticist Madeleine van Oppen stands like a coach directing her team. A doctoral student from Van Oppen's lab at the University of Melbourne in Australia approaches with an update. One species of coral appears ready to spawn sooner than expected. "That's not helpful," Van Oppen declares. She strides to a large aquarium, reaches in up to her elbows, and lifts out a basketball-size piece of coral. "Move," she orders, marching past to deposit her load into a small bucket of saltwater, in order to isolate the coral and to avoid accidental cross-breeding.

That imperative—to move, and move fast—is now the mantra for an entire field of coral research and for Van Oppen in particular. The relentless rise of global temperatures is imperiling coral reefs around the world. Just 75 kilometers offshore from the research center, Australia's Great Barrier Reef—the world's largest—has been battered by a string of marine heat waves that have killed half its coral. The threat has transformed Van Oppen into a leading advocate for something considered radical just a few years ago: creating breeds of coral that can withstand underwater heat waves. And it has helped make Australia, which recently committed a hefty $300 million to coral research and restoration, a global magnet for reef scientists.

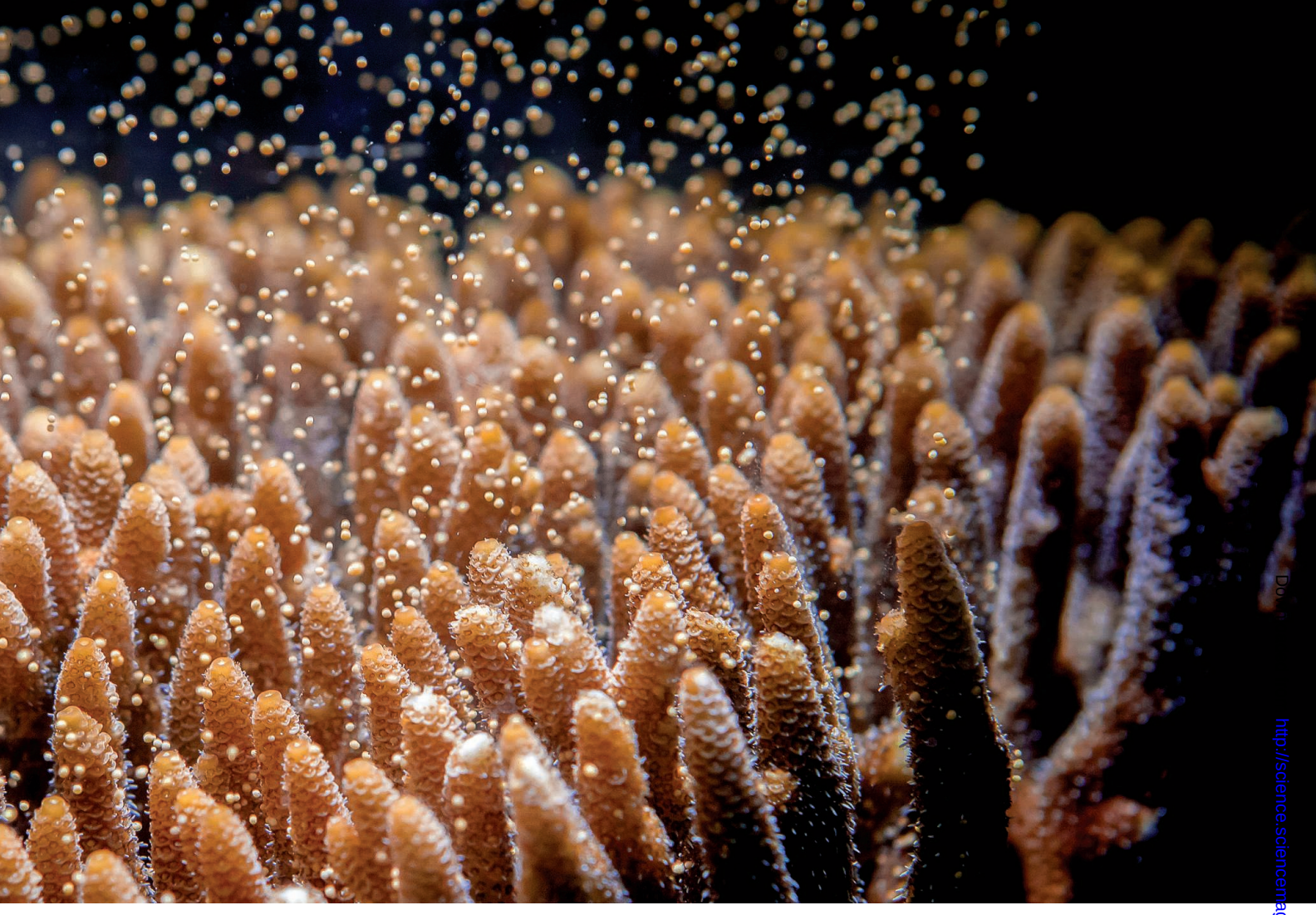
One major attraction is the National Sea Simulator, a $25 million facility nestled in eucalyptus-lined hills on the shore of the Coral Sea, which was opened in 2013 by the Australian Institute of Marine Science (AIMS). Here, in dozens of seawater tanks where conditions can be precisely matched to those of the ocean today or in the future, Van Oppen and other scientists are tinkering with creatures that are the very cornerstones of reef ecosystems. Imagine ecologists cultivating whole new breeds of trees to restock a devastated wilderness. In the minds of some researchers, the work could help shape the future of some of the world's richest underwater places. But the endeavor will first have to overcome formidable technical challenges—and concerns that such interventions could bring new problems.

Van Oppen and others are re-engineering corals with techniques as old as the domestication of plants and as new as the latest gene-editing tools. And the researchers are adopting attitudes more common to free-wheeling Silicon Valley startups than the methodical world of conservation science. Just as tech entrepreneurs are urged to "fail fast, fail often," scientists are pushing to quickly test ideas and ditch the least promising ones in the hunt for results that can be moved from the lab to the ocean.

At the sea simulator, entire research projects hinge on what transpires over the next 10 hours. Coral spawn only once per year, releasing the genetic material that is the foundation of this work. On this night,

PHOTO: MIKAELA NORDBORG/AUSTRALIAN INSTITUTE OF MARINE SCIENCE

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A colony of *Acropora millepora* releases bundles of eggs and sperm. Researchers trying to create hardier hybrids have just hours to use the precious material.

5 days after a full moon, much of the coral that researchers have collected offshore and moved to the lab appears ready to release thousands of bundles of eggs and sperm. The spawning will set off a frenzy of scooping, mixing, and testing. The eggs will die within hours if not fertilized by sperm, and this chance won't come again for another 12 months. The feeling is electric, caffeinated, like the start of an all-night marathon for computer hackers. It's only fitting, because many of the people here are bent on trying to hack coral.

AS VAN OPPEN WORKS, she can hear the clock ticking for coral reefs. In the past decade, heat waves have turned vast swaths of reef from multihued oases to algae-coated deserts. Reef-building corals—really a mutualistic pairing of an animal that builds a hard skeleton with a single-celled plant that lives within the animal's cells—show few signs of adapting to the rapid change. If global temperatures rise by 2°C, the Intergovernmental Panel on Climate Change has concluded, reefs as we know them will be virtually gone worldwide. Today, the planet is on course to crack 3°C by 2100. Then there is the added threat of ocean acidification. The sea's absorption of carbon dioxide lowers the pH of seawater, making it corrosive to the calcium carbonate shells that corals and many other marine creatures build. Van Oppen has a habit of punctuating the grim news about coral with a strained laugh. "We're really trying to repair what humans are destroying," she says, and then laughs.

Seven years ago, at a conference, Van Oppen sat down with Ruth Gates, a renowned coral biologist and conservation advocate from the University of Hawaii (UH) in Honolulu, to discuss whether they could give coral reefs an artificial advantage in the evolutionary race against climate change. Van Oppen, then a full-time scientist at the lab here, had already tried to breed coral that could withstand higher temperatures. And Gates was a pioneer in understanding why corals evict their tenant algae when stressed, a process known as coral bleaching. The two wondered whether, with a little coaxing, they could make both organisms more resilient.

It was an idea on the fringe. Coral conservation has traditionally focused on minimizing damage from insults such as water pollution, invasive starfish, and destructive fishing or tourism. In the Caribbean, some conservationists have worked to "replant" damaged coral. But Gates and Van Oppen had something more intrusive in mind. They wanted to try to alter the genetics of coral or the microbes that live on it. They dubbed the effort "assisted evolution."

When the duo promoted the idea in a 2015 paper in the *Proceedings of the National Academy of Sciences*, it was still outside the mainstream, says Steve Palumbi, a marine biologist at Stanford University in Palo Alto, California, who chairs a National Academy of Sciences committee studying ways to help coral. "They were ahead of the curve for sure," Palumbi says.

Then, two things happened. Later that year, the charitable foundation of the late Paul Allen, a co-founder of Microsoft, gave Van Oppen and Gates $4 million over 5 years to pursue the work. And an epidemic

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Wanted: super corals

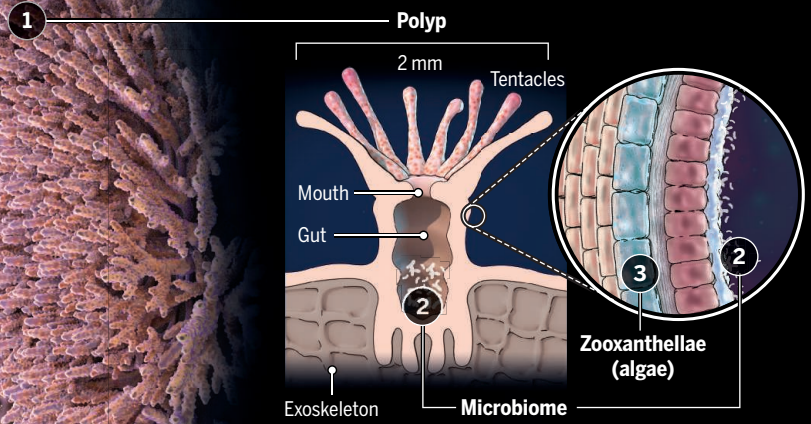
Rising ocean temperatures and ocean acidification pose major threats to the planet's coral reefs. If temperatures rise 2°C above preindustrial levels by 2100, virtually all coral reefs will be wiped out, according to the United Nations Intergovernmental Panel on Climate Change. Recent heat waves have already taken a major toll, killing more than half the coral on Australia's Great Barrier Reef. Now, scientists are trying to help reefs adapt by altering coral biology in the laboratory.

Acropora tenuis

Acropora loripes

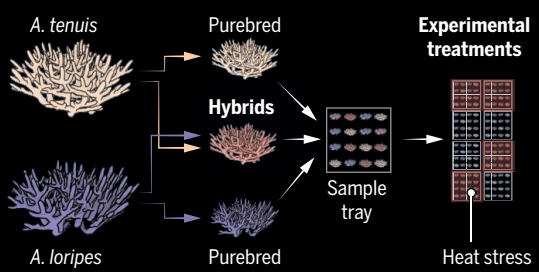
A complex partnership

The term "coral" encompasses an entire microcosm. Scientists are working to alter each part, hoping it will enhance the entire system's heat tolerance.



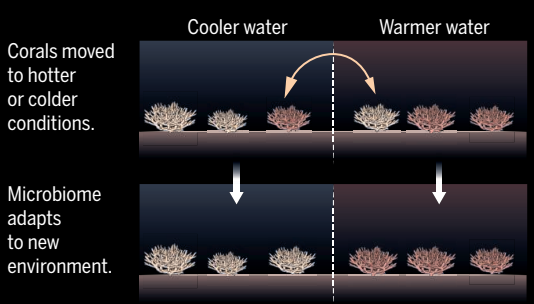
1 Breeding for a hotter world

Cross-breeding could create hybrids that thrive in warmer seas. Researchers also rear corals in hotter water to see whether offspring inherit adaptations and manipulate genes for heat tolerance.



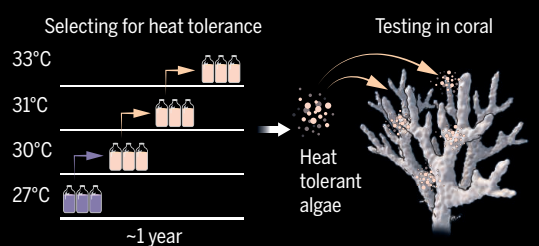
2 Manipulating the microbiome

To help corals resist bleaching and other stresses, scientists are trying to evolve new bacterial mixtures (below). They are also exploring genetic engineering of coral bacteria.



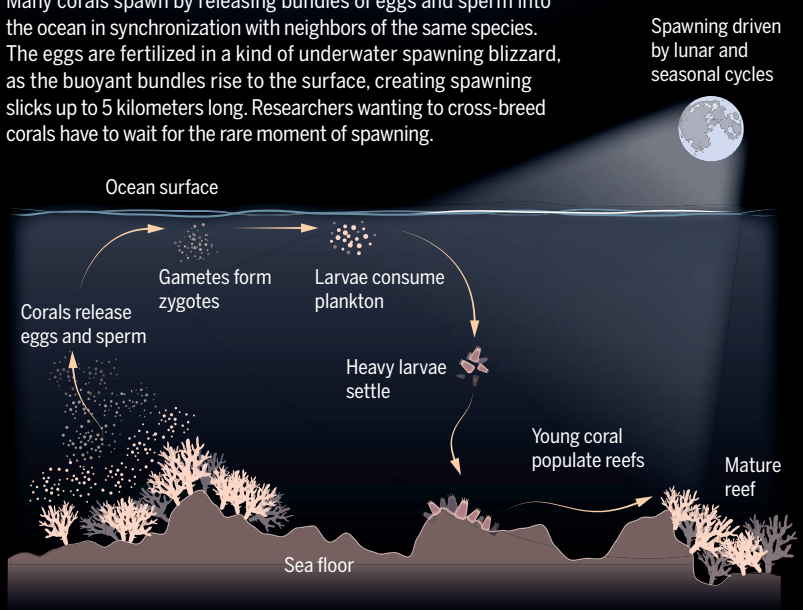
3 Adapting algae

Raising symbiotic algae in hotter conditions could create heat-tolerant strains that help prevent bleaching. Researchers are also altering algae DNA, a potential step toward genetic engineering.



A once-a-year breeding frenzy

Many corals spawn by releasing bundles of eggs and sperm into the ocean in synchronization with neighbors of the same species. The eggs are fertilized in a kind of underwater spawning blizzard, as the buoyant bundles rise to the surface, creating spawning slicks up to 5 kilometers long. Researchers wanting to cross-breed corals have to wait for the rare moment of spawning.



GRAPHIC: C. BICKEL/*SCIENCE*

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of heat waves severely damaged coral reefs around the world between 2014 and 2017. Suddenly, the idea of intervening to help save coral seemed less far-fetched. "The coral biology world," Palumbi says, "has undergone a radical transformation over the last 5 years."

CORAL'S MOST REMARKABLE characteristic—being an animal that is part plant—is also its Achilles' heel in a hotter world. Normally, coral polyps—the individual coral organisms, which resemble a sea anemone the size of a pinhead—live in harmony with their algal partners, which help feed the polyps and give corals their bright colors. But during heat waves, the relationship sours. Overheated polyps perceive the algae as an irritant and eject them like unwanted squatters. The coral is left bleached, bone-white and starving. If the heat persists, the coral won't take in new algae and can die.

The bond between coral and algae is complicated, however, and still not fully understood. Just 25 years ago, for example, researchers believed that coral housed just one variety of symbiotic algae. Now, they have identified hundreds. And they are just beginning to examine the role played by the coral's microbiome, the menagerie of bacteria that inhabit a coral polyp.

But the complexity also offers multiple paths for scientists trying to forge a less fragile bond between coral and algae. Today, four major lines of research exist: One involves cross-breeding corals to create heat-tolerant varieties, either by mixing strains within a species or by crossing two species that would not normally interbreed. The second enlists genetic engineering techniques to tweak coral or algae. A third tries to rapidly evolve hardier strains of coral and algae by rearing them for generations in overheated lab conditions. A fourth approach, the newest, seeks to manipulate the coral's microbiome.

On this November evening, one of Van Oppen's main experiments is to develop new hybrids. The candidates for this night's matchmaking are pale brown chunks of the small, spiky, and ubiquitous corals *Acropora tenuis* and *A. loripes*. Although those coral live side by side on the Great Barrier and other reefs, *A. loripes* spawns several hours after its cousin, effectively keeping the species separate. But Van Oppen can overcome that in the lab by mixing their spawn by hand.

Before the mixing can begin, however, Van Oppen's team has to collect the eggs and sperm, and coral are fussy spawners. Shifts in water temperature and even bright light can stop them—hence the red headlamps. But if all goes well, a tiny bundle of egg and sperm will emerge from the mouth of each of the thousands of polyps that make up the chunks of coral sitting in the tubs. The buoyant spheres rise through the water, like an inverted snowstorm.

At about 6:30 p.m., the *A. loripes* starts, setting off a frenetic ballet of technicians and researchers. "It's gonna be chaos," one declares gleefully.

Plastic cups and mixing bowls are the low-tech tools of the trade. Van Oppen leans over a tub, headlamp shining, gently dips a cup into a carpet of fresh spawn, and carries it into the fertilization room. Whereas the darkened spawning tubs have an atmosphere of awe and mystery, the fertilization room is all business. Under glaring fluorescent lights, Van Oppen pours the cup's contents into a small tube ending in a filter, which catches the bound-together eggs and sperm. She gently rinses the bundles to break them apart, separating the sperm into a bowl and leaving behind eggs resembling pink grains of sand.

"It's quite relaxing, actually," Van Oppen says, as she stands still for a moment, quietly bathing the eggs in saltwater again and again. She will pour the eggs into a bowl, one of many in a row, each filled with a swirl of floating eggs and marked with a code denoting the particular hybrid she's creating. The sperm goes into a large glass bottle with a spigot, to await fertilization later that night. When the time is right, Van Oppen will pour sperm from one species into bowls of eggs from another and thus start a new generation.

Some of her early work with hybrids has been promising. Last year, her team reported that one group of *A. loripes-A. tenuis* hybrids tolerated hotter, more acidic water better than purebred *A. tenuis*, with survival rates 16 to 34 percentage points higher. Now, the researchers are waiting for the hybrids to mature to see whether their offspring are also viable and resilient. Meanwhile, in the Hawaiian lab founded by Gates, scientists have found that they can create corals that fare better in warmer water by crossing variants within a single species.



To avoid disrupting the spawning of light-sensitive corals, researchers wear red headlamps as they work.

PHOTO: CAMERON LAIRD

IN PAST YEARS, Gates would have kept tabs on the spawning. But not tonight. Just a month earlier, in October 2018, Gates died at age 56 from complications during surgery for diverticulitis, an intestinal inflammation. She also had cancer that had spread to her brain.

Van Oppen and Gates were a bit like the comedic duo Stan Laurel and Oliver Hardy. Gates, stocky and with a showperson's flair, was a natural as the public face of coral science. She appeared in the 2017 Netflix documentary *Chasing Coral* and spoke to the United Nations, the Aspen Ideas Festival in Colorado, and many media outlets. "She was such a sharp mind, and also she was such a fabulous science communicator," Van Oppen says. "It's a huge loss."

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Van Oppen is more reserved and slight, speaking in quiet tones, her English softened with traces of her native land, the Netherlands. The lab, it seems, is her natural habitat. "I'm actually quite an introverted person," she says.

Gates's death has reinforced Van Oppen's sense of urgency. And it has helped push her into the spotlight, replacing Gates as the most prominent spokesperson for assisting coral evolution. During spawning, a cluster of journalists surrounded her, like pilotfish hovering around a shark.

Despite her reserve, Van Oppen is a whirlwind of energy, says her longtime mentor and former Ph.D. adviser Jeanine Olsen, an expert in marine genomics retired from the University of Groningen in the Netherlands. "When I see how productive she is, and her ability to bring people together and go after this kind of grand challenge question, it takes my breath away," Olsen says.



PHOTO: CAMERON LAIRD

BREEDING NEW CORAL HYBRIDS is just one strategy Van Oppen is pursuing. In another room at the lab here, tiny vials filled with a brown-tinted liquid sit in stainless steel chests resembling refrigerators. Each holds samples of the symbiotic algae. In one experiment, new generations are exposed to progressively warmer temperatures, in hopes of selecting for strains that better tolerate heat.

The simulator also houses large tanks in which corals themselves are exposed to similar stresses: water temperatures and carbon dioxide levels mimicking what's expected later in the century. Van Oppen—who still holds a research position in the Townsville lab even though she is based in Melbourne—is curious to see whether creatures raised in those challenging conditions will adapt by turning up or down certain genes and then passing on some of those "epigenetic" changes to their offspring.

This lab has drawn other researchers pursuing their own approaches. While Van Oppen stirs together sperm and eggs, in a nearby building Phil Cleves, a postdoctoral student at Stanford, hunches over a microscope, gazing at a row of newly created coral embryos lined up in a small petri dish. Using a joystick, he guides the glass tip of a needle less than a micron across until it punctures an embryo's outer membrane and delivers new genetic material.

Last year, Cleves became the first to report successfully using the CRISPR-Cas9 gene-editing tool on coral. CRISPR is often touted as a method for making genetically modified species. But Cleves says he isn't interested in creating new kinds of coral. Rather, he sees CRISPR as a tool for deciphering the inner workings of coral DNA by knocking out, or disabling, genes one by one. He hopes to identify genes that might serve as "master switches" controlling how coral copes with heat and stress—knowledge that could help researchers quickly identify corals in the wild or in the laboratory that are already adapted to heat.

Once Cleves has punctured an embryo, a puff of air injects a droplet filled with the RNA and enzyme molecules that snip the DNA. The researchers will later expose those knockout embryos to different temperatures; if embryos that have had certain DNA sequences removed die at higher rates, the researchers could be a step closer to identifying key resilience genes. Tonight, however, Cleves is essentially a one-man assembly line, manufacturing genetically modified coral. He'll process a thousand embryos by 2:30 in the morning.

ALTHOUGH CLEVES IS NOT focused on engineering new corals, some of his collaborators are thinking seriously about how genetic modification could help blunt the climate threat. One is Line (pronounced "Leena") Bay, a coral geneticist at AIMS who is also heading a committee advising the Australian government on how to spend $70 million it has committed to research into coral adaptation and restoration.

The committee has been weighing a smorgasbord of potential interventions, many outside the realm of genetics. Some applicants want to try to dim the sun over reefs by spreading a thin sun shield over the water or by spraying saltwater into clouds so that they reflect more sunlight. Other researchers are looking at corralling coral spawn and steering it to reefs most in need. Some researchers envision creating an entire aquaculture system—essentially coral farms—to raise hardier strains created by work like Van Oppen's, which could then be transplanted to ailing reefs.

Genetically engineering corals to make them better able to withstand heat and resist bleaching is among the possibilities, Bay says. She concedes that the idea will face resistance, like all proposals to release modified organisms into the environment. But that doesn't mean it should be shelved, she says. "The worst thing that we could do is ignore the genetic engineering because it's frightening for some people, and then get 10 or 15 years down the road and realize it's the only option."

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Coral researchers Line Bay (left) and Madeleine van Oppen (right) want to figure out how to help corals adapt to warming seas, before it is too late.

Some scientists are already taking the first steps. In 2018, a team of scientists from the United Kingdom and Saudi Arabia reported successfully altering the genome of chloroplasts inside symbiotic algae, noting that the technique could help reveal the mechanisms behind coral bleaching. And Van Oppen recently received a $2 million grant from the Australian government to delve further into the coral's microbiome and explore the potential for genetically engineering the microbes to help coral become more resilient. Her team is also examining the properties of different microbes as a first step toward creating bacterial cocktails othat could help their coral hosts by absorbing molecules released during heat stress.

Palumbi sees the potential for such efforts to accelerate evolution. But he's betting that nature might offer solutions faster. Working on reefs in the South Pacific, he has found that colonies of a single species of coral can show different levels of heat tolerance depending on their location on the reef. Finding out what makes existing corals more heat resistant could guide efforts to propagate the most resilient strains. "It's easier to find climate-resistant corals than it is to make them," he says.

Either way, such efforts to re-engineer coral reefs make people such as David Wachenfeld, chief scientist for the Great Barrier Reef Marine Park Authority here, uneasy. The authority is supposed to protect the reef and regulate activities there. In the past, that meant a hands-off approach. Now, he concedes that "it is almost inconceivable that we're not going to need these tools." But, he adds, "That doesn't mean I'm happy about any of this. This is crisis management."

He ticks off a list of potential difficulties. Scientists focused on breeding heat-loving coral have to avoid weakening other key traits, such as coping with cold. Introducing a new coral on the scale needed to make a dent on a network of 2900 reefs spanning an area half the size of Texas is a daunting challenge. Even in its damaged state, the Great Barrier Reef still contains hundreds of millions of corals—enough to swamp the genetic impact of new coral species.

Then there's the "cane toad" question. In Australia, the toad looms over talk of introducing any new organism into the nation's territory. First released in Australia in 1935 to combat beetles that damaged sugarcane, the cane toad quickly morphed into a toxic pest that poisoned native wildlife and showed little appetite for the beetles. Could some kind of "super coral," as some researchers have dubbed them, also run amok in delicate coral ecosystems?

Wachenfeld says that comparing engineered corals to cane toads is probably a stretch. For corals, scientists are working with the same basic organisms, often taken from the Great Barrier Reef, and not aiming to introduce a new predator. "That said, of course there are risks, and we must proceed with caution," he says.

The issue is also sensitive in Hawaii. There, a researcher in Gates's lab says state regulators discouraged researchers from seeking a permit to release some corals created in the lab by breeding two groups of the same species—one that resisted bleaching and another that didn't. "That is not a very genetically scary organism at all," compared with other modified organisms, says Crawford Drury, a coral ecologist at UH. "But there is a baseline level of discomfort."

AUSTRALIAN REGULATORS appear slightly less reluctant. In early March, Van Oppen got permission to move cross-species hybrids to the open ocean for the first time. Last week, her team took baby hybrid corals growing on terra cotta tiles out to the Great Barrier Reef and installed them on underwater racks, skewered on steel rods like oversized shish kebabs. Researchers will monitor the corals' survival and growth in the coming months. To ease concerns that the exotic organisms might spread, she will remove them before they are sexually mature.

For Van Oppen, moving forward with such tangible studies makes the frenzy of spawning nights worthwhile. In November 2018, after a long night scooping and stirring coral spawn, she seemed relaxed as she ate lunch at the laboratory's café. The coral had spawned on cue, so a new year of experiments was underway. She planned to stay up late again for another reason—to raise glasses of champagne with her research team and toast a successful spawning season.

Still, she feels the pressure to keep moving at a breakneck pace, even though solutions are a long way off. "Since we started this work, we've lost well over half of the Great Barrier Reef—at least—and lots of other reefs in the world," she recalled. It's humanity's fault that corals are in hot water. Now, she says, it's up to humanity to help the corals keep up. ■

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The reef builders

Warren Cornwall

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