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HOW TO BUILD AN ARTIFICIAL HEART

Millions of hearts fail each year. Why can't we replace them?

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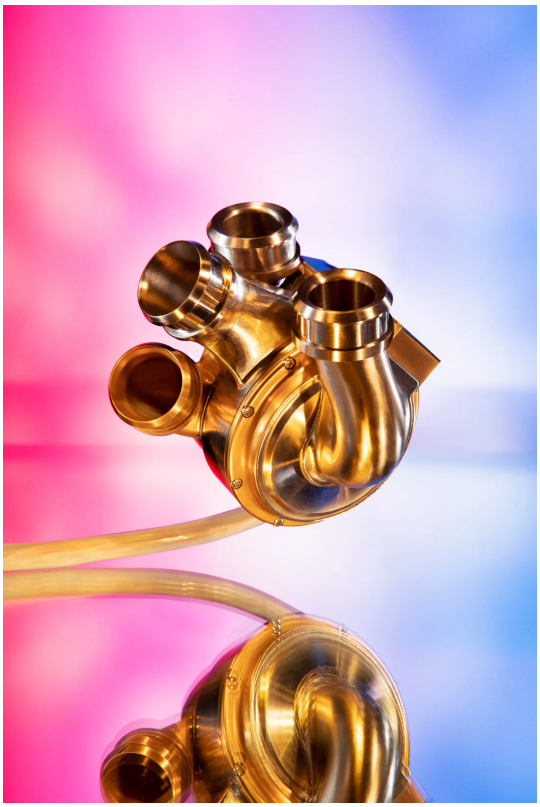

The Bivacor heart contains a single titanium chamber with a rotor that spins at its center, sending blood out to the body. Photograph by Zen Sekizawa

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Daniel Timms started working on his artificial heart in 2001, when he was twenty-two years old. A graduate student in biomedical engineering, he was living with his parents in Brisbane, Australia. He was searching for a dissertation topic when his father, Gary, who was fifty, suffered a massive heart attack. At first, the problem seemed to be a faulty valve; soon they learned that Gary's entire heart was failing. Heart failure is a progressive condition—a person can live for years while his heart slowly gives out. There was a narrow window of time. A course of study had presented itself.

Gary was a plumber, and Timms's mother, Karen, was a high-school science assistant. Theirs was a tinkering, experimenting household; as a kid, Timms and his father had spent countless afternoons in the back yard building an elaborate system of fountains, ponds, and waterfalls. It was only natural that he and his dad would work together on a heart. They bought tubes, pipes, and valves at the hardware store and, in their garage, constructed a crude approximation of the circulatory system. Timms started reading about the history of the artificial heart. The first human implantation had been done in 1969, by a surgeon named Denton Cooley, of the Texas Heart Institute, in Houston. The patient, Haskell Karp, had been sustained for sixty-four hours—a great success, considering that his heart had been cut out of his chest. Engineers felt sure that, within a few years, they'd have the problem licked.

From there, however, the story became uncertain, even contentious. It was hard to design a small, implantable device that could beat thirty-five million times annually, pumping two thousand gallons of blood each day, for years on end. In the following decades, patients survived for days, months, even years on various kinds of artificial hearts, but their quality of life was often poor. They were connected by tubes to large machines; they frequently suffered from strokes and infections; their new hearts were too big or had parts that wore down. Every year, heart disease killed millions around the world. Only a few thousand transplantable hearts were available. And yet, Timms learned, existing artificial hearts could be used only temporarily, to "bridge" patients to transplants that might never come. There was no such thing as a permanent artificial heart.

Reviewing the designs, Timms saw that many had taken shape in the nineteen-sixties, seventies, and eighties. He thought that improving them substantially should be straightforward. In the past, most artificial hearts had been made of flexible plastic; he'd create one from durable titanium. Their pumps had often been driven pneumatically, by air pushed into the body through tubes; he'd use an electromagnetic motor. Most crucially, where traditional artificial hearts had been "pulsatile"—they squeezed blood rhythmically out of artificial ventricles—his would move blood in a continuous flow: instead of beating, it would *whoosh*. In a lab notebook, he sketched a possible heart. Blood would flow

into a small chamber with a spinning metal disk at its center; the disk, like a propeller, would push blood outward into the lungs and the rest of the body. It was a clever, parsimonious design that, instead of seeking to emulate the biological heart, completely reimagined it. Beneath the sketch, he wrote, "Fuck yeah!"

In their garage, he and his dad built a prototype. Made of clear plastic, it successfully moved water through their mock circulatory system, in which tiny beads served as blood cells. But there was a problem—a spot beneath the rotating disk where the currents stalled and the beads got stuck. This eddy was dangerous; blood cells that hang around together tend to coagulate, creating clots that can cause strokes. Over Skype, Timms talked with a researcher in Japan who worked on the magnetic-levitation systems used in high-speed trains. They decided that stronger magnets could be used to suspend the disk away from the walls of the heart, so that blood could flow around it more easily. This "maglev" approach would also eliminate wear and tear: none of the parts would touch.

Timms was still a graduate student when he finagled a meeting with some cardiologists at the Brisbane hospital where his father was receiving treatment. He pulled the plastic pump out of his backpack and explained how a heart based on his design would function. One doctor, incredulous, walked out of the meeting. Another secured Timms a small stipend and a room in the basement. By 2004, while Gary was recovering from valve-replacement surgery upstairs, Timms was working on prototypes downstairs. Soon he used one to keep a sheep alive for a couple of hours. Like the artificial-heart engineers of the past, he anticipated that further progress would come quickly.

Today, more than a decade and a half later, Timms's company, Bivacor, has an engineering office in Cerritos, a suburb of Los Angeles. About a dozen engineers work in a building surrounded by palm trees and flowering hedges. Last year, before the pandemic, Wilson Xie, a twenty-three-year-old biomechanical engineer, stood over a lab bench, using zip ties to attach the newest version of the Bivacor heart to a mock circulatory system. The system, known as "the loop," was a vast improvement on the one Timms and his father had built; made of plastic tubes and about four feet tall, it resembled a model roller coaster. Filled with sugar water mixed to the viscosity of human blood, it used valves to simulate different circulatory circumstances: high pressure, low pressure, standing up, sprinting. The heart attached to it was solid and steampunk, made of black and gold titanium. Four openings were designed to lead to the aorta, the vena cava, the pulmonary artery, and the pulmonary vein; a cable connected it to a black dictionary-size control box. The cable would pass through the skin of the abdomen; users would need to carry the box with them at all times.

As Xie adjusted the valves of the loop, air was pumped out with a hiss. Nicholas Greatrex, an Australian electrical engineer, entered a command on a computer, and current began flowing to the heart's electromagnets. Water began to course through the loop, moving with a low, vibrating hum.

The Bivacor and human hearts work on entirely different principles. A human heart has two distinct sides. Blood first loops from the smaller, right side to the lungs and back, so that its oxygen can be replenished; it then crosses over to the larger, stronger left side, which pumps it forcefully into the body. The Bivacor heart is one combined chamber. It sends blood in two directions using its spinning disk, or "rotor," which has two differently contoured sides, each shaped to

create the appropriate level of blood pressure. Where the heart of a healthy adult beats anywhere between sixty and a hundred times a minute, the Bivacor spins at between sixteen hundred and twenty-four hundred r.p.m.

Take the pulse of someone using such a heart, and you'd feel only a steady pressure, as in a garden hose. But some heart surgeons and cardiologists are uncomfortable with the idea of a pulseless heart. Tapping the computer keyboard, Greatrex instructed the rotor to oscillate its speed. "By accelerating and decelerating the rotor, we can create an artificial pulse," he said. I reached out and touched one of the loop's white rubber hoses. Uncannily, it was warm; beneath my fingers, it began to pulse with a familiar human rhythm.

"Blood pressure of a hundred over seventy," Greatrex said triumphantly, touching his own wrist. "A doctor might look at that and say, 'You're doing pretty well!' " According to the Centers for Disease Control and Prevention, an estimated 6.2 million Americans suffer from some form of heart failure, often feeling weak, out of breath, and unsteady. Having this kind of artificial heart would turn back time.

Bivacor is in a transitional stage. It has never sold a product and is still run entirely on venture capital, angel investment, and government grants. Its hearts have been implanted in sheep and calves, which have survived for months, occasionally jogging on treadmills; it's preparing to submit an application to the Food and Drug Administration for permission to perform human implantations. To cross the animal-human threshold is to enter a harsh regulatory environment. In the early days of artificial-heart research, a team could implant a device in a dying person on an emergency basis—as a last-ditch effort to save his life—and see how it functioned. Ethicists were uneasy, but progress was swift. Today, such experimentation is prohibited: a heart's design must be locked in place and approved before a clinical trial can begin; the trial may take years, and, if it reveals that the heart isn't good enough, the process must start again. Bivacor is currently deciding which features will be included in the clinical trial of its heart. A wrong decision would likely sink the company; almost certainly, there wouldn't be a second attempt on the summit.

Timms, trim and sandy-haired, is now forty-two. Since his days in Brisbane, he has devoted almost all of his working life to the heart, moving to Japan, Germany, Taiwan, and Houston to work with particular surgeons or engineers. Quiet and alert, he is the opposite of a TED talker: he prefers not to tell people what he does for a living, lest the ensuing conversation tempt him to hype a project that has blown every deadline. Wearing jeans, running shoes, and a rumpled dress shirt unbuttoned to the third button, he led me into a back room where half a dozen prototype hearts had been operating continuously for as long as sixteen months. "It's really important to show that they never, ever stop," he said, above the hum of moving water. Timms himself looked as if he hadn't slept properly in a couple of decades.

On our way out of the lab, we passed a conference room where an engineer was discussing, on video chat, how the Bivacor could be tested before implantation: "Your thumb goes on the left inlet port, and you're going to very gently push," she said. In Timms's office, the furniture might have belonged in a home study. (It was a gift from an early investor—the owner of a Houston furniture store.) A pressed shirt haunted a hanger on the wall, and a road bike leaned in one corner.

From his creaky desk chair, Timms recalled driving his father to the hospital, in 2006. Gary's valve-replacement surgery had helped him regain heart function, but only temporarily. "He'd got a clot on his mechanical valve," Timms said. "It was backing the blood flow up into the left side of his heart and into his lungs." Timms mimed the buildup with his hands, tracing a path from his left breast to his sternum and up his neck—the blood piling up, like water struggling to navigate a drain. "That's when you get edema," he said. "You cough up blood because it's transferring across the pulmonary membrane."

Two weeks later, Timms was in Germany, meeting with pump engineers, when he learned that his father had taken a decisive turn for the worse. He flew home immediately, but arrived too late for a final conversation with his dad. "He was in I.C.U., with the trach and everything," Timms said. "His dying made me even more resolute. It was, like, That's it. We're gonna do it, at any cost."

I asked Timms if, two decades ago, he'd actually believed that he might invent an artificial heart in time to save his father.

He swivelled back and forth, nodding. "At that stage, I was, like, if there was a device that could be implanted for him, then maybe he could stay around for another five or ten years—for the time when I got married and had kids. He could experience that. That was the philosophy then. Just another five or ten years of life." He laughed. "That still hasn't happened," he said, referring to marriage and children. He gestured around his office. "I've been stuck on *this*."

Before the heart was replaceable, it was untouchable—a forbidding marker of the surgical frontier. Nineteenth-century physicians thought that, when it came to surgery, the heart was "the limit set by nature." In the first half of the twentieth century, anesthesia made surgeons braver; they began darting in to mend arteries and valves while the heart was still beating. They tried cooling patients to hypothermic levels, then operating on their hearts quickly, while they were stopped. It wasn't until the nineteen-fifties, with advances in the heart-lung machine, that open-heart surgery became routine. Blood travels out of the body and into the machine, bypassing the heart and lungs, and giving surgeons access to a still and bloodless heart, which they can treat almost like an ordinary muscle.

Early heart-lung machines were desk-size, and could be used safely only for short intervals; still, they made an artificial heart seem both desirable and feasible. So did several other converging trends. More people were living into their sixties and seventies, when hearts start to deteriorate; by mid-century, as many as forty per cent of American deaths were caused by heart disease. These statistics were of grave concern to policymakers. In 1948, Congress—a group of aging men—passed the National Heart Act, initiating a decades-long expansion in federal funding for cardiological research.

It was the Apollo era, and the artificial heart seemed like an inner moon shot to rival the outer one. In 1964, the National Institutes of Health launched the Artificial Heart Program, a multimillion-dollar engineering effort that aimed to put hearts into patients by the end of the decade. Structured like a NASA project, it awarded grants and

contracts to teams of engineers who competed to develop the best valve, pump, or power source; a few groups experimented, unsuccessfully, with nuclear-powered hearts. *Time* and *Life* devoted covers to the work. As the medical historian Shelley McKellar writes, in "Artificial Hearts: The Allure and Ambivalence of a Controversial Medical Technology," the high expectations for artificial-organ implants "did not necessarily reflect contemporary surgical reality."

The true difficulty of the challenge quickly became apparent. At Maimonides hospital, in Brooklyn, Adrian Kantrowitz, a surgeon-inventor who had helped perfect the pacemaker and the heart-lung machine, began working on pump designs. He landed on a clever approach: instead of replacing the heart, he would install a pump just outside it, compensating for the failing heart and perhaps giving it time to heal. Kantrowitz's prototype pumps were tested on dogs, and by 1966 he was ready to implant them in people. But the first human patient to receive one died after bleeding extensively; the second—a sixty-three-year-old bedridden diabetic woman who'd had two heart attacks—survived for twelve days but died after a series of strokes.

When Kantrowitz retrieved his pump and opened it up, he found clots. He had encountered an obstacle that would become known as "hemocompatibility." Subjected to too much force or pressure, blood cells can tear apart; caught in eddies or crevices, they can stick together; on textured surfaces, they can catch and form tangled beds that narrow passages. Kantrowitz's devices mangled the blood they pumped, and, as the "blood damage" mounted, the consequences spread.

Meanwhile, at Baylor College of Medicine, in Houston, Michael DeBakey and Denton Cooley, widely regarded as the world's best heart surgeons, navigated a different set of complexities. DeBakey and Cooley began as partners, performing vast numbers of heart surgeries at a prodigious pace. Then, as the journalist Mimi Swartz explains in "Ticker: The Quest to Create an Artificial Heart," the two men fell out. Cooley left DeBakey's practice in 1960, and later founded the Texas Heart Institute, just down the road. DeBakey, meanwhile, hired Domingo Liotta, a pioneering Argentine heart surgeon, to work on artificial hearts. By 1969, Liotta had begun implanting prototypes in calves. The results were discouraging—of seven animals, four died on the operating table—and DeBakey thought they weren't yet ready for use in humans. But Cooley was eager to move the work forward; he had patients waiting for donor hearts not just at his hospital but in nearby motels. Without informing DeBakey, he hired Liotta to moonlight at the Texas Heart Institute, with an eye to using his heart there.

Cooley began looking among his patients for a candidate. Haskell Karp, a forty-seven-year-old printing estimator from Skokie, Illinois, had been hospitalized thirteen times for heart trouble; he was routinely so out of breath that he struggled to brush his hair. Cooley would see whether Karp's heart could be surgically repaired, but Karp and his wife agreed that, if it couldn't be, Cooley could implant Liotta's prototype, in the hope that a donor heart would later become available. "Mr. Karp was wheeled into the surgical ward," Cooley later wrote, in a memoir. "He was pale, sweaty, and breathing with difficulty. His blood pressure had fallen to half its normal level." Halfway through the

operation, it became obvious that his heart was unfixable.

In its place, Cooley installed an air-powered device connected by hoses, which ran through Karp's side, to a refrigerator-size console. The heart's ventricles were made of rubbery plastic, with a bendable polyester lining; when air was driven between the lining and the plastic, the ventricles contracted and the heart pumped. The device kept Karp alive for sixty-four hours, until the transplanted heart of Barbara Ewan, a forty-year-old mother of three, could replace it. Still, Karp died thirty-two hours later, of pneumonia and kidney failure—consequences of the advanced heart disease that had made him a candidate for the risky procedure in the first place. Cooley regarded the operation as a success. But DeBakey, incensed by what he saw as the theft of his artificial heart, doubted whether his former partner had acted ethically. There were a series of investigations, and Cooley was censured by the American College of Surgeons. Observers disagreed about whether the surgery was heroic or reckless, but, either way, a new difficulty had emerged: by the time people were willing to try an artificial heart, they were so sick that they were almost beyond saving.

Willem Kolff, the Dutch-born internist who had invented dialysis, in the nineteen-forties, was undeterred. He aimed to create not just a bridge to transplantation but a heart so good that it could be used permanently. In Kolff's lab, at the University of Utah, a physician-engineer named Clifford Kwan-Gett created a ventricle gentle enough to avoid blood damage. Robert Jarvik, a gifted biomedical engineer who joined the Utah team while he was in medical school, relentlessly refined the design and the manufacturing process, giving the heart space-saving and more hemocompatible lines. When Jarvik arrived, in 1971, the group's prototype could sustain a calf for just ten days. But progress was steady; within a decade, a calf named Alfred Lord Tennyson lived for two hundred and sixty-eight days on what was by then called the Jarvik-5 artificial heart.

In December, 1982, the heart surgeon William DeVries implanted an upgraded version of the heart—the Jarvik-7—in Barney Clark, a sixty-one-year-old dentist. Clark's heart had been functioning at about a sixth of its normal capacity; he felt so bad that, upon meeting some calves and sheep living with Jarvik hearts, he said, "I believe they feel a lot better than I feel at this time." The surgery drew international attention, often centered on the personalities of the participants: DeVries, accomplished and "Lincolnesque"; Jarvik, young and handsome; and Clark, a charismatic Everyman who had flown combat missions in the Second World War. Television networks broadcast video of the seven-and-a-half-hour surgery; afterward, reporters attended daily press briefings held in the university's cafeteria.

Clark lived for a hundred and twelve days, with tubes connecting him to a four-hundred-pound pump and control console. He was, by turns, in decline and recovering, miserable and optimistic; briefly, he stood, and even used an exercise bike, but more often he was in bed and short of breath, drawing air through a respirator mask. One of his mechanical valves had to be replaced in a follow-up surgery; he suffered from nosebleeds, seizures, kidney failure, and pneumonia. Speaking above the chugging sound of the heart's pneumatic pump, not long before he died of sepsis and organ failure, Clark said, "It has been a pleasure to be able to help people."

The F.D.A. had given DeVries permission to implant seven artificial hearts, and he moved forward. In 1984, DeVries

installed a slightly improved Jarvik-7 in William Schroeder, a fifty-two-year-old former Army munitions inspector. Before the surgery, Schroeder asked for the last rites; he ended up living for six hundred and twenty days, moving out of the hospital into an apartment, and occasionally using a new, portable pumping unit, with three hours of battery life, to go untethered in the hallways or on drives with his son. On the phone with Ronald Reagan, Schroeder complained in jest about the tardiness of his Social Security check; reporters, feeling his chest, marvelled at his heartbeat, which seemed more powerful than a normal man's. Still, Schroeder suffered from a variety of ailments, including strokes, one of them massive. After he succumbed to chronic infections and lung problems, he was buried with a gravestone featuring a drawing of two overlaid hearts—a human one and the Jarvik-7.

The hearts were getting better, as were the surgical techniques. But incremental improvements left the essential contours of the technology unchanged. DeVries did a few more implantations, with varying degrees of success; in Sweden, a man who had been given a Jarvik-7 did extraordinarily well, going for extended walks and eating at his favorite restaurants. Still, he died after seven and a half months, sparking a legal debate about whether he'd been alive in the first place. (According to Swedish law at the time, he'd died when his heart stopped.) The attitudes of doctors, patients, and reporters began to cool. Confidence in the idea of permanent heart replacement started fading, and funders wondered if the money wouldn't be better spent elsewhere. What was the point of a short-term artificial heart? Were surgeons trying to save their patients, or just experimenting on them? Were the days of life gained worth having?

The first artificial-heart engineers had achieved a narrow kind of success. Their devices could sustain patients for long periods, but not permanently; they made heart failure survivable, but with a quality of life that seemed too low. A qualified wonder; a mixed blessing. "They did it," Timms said, in his office, as we discussed this history. "But nobody wanted it." A sobering conclusion for someone trying to do it again.

A couple of decades ago, at the beginning of my senior year of college, I found myself living next to two charming women: Suz from Montana and Jess from New Jersey. We became friends, and I soon learned Jess's story. During her senior year of high school, she had a massive heart attack. After receiving the last rites, she was saved through the implantation of an experimental heart pump—a "ventricular assist device," or VAD, called the HeartMate. The device, loosely descended from the ones that Adrian Kantrowitz had pioneered in the nineteen-sixties, was not an artificial heart; it replaced the function of the left side only, leaving the right side in place. Jess had attended prom and performed a lead role in her high school's production of "How to Succeed in Business Without Really Trying" while connected through a wire to a battery in a handbag. She also learned to walk using a prosthesis, because a complication after the heart attack had required the amputation of her left leg above the knee. A few days before her high-school graduation, she received the transplanted heart of a teen-age girl who'd died after a car crash. Not long afterward, she developed non-Hodgkin's lymphoma, likely resulting from the immunosuppressive drugs she took to prevent rejection. When I met Jess, all this was behind her; she was battery-free, cancer-free, getting a college degree.

We stayed friends after college. Jess worked in health care, as an organ-donation advocate. Her trick was to be both

sweet and steely. She travelled the world, beat cancer twice, went to concerts, ate a lot of dessert, had boyfriends, earned promotions. Generally, she acted like a young person, not like a living miracle. It was only by observing the ease with which she navigated any medical setting—bonding with nurses, sending e-mails from her hospital bed—that I grasped the degree to which she lived provisionally, and with courage.

Curious to meet some of the people behind the HeartMate, I travelled to the Texas Heart Institute, in Houston. Situated near St. Luke's hospital, within the city-like Texas Medical Center—the world's largest medical complex, with ten million patient visits a year—T.H.I. is the Vatican of cardiology; it contains a substantial museum dedicated to the history of heart surgery and pump devices. Not far from where Denton Cooley had implanted the first artificial heart, more than five decades ago, I sat in a windowless conference room with two surgeons, O. H. (Bud) Frazier and Billy Cohn. Cohn, intense in a black button-down and jeans, was fifty-nine; Frazier, laconic in a sports coat, trousers, and tortoiseshell glasses, was seventy-nine. Both men wore cowboy boots. Between them, they had implanted more than a thousand "mechanical circulatory support" devices. Today, the vast majority of patients receive VADs, which usually assist or replace the left side of the heart—an LVAD. But Cohn and Frazier, like Timms, are among the small group of researchers who are still working to develop a complete, permanent heart replacement. In 2011, they implanted two HeartMate IIs simultaneously—one for the left side, one for the right—into a fifty-five-year-old man whose heart had failed completely and been removed; the VADs amounted to an artificial heart that kept him alive for five weeks.

Frazier's career began during the golden age of the artificial heart and extended into its wilderness period. In 1963, he arrived at Baylor College of Medicine and studied under Michael DeBakey; he joined Cooley at T.H.I. in the seventies, and was still there in the eighties, when the discovery of cyclosporine, an immunosuppressive drug, made heart transplantation dependably survivable. Convinced of the value of heart pumps as bridge devices, he began working in a basement lab stocked with pigs, sheep, cows, and goats; over decades, he partnered with engineers to test and refine almost every heart pump currently in existence, including the original HeartMate. (Earlier, in Cerritos, I'd watched a video of a Bivacor-powered calf strolling on a treadmill in Frazier's lab; Frazier and Cohn are advisers to the company.)

"Here's this guy, O. H. Frazier," Cohn said, pointing to a photograph on his laptop of Frazier in bloodstained scrubs, taken long ago. "Total rock star." Frazier chuckled.

Cohn, radiating messianic energy, described how, in 1986, Frazier had been the first surgeon to use the HeartMate successfully, as part of a clinical trial that lasted until 1993. After it was approved by the F.D.A., in 1994, around four thousand people received one worldwide. It was doughnut-shaped, with a mechanical "pusher-plate" pump, and one of its core innovations was the use of specially textured plastic and titanium on which blood cells could grow a smooth, biological surface. Early versions were powered by air, delivered through a hose; later models, like the one Jess received, were motor-driven. The device had a life span of a year and a half at most, but that was enough for patients who came into the hospital blue-lipped and close to death. "You put 'em on the breathing machine, you made a *big* cut, you put

this pump in their abdomen, you hook it up, and, at the end of the operation, the lips turn pink." The challenge was, and remains, a lack of transplantable hearts: "At a year and a half, it would break, and you'd better find 'em a transplant in that period of time, or they would all die."

To address this problem, Frazier began working with a Massachusetts-based heart-pump company, Abiomed, to design a next-generation artificial heart, the AbioCor. Devised in the early nineteen-nineties, the heart was traditional in some ways (it had two chambers, like a real heart) and futuristic in others. There were no air hoses or electrical cables leaving the body; completely self-contained, the AbioCor used hydraulic fluid, which could be recirculated, to squeeze its ventricles. It was powered by a battery that could be recharged wirelessly, through the skin. In theory, you could swim with it.

"Super, super ambitious," Cohn said, pulling up a diagram. "They spent a quarter of a billion dollars developing this. Several hundred animals, half of 'em done here, by Bud and his team." In 2001 and 2002, the heart was installed in fourteen patients. That's when the ambitious plans began to falter. "By nine months, all of them except four had died from either complications or device failure," Cohn recounted.

The F.D.A. gave Abiomed permission to implant sixty more devices, but it was clear that the heart would need to be updated, and then approved all over again—a lengthy process for which no one had the fortitude. "Abiomed threw in the towel," Cohn said. "They were, like, 'This is too hard!' " One problem was that the heart was so large that it fit only in the chests of the biggest male patients.

"You know, your heart beats a hundred thousand times a day," Frazier drawled.

"Thirty-five million times a year," Cohn said.

"So, looking back on it, it's amazing it lasted as long as it did," Frazier said.

Throughout the eighties and nineties, even as he helped with the HeartMate and AbioCor, Frazier argued that engineers should shift from pulsatile pump designs to ones based on the more mechanically straightforward principle of "continuous flow"—the strategy that Bivacor later adopted. Some researchers argued that the circulatory system might benefit from the pulse; there's evidence that blood-vessel walls expand in response to a quickening beat. But Frazier had come to believe that, whatever the benefits of pulsation, they were outweighed by the virtues of durability and simplicity. He began working on two continuous-flow designs in parallel—one with a cardiologist named Richard Wampler, the other with Robert Jarvik—implanting them in animals, taking them out, disassembling them, and analyzing how they'd performed. By the two-thousands, the designs had come into use as the Jarvik 2000 and HeartMate II, respectively.

On his laptop, Cohn pulled up a diagram of the HeartMate II. Essentially, it's a narrow pipe filled by a corkscrew; as the screw turns between two bearings, it acts like a stationary propeller, pushing blood continuously out from the heart

and into the aorta above it. (In farming, the same design—a so-called Archimedes' screw—is used to pump water for irrigation.)

Cohn pointed to the screw: "One moving part, suspended by ruby bearings. People said, 'Well, you can't have bearings in the blood.' It turns out you can! There's enough blood washing over them that they stay cool and clean. One of these on a bench will pump forever." Clots are still a problem, as is infection. Still, more than a thousand people each year now receive HeartMate IIs or similar devices, living with them as they inch their way up the transplant list; a HeartMate II kept Dick Cheney alive, with a fainter pulse, from 2010 to 2012, until he could receive a transplant.

In the summer of 2019, I got an e-mail from Jess. "I recently celebrated twenty years with my heart transplant," she wrote to a group of us. "But heart transplants don't last as long as native hearts." I hadn't known this; I'd assumed that her transplant was permanent. In fact, her borrowed heart was giving out. She'd been short of breath and, one night, had almost collapsed while walking home to her apartment. Now she was back in the hospital, waiting for a second heart. "It could be weeks, or months, or (less likely) tomorrow," she wrote. "Please send good vibes."

I visited Jess in the critical-care unit, where we talked about restaurants, careers, and television shows. We looked at a few photos of my son, who was around a year old. I was about to visit again when she died.

"She did great," Cohn said. "Many heart-transplant recipients are dead in ten years."

"Recently, I went to a birthday party for a guy I transplanted thirty years ago," Frazier said. "But those are rare, rare, rare. Only about five per cent of transplant recipients make it to thirty years." The artificial pumps on the market are considered bridge therapies, and heart transplants "destination" therapies; but, if you live long enough, the transplants, too, are merely bridges.

I asked Frazier and Cohn how they felt about all the people who had died while, or after, using their devices—whether they lingered in the mind, and how.

"Martyrs," Cohn said. "They were clinging to life. The technology may not have been there, but it sure beat drawing their last breath. Many of them spent years with their loved ones, doing the stuff they enjoyed. Some went to the I.C.U., were gravely ill for six weeks, and then died, when in retrospect they would've been better off if we'd just let 'em die. But you don't know! It's a statistics game, and they were willing to go for it, for a couple more days of life. And it advanced the field, every time."

"I had a lot of experience working with leukemic children when I was a medical student," Frazier said, quietly. "They all died. In fact, the doctors at Texas Children's wanted to stop the work."

"Because you were torturing them with these poisons," Cohn said.

"They looked awful," Frazier said. "Their bellies swelled, and they lost their hair, and it scared the other children. But

they kept plugging away with it. And I think that helped me. Because the first twenty-two people of the seventy that we put the first LVADs into all died."

It was getting late. Frazier led me through the deserted office area, along a series of twisty, silent corridors, and finally down an elevator to the basement. We entered his lab—the vast lair where he'd spent most of his working life. We passed through a veterinary operating theatre and a pathology lab, where deceased animals and failed pumps could be disassembled and analyzed.

"We've got pigs in here," Frazier said, opening a door. There was an animal smell, and a large pink pig lumbered into view, snuffling.

"Pigs have a heart that's most like the human heart," he said, closing the door. He gestured down the corridor: "Goats. I don't like to do goats. They're too smart!" He laughed. "They look up at you."

We went deeper into the lab. In a carpeted conference room, a display case contained a few dozen artificial hearts and heart pumps—the history of the field, more or less. "The one in the middle is the AbioCor," Frazier said, indicating a heart-shaped twist of metal and plastic. "This is the old Jarvik-7": two yellow-beige ventricles with tubes running out. "That's a HeartMate II": a gray metal cylinder with white tubing at either end, like something you'd find under a sink. Framed on a wall, an issue of *Life*, from September, 1981, declared, "THE ARTIFICIAL HEART IS HERE."

Frazier pointed to a big metal pump, and to a white bit of tubing protruding from it—a "long inlet," he said. Until it was corrected, it had doomed the device to failure. Small differences, iteratively tweaked, their effects uncovered only after death. It was invention in slow motion.

The AbioCor was cancelled. The Bivacor is years away. Today, the only company manufacturing and selling artificial hearts that are actually implanted in people is SynCardia Systems, of Tucson, Arizona. The company was formed as a rescue mission. Symbion, the Utah company that Robert Jarvik helped found, had lost F.D.A. approval for the Jarvik-7 heart in 1990, because of quality-control issues; its heart technology was acquired by another firm, which ran a decade-long clinical trial with an improved version of the heart, only to exhaust its funding in 2001. For a time, it seemed that the technology would vanish from the earth. But two heart surgeons and a biomedical engineer scraped together the venture capital to buy the rights to the system; they rebranded the heart as the SynCardia Total Artificial Heart, or T.A.H. The company, now based in a handful of buildings surrounding a sandy parking lot, sells somewhere north of a hundred hearts a year, all descended from the old-style, air-powered Jarvik-7. Although SynCardia has succeeded in building a network of surgeons capable of installing its heart, the company is only tenuously in business. A few years ago, it declared Chapter 11, and was bought by new investors. It coped with the coronavirus pandemic, which has led to the cancellation of surgeries around the country, by manufacturing hand sanitizer.

With Karen Stamm, SynCardia's director of program management, and Matt Schuster, an engineer, I watched through a window as a technician in a clean room assembled one of the hearts. "The key to being able to build the artificial heart is the material we use," Schuster said. "Segmented polyurethane solution. You'll hear us call it 'spuzz'—S.P.U.S." Stamm laughed. "We actually manufacture SPUS here on campus," Schuster continued. "It's our own proprietary mix. It comes out of our manufacturing equipment almost like a sap, or a thick honey." Using a dental pick, the technician carefully manipulated layers of the molded honey. A translucent something shifting over another translucent something. The assembly process takes two and a half weeks.

We walked through a lab dedicated to "explant analysis"—"If we get a heart back, we'll take it apart and inspect it," Schuster said—and into another room filled with a few dozen water tanks on shelves. Inside each tank was a heart, beating; next to the tanks were the air pumps, or "drive units." The sound in the room was deafening: a fast, loud *whump-whump, whump-whump,* and within that a mechanical clacking, like a typewriter. The sounds cycled twice a second—an industrial rhythm, as though we were in a factory for the manufacture of circulation. "This is where we run our long-term studies," Stamm shouted, above the din. On one side of the room were the fifty-c.c. hearts, used by smaller patients; on the other, the seventy-c.c. models, used by larger ones. "There's the driver, which is the mechanical sound," she said, pointing to a lunchbox-like mechanical pump that was connected by an air tube to a heart inside a tank. "Then you hear the clack-clack—that's actually the valve inside the heart."

The drive unit has been a focus of innovation for SynCardia. Its heart can be driven by one of two units, the first the size of a mini-fridge, the second the size of a toaster—both much smaller than the ones DeVries's patients used. The drivers need to be serviced after a few months; when a warning light comes on, a caregiver unplugs the drive line and reattaches it to another unit as swiftly as possible, lest the user's heart skip a beat. As I watched, the water in the tanks rippled slightly, in rhythm. It takes a lot of *whump* to push five or six litres of blood through the body every minute.

"What does this actually sound like in a person?" I asked.

"It's much quieter," Stamm said. "But you can hear it. I've heard stories where patients say that, if they open their mouths, other people can hear the clicking." She told me that some patients couldn't tolerate the noise at first. But then, she said, "they couldn't sleep without the sound of the *ca-chunk, ca-chunk*."

We continued through a warehouse area, where a dozen or so hearts were kept on shelves, ready to ship; surgical kits, containing the materials required to install them, were boxed in a separate stack. Then we traversed the parking lot to another building, where a group of engineers waited with safety glasses in a high-ceilinged lab space. One of them handed me a small piece of hourglass-shaped plastic: the SPUS. See-through but slightly milky, slick but grippy on my fingertips, it was almost surreally stretchy—I pulled on its ends, drawing the neck of the hourglass to several times its initial length, and it effortlessly returned to its original shape.

Through a doorway I spied a giant, well-worn machine, perhaps a dozen feet tall, combining aspects of an oil derrick

and a KitchenAid. “The SPUS reactor,” Troy Villazon, SynCardia’s production manager, said. “It’s from the early sixties.” SynCardia had acquired the machine in the early twenty-tens, to insure a steady supply. “The machinery itself has gone through the whole history of this material,” Villazon said. For a while, we stood speculating about whether this very machine had been used in the creation of the Jarvik hearts. “It very well might have,” Schuster said.

I stopped in front of a whiteboard where four photographs of SynCardia patients had been arranged above the usual hand-drawn schematics. A Black man in a hospital bed, holding a shopping bag; a balding white man on a golf course, with a slender air hose running out from under his shirt and toward his clubs; a blond man, perhaps in his teens, carrying a backpack; and a young brother and sister sitting together. “We like to keep some motivation up on the wall,” Villazon said. The boy, nine years old, was the youngest person ever to receive a SynCardia heart. The longest-surviving SynCardia patient has been using the heart for almost seven years—an achievement that, in the nineteen-eighties, might have made the cover of *Life*.

One of the biggest problems that SynCardia faces is obsolescence. The Jarvik-7, on which the SynCardia heart is based, was designed nearly forty years ago; the company’s initial F.D.A. approvals are decades old. Today, changing any single part of the heart—a bolt, a valve, a resistor—can require a new approval process. As suppliers go out of business or update their offerings, SynCardia engineers must hunt down, test, and then win approval for replacement components. They live in fear of a fatal malfunction in the SPUS reactor: constructing and securing approval for a new one could take a year, leaving potential new patients without hearts. Maintaining a legacy device is expensive. “Even if you’re not improving it or changing it, just to keep manufacturing that same thing—people don’t realize,” Schuster said. “I’ve worked in aerospace, and I can tell you, it’s often easier to make massive aerospace-defense changes than it is to change something on an artificial heart.” Listening, I imagined the focus with which users of the heart must track SynCardia’s ups and downs.

In the United States, there are fewer than twenty hospitals at which surgeons have been trained to install the heart. “It’s a narrow market,” Don Webber, the C.E.O. of the company, told me. He took out his phone and pulled up a spreadsheet that listed all the candidate patients for the heart at that moment. “We have a daily sheet that comes out,” he explained. “We’ll get a phone call, or a text or an e-mail, that says, ‘We may have a patient.’ ” On the phone’s screen, rows of patients scrolled by, color-coded.

SynCardia faces the same problem that Cooley encountered in the nineteen-sixties: you have to be very sick to consider cutting your heart out of your chest, but if you wait too long, and get too sick, you are beyond saving. “There are cases that sit there,” Webber said, alarm in his voice. “You see it on the list this week, you see it on the list at the end of the week, you see it on next week’s list. They’re just waiting, and waiting, and waiting.” The longer a patient waits, the less likely she is to survive the implantation of the artificial heart and any subsequent transplant. “It’s not a clean decision,” Webber said. “You have several people that are on that team”—surgeons, cardiologists, hospitalists, all of whom have to agree.

Business scholars use many different metaphors to describe invention and innovation. They say that technologies can progress in continuous and discontinuous ways; that new products must climb an "adoption curve," or leap across a chasm of usability. Nobody wanted mobile phones until they got so small that everyone wanted one. Electric cars have seemed impractical, but hybrid engines, by giving drivers a taste of the technology, have speeded their adoption.

The artificial heart faces a unique challenge. Only those confronting imminent death are willing to use today's models. And yet nearly six hundred and sixty thousand Americans die of heart disease annually—a pandemic-level death toll about which we feel little sense of emergency. An increasing number of us live with diseased hearts and suffer the consequences. To realize their full potential, artificial hearts must get good enough that people actually want to use them; they must be preferable not to death but to a failing heart, the way hip replacements are preferable to failing hips. Meanwhile, until they achieve wider adoption, they will remain a niche product—and so be unavailable to many people who need them. For another moment, Webber scrolled his list; I wondered whether Jess should've been on it. Then he put the phone away.

The engineers at SynCardia are charged with sustaining a legacy technology, but they also understand that it needs to advance. Before I left Tucson, Villazon told me about a next-generation heart that SynCardia was developing. The heart would use a new, battery-driven pump engine, which could be housed entirely within the patient; like the AbioCor, it would be wireless, without an external driver. At the same time, it would pump blood using the company's preëxisting, SPUS-based ventricles, which had already been approved by the F.D.A. By hooking this new engine up to its old car—a hybrid model—SynCardia hoped to develop and market the heart quickly, and to bring its existing customers along. The new heart could be a reliable, permanent implantation, Villazon said. It might be used by people a little further from the precipice.

I'm no Bud Frazier, but I've seen a lot of artificial hearts, and Villazon's design struck me as both simple and ingenious. And yet SynCardia's engineers were busy—manufacturing, selling, and updating the current heart, saving more than a hundred lives a year. They were struggling to find time to get the new heart up and running. They'd 3-D-printed a few prototypes and shopped the specs around; they were talking with investors.

The Bivacor team, in Cerritos, is blissfully unencumbered by the technological past. When I visited, everyone was going out for Thai—a weekly team lunch. It was a large group for the restaurant, but a small one for the design of an artificial heart. Timms sat at one end of the table, near Nicholas Greatrex, the electrical engineer.

"Now that you're getting closer to putting a device in a person, how does it feel?" I asked. "Is it exciting, or freaky, or what?"

"The closer you get to it going into a human, the more you think about everything that can go wrong, and what you can do," Matthias Kleinheyer, a bearded engineer, said. "Even if I had no doubt that the system is performing the way it's supposed to, it would still be very scary." Kleinheyer is in charge of the heart's backup systems; there are backups to

the backups to the backups.

“Nick wants to go and live with the person who gets the first heart,” Timms said.

“Yeah,” Greatrex said.

“In case something goes wrong, we could fix it right away,” Timms said.

I pictured Timms, two decades younger, tinkering in the garage with his dad. Once the company shipped its heart—to a human implantation, a clinical trial, and eventually the market—its design would have to be set in stone. The process of approval was at odds with the process of improvement.

“If I could, I’d just keep working on it and working on it and working on it,” Greatrex said. “I’d never implant it.” People laughed, but he wasn’t exactly joking.

If patients in need of artificial hearts can wait too long before taking the leap, the engineers who design them face a parallel decision. Implant too soon, and the device may be immature; chase perfection, and it may never leave the lab. Back at the office, I talked with Timms about the question of wireless hearts. Investors have offered to give the company more money if it will design a wireless, rechargeable heart right away; gritting his teeth, Timms has decided to refuse the funding, saving wireless charging for version 2.0. “We’d rather keep the money to make sure that the device works properly in the body,” he said. “If we do the test flight, and we try to do too many things at once, we’re going to crash.” It was, he thought, the most consequential design decision the team had made; if it prevents broader adoption of the heart, it could bring the whole effort to an end. “I hate the drive line so much,” Timms said. “I mean, that thing has to go.” But not yet.

In the lab, Greatrex walked me through a technical innovation of which the team was especially proud. The human circulatory system is housed within a body that is constantly adjusting its configuration in space. As a result of the body’s movements and exertions, the rate of blood flow changes. Lie down and it generally decreases; stand and it speeds up. Run or jump and it spikes, in order to feed oxygen to the muscles. All this movement poses a challenge for Bivacor’s maglev rotor. As the body moves and stops, and as blood flow surges and ebbs, the disk can find itself pushed toward the walls. Ideally, the rotor would resist the currents—floating and spinning as if weightless, holding the position no matter the circumstances.

On a whiteboard, Greatrex outlined the elaborate magnet-control systems that the heart uses to sense and adjust to the forces around it. Timms himself had worked out the math that made the adjustments possible—a difficult problem in fluid dynamics. The engineering depended on digital technologies that had been unavailable to previous generations of designers.

Greatrex handed me one of the rotors: a coin-shaped object, a few inches across, made of burnished gold-colored titanium. It was a source of regret for the team, he said, that, in the final production version, the titanium would be a

more practical gray. I hefted it. On one side, eight metal tines clustered, Stonehenge-like, in the center. On the other, eight curving, windswept triangles studded the edges, as though sails, or shark fins, were performing a circumnavigation. An intricate pattern of whorls filled the middle of the disk—machining marks, or waves on the sea.

"I think if you showed that to a bunch of people no one would figure out that it's part of an artificial heart," Greatrex said.

I turned it in the light and snapped a photo. It was a strangely evocative object—a beautiful one. It wasn't biological, but it didn't seem entirely mechanical, either. It had the idiosyncratic, refined particularity of something that had evolved. In a way, it had. ♦

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