

# Mozambique

My first epidemic began quietly, as most epidemics do. It was May 1978, and I was working as a physician at the Central Hospital of Beira, Mozambique, which was the only hospital for hundreds of miles. One morning I was summoned to attend to a dangerously debilitated man in his thirties. The man's family had brought him a great distance from the *mato*, or countryside. The ailing man was so severely dehydrated that when I gently pinched his skin, it tented, meaning it retained the profile of a small tent where I'd pulled it away from the underlying tissues. His eyes were sunken, his gaze terrified. He was clearly near death.

Three months earlier, I had arrived in Beira with my wife Andy (short for Adrienne), who's a nurse, and we had begun caring for patients in the city's Central Hospital. Beira is a major port city in southeastern Africa and Mozambique's second largest urban center. It lies some seven hundred miles north of Maputo, the capital, in a flood-prone rice-growing region on the Mozambican coast. Although it is not a spectacular city, it does have its share of natural beauty, with long, curving white sand beaches rimmed by the warm waters of the Indian Ocean. The beauty of Beira's beaches, where well-off white Rhodesians once played, could have blinded the casual observer to the existence of ancient diseases rife in the population, diseases scarcely known in Western societies.

Beira was then an impoverished city of about three hundred thousand in a nation that had wrested its independence from Portugal just three years earlier. Andy and I were part of a small troop of profes-



**FIGURE 1.** Drs. Paul Epstein (right) and Steve Gloyd with a Mozambican colleague in Caia, Mozambique, in 1978. In the background is the Zambezi River, one of Africa's four largest rivers. (Photo courtesy of Paul Epstein)

sionals, of all stripes and from numerous countries around the world, known as *cooperantes*, or international aid workers, who converged on Mozambique to help the fledgling nation rebuild its health care system, its economy, and its society (figure 1).

To prepare for my work in Africa, I had audited a course on tropical diseases taught by top experts at the Harvard School of Public Health. Upon our arrival in Mozambique, I had also undertaken six weeks of on-the-job training in the sprawling 1,600-bed complex of the Central Hospital of Maputo, the country's most modern city. In the vast, open wards of the Maputo hospital, a collegial group of local and foreign doctors had given me a hands-on crash course in recognizing and treating the many afflictions common in southern Africa, including well-known diseases like malaria and tuberculosis, along with a multitude of life-sapping diseases caused by worms of all sorts and sizes. These included hookworm, which lives on blood and causes anemia, weight loss, and stunted growth, and schistosomiasis, or snail fever, a debilitating ailment endemic in Mozambique that causes urinary tract and kidney disease.

My suspicions about what was ailing the desiccated, frightened man in Beira did not derive from the training I'd received in Maputo. Instead,

the deathly ill man recalled images in tropical disease textbooks I'd studied in Boston. His sunken eyes and dehydration presented the classic picture of cholera, a waterborne disease capable of blossoming into a raging epidemic.

Completing the diagnosis required microscopic examination of the patient's stool for the cholera bacillus. Other strains of bacteria, as well as some viruses and parasites, can cause diarrhea that results in extreme dehydration, and we needed to rule out these infections. I placed a drop of the man's watery stool on a glass slide and peered at it under the microscope. I saw hordes of wriggling, comma-shaped microbes dancing on the slide—telltale signs of *Vibrio cholerae*. The diagnosis was established when the organisms later grew in petri dishes containing agar made with small amounts of sheep's blood.

Andy and I had become familiar with the host of serious but preventable diseases that afflicted Mozambicans and those in neighboring nations, resulting from poor nutrition, inadequate sanitation, and poverty. But cholera—with the exception of a brief appearance in 1973—had not been among those ills.

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When we applied to work in Mozambique in 1976, the former Portuguese colony had been independent for a year. Mozambique's revolutionaries in the Front for the Liberation of Mozambique (FRELIMO) had fought a successful thirteen-year war for freedom from colonial rule, a war that ended when colonial soldiers returned to Portugal and overthrew their dictator, in turn freeing the nation's African colonies. The revolution held the promise of a better life for Mozambicans, but its immediate aftermath had major repercussions. Upon independence, the Portuguese fled en masse—more than a quarter million Portuguese left the city of Maputo alone.

The fleeing Portuguese packed up their riches as they exited, and, in some instances, they sabotaged development projects on the way out. But the losses to the country weren't solely material. The exodus included virtually the entire professional class of Portuguese settlers, including teachers, foresters, mining specialists, engineers, and doctors. Under Portuguese rule, education for most Mozambicans had ended after fourth grade, with the exception of students sent off to seminaries. When the Portuguese left, most Mozambicans were illiterate.

Because Mozambique needed so many kinds of experts to build its new infrastructure, Mozambique's first president, Samora Moisés

Machel, and his government reached out around the world for assistance. My wife and I were part of the wave of international *cooperantes* who responded to that call. Indeed, during our time in Beira, Andy and I worked alongside *cooperantes* from, among other places, England, Holland, Sweden, Russia, Bulgaria, Cuba, Zambia, Brazil, and Chile.

The new government had many concerns to address. Perhaps the most immediate had to do with medical care for their newly liberated citizens, who were overwhelmingly rural farmers. Many nurses had departed, and almost all of Mozambique's Portuguese doctors had abandoned the country, leaving just a handful of physicians to care for a population of twelve million.

Fortuitously, President Samora Machel, whom Mozambicans knew simply as Samora, was a trained and experienced nurse, and he assigned health care a high priority in those early heady days. Samora's aim was to develop a well-distributed health care system that integrated public health services. Achieving these worthy goals was difficult with so few resources and health practitioners at hand. At Samora's insistence, neighborhood health clinics were opened throughout the country and stocked with a carefully selected list of imported generic medications. These efforts led the World Health Organization to recognize the Mozambique health care system as exemplary. But that was only a beginning. One of the important tasks for medical *cooperantes* was the training of Mozambican nurses, nurse practitioners, and new doctors in the nation's one medical school in Maputo.

From 1976 to 1978, we waited while our applications to work in Mozambique wound their way through the fledgling, byzantine Mozambican bureaucracy. At last we were informed that we would be welcome for a two-year posting. Although we were officially employees of the Mozambican Ministry of Health, our sojourn had been arranged by the American Friends Service Committee, the Philadelphia-based Quaker organization that supports humanitarian aid and peacemaking efforts around the world.

Upon our arrival in the country in February 1978, we were relieved to discover that we could speak our rudimentary Portuguese haltingly with Mozambicans. (It would be six months before we could hold our own in a dinner conversation.) Assured that we were capable of taking a medical history, we got to work immediately. Our children adapted in a different fashion. They played silently for the first six weeks with the children of our Mozambican, Chilean, Swedish, and Portuguese neighbors and coworkers. Then, suddenly, they began to speak the lingua

franca fluently, interjecting the word *coisa* (thing) for whatever object they could not yet name. It was an exciting time.

With FRELIMO's explicitly race-blind policy, we felt welcomed and accepted in this beautiful port city of a million people, with its vistas of the radiant Indian Ocean. With our children we walked downtown and through shantytowns, exploring the spicy and delicious victuals. Fish and shrimp and chicken were abundant—and cold, cold beer (*bem gelado*) as well. In our hotel, there was only the occasional mosquito, but crickets, birds, and roosters could be heard everywhere.

During our six weeks of training at Maputo's Central Hospital, a delightful, well-trained Cuban hematologist befriended me, easing my transition from Western to tropical medicine. When Andy arrived in the surgical ward, her first patient was a man who'd been bitten almost in half across his abdomen by an alligator while crossing a nearby river. With surgery and good medical care, the man survived intact.

Most of the diseases afflicting Mozambicans presented with signs almost as obvious as an alligator bite; thus diagnosis was generally easy. Prevention, on the other hand, was difficult to implement, given the country's low level of development, which made even simple preventive measures for many common maladies hard to come by. Few women or children wore shoes (figure 2), which would have spared them the anemia caused by hookworms that enter the body through the skin of the foot and then line the sides of the intestines. (Men, who benefited more from the country's limited prosperity, were more apt to be shod.) From our vantage point on the ground, the shape the nation's development would take was not obvious. Even today, the questions of how to develop and to power that development remain central issues for Mozambique, as they are for many underdeveloped nations.

Shortly after arriving, we were posted to Beira, the second largest city in Mozambique. After completing our training at the seven-hundred-bed Central Hospital in Maputo, Andy and I launched our family's four-day trip on the northerly road to Beira in a spirit of adventure seeking and with a sense of purpose. We traveled a hardscrabble highway, which was intermittently paved, and ascended onto the vast African savannah dotted with wide-crowned acacia, mango, and cashew trees. If Maputo had seemed exotic, the landscapes and civilization we encountered on our journey to Beira were even more so. We stayed overnight at a hotel in the beach town of Vilancoulos, where we were the only guests. We were served by a Mozambican staff that otherwise stood quietly behind nearby palm trees, shoeless but clad in white colonial-era uniforms, as



**FIGURE 2.** Mozambican boys near *canisos* (houses made of sugarcane stalks) in Buzi, Mozambique, a sugarcane-growing area west of Beira, in 1978. Many women and children then lacked shoes, which put them at risk for parasites, such as hookworm, that enter the body through the feet. (Photo by Paul Epstein)

if the revolution had never happened. We swam for the first time in the surprisingly warm sea. That evening, the four of us stood surprised and transfixed, watching a lunar eclipse from the hotel balcony. The moon seemed just a few feet away as it dropped into the sea.

Two days later, following a stop in Xai-Xai to visit a Mozambican friend who had studied in Boston and taught us Portuguese and Mozambican history, we reached Beira. The city had been a major trading center for goods from Salisbury, Rhodesia (now known as Harare, Zimbabwe), in the heyday of colonialism. By the time we arrived in 1978, however, it was a diminished outpost populated by a few Indian shop owners and many unemployed Mozambican men. Women were barely in evidence in the modern part of Beira, which the locals called the “cement city.” The town’s center seemed almost abandoned. The real life of Beira, we discovered, could be found on its outskirts. Dirt roads and narrow paths weaved among houses made from sticks and stones, cement, or sugarcane stalks. Outside, children played and women sewed and sold goods from stalls, keeping one another company. Women tended the cooking fires, and the air was infused with the sweet scent of



**FIGURE 3.** Adrienne (Andy) Epstein interviews a father and son in the emergency room at the Central Hospital of Beira, 1978. She was performing triage—treating some patients then and there, admitting others to a hospital bed, and sending others to an outpatient clinic. (Photo by Paul Epstein)

burning acacia. We lived nearby, and from our cement house we could hear *batuki* (drumming) well into the wee hours on the weekends.

I was soon appointed chief of medicine at the Central Hospital of Beira, and I set about working with the thirty other international doctors and one dentist. Each medical *cooperante* put in one twelve-hour work shift a week in the hospital's emergency ward. Andy worked there each day as well, performing a form of triage, determining when patients required hospital admission, simple packets of pills, or treatment in a neighborhood health center (figure 3).

In the evenings, our home was a magnet for this multicultural crowd of international coworkers, Portuguese friends and coworkers, and Mozambican locals and their families. The children, lacking television to mesmerize them, kept us entertained with their improvised theatrical and musical productions.

Conditions varied on the hospital's wards. A common problem on the women's ward was severe anemia from hookworm, acute malaria, or both. The problem was exacerbated when women were pregnant, as the body's blood volume rises from five to seven quarts and already

scarce iron is stretched even thinner. Other patients had one or more of a range of debilitating diseases, including mosquito-borne elephantiasis, amoebic dysentery, and schistosomiasis. Mosquitoes infected and reinfected our patients with malaria, and they infected Andy and the children with malaria as well, despite the chloroquine pills they took to prevent it. Then there were the diseases imposed on Mozambicans solely as a result of inadequate sanitation, poor nutrition, or both, among them rickets and gastroenteritis from many sources. “It’s a wonder there are so many people walking about,” I wrote in one of my earliest letters to our sponsors in Philadelphia. On the other hand, the pervasive diseases of industrialized societies—diabetes, hypertension, and heart disease—seemed nonexistent.

Our work was demanding but rewarding. After working all morning in the hospital, we’d head out to the shantytowns—the *bairros*. Andy worked in the health clinic of a *bairro* called Inhamudima near our home, while I worked in another clinic out in Munhava, the largest of the *bairros* ringing the cement city. The locals introduced us to locally available foods, and we taught them about nutrition and other healthy practices. We saw patients—usually about twenty-five each day—throughout the afternoon. The medical and social needs were enormous.

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An epidemic is defined as an unusual occurrence of disease—an unexpected number of cases occurring in a particular time and place. Understandably, epidemics are often not immediately recognized. But in the case of the cholera epidemic that erupted in Beira in 1978, the breadth of the outbreak was evident in a matter of days.

That the disease was cholera made the episode all the more remarkable. Cholera had spanned the globe in seven pandemic waves since the 1800s, including the London cholera epidemic in the 1850s that crusading epidemiologist John Snow had helped stop. Epidemiologists knew that cholera was circulating in Asia in the late 1970s and was, in fact, considered a permanent blight in the many countries bordering the Bay of Bengal, reaching from India all the way to Thailand. But the disease had been absent from Africa for most of the twentieth century, so its appearance in Mozambique was surprising. The deathly ill man from the *mato* was the first, or “sentinel,” case of the epidemic, and his illness indicated that the seventh pandemic wave had now spread to East Africa. In the weeks that followed his arrival, hundreds of people in



**FIGURE 4.** Nurse-practitioners-in-training examine a patient at Beira Central Hospital, Beira, Mozambique, in 1979. The hospital's facilities were barely adequate to provide modern medical care to Mozambicans. (Photo by Paul Epstein)

all stages of the disease found their way to us, to Beira's neighborhood clinics, and to clinics in surrounding towns and villages. In addition to those presenting as ill, we knew there were thousands more in the Mozambican countryside who were carrying the bacteria but showing no symptoms. It was truly a major epidemic.

When the cholera epidemic first hit, we were fortunate to have the staunch support of the province's health officer, the capable Dr. Pascoal Mocumbi, a practicing obstetrician and gynecologist who would later become the nation's minister of health and then its foreign minister. Working together, in short order we organized a thirty-bed ward staffed by four doctors and eight nurses.

Treatment of cholera demands immediate administration of fluids, a therapy that is the only real cure for the disease. (Antibiotics are generally useless as treatment, though they can be preventive.) Without treatment, a patient might lose up to seven quarts of fluid a day from blood and tissues as a result of severe diarrhea, and such extreme dehydration results in a fatality rate of up to 50 percent. Treated properly, cholera can have a case fatality rate of less than 1 percent. We developed protocols,

which included giving all but the most severe cases of dehydration an oral salt-and-sugar solution. We knew from work in Bangladesh that such a regimen could treat the majority of patients. Patients who were too weak to drink or who were vomiting required intravenous administration of this simple fluid mix.

Doing medical work in a poor developing country like Mozambique presented many unexpected challenges. The water in the salt-and-sugar solutions had to be free of pathogens, and that meant that every liter of water had to be boiled, using heat derived mostly from burning wood and charcoal. Plastic catheters and other disposable supplies readily available in developed nations for administering intravenous fluids were nonexistent in Beira. We needed steel needles to deliver fluids directly into veins, but they were dulled from repeated use. A one-time shipment of plastic disposable IV equipment from our sponsors arrived, but when it ran out, Mozambique could not afford to order more (figure 4).

The cholera epidemic tried our medical and nursing skills, it taxed our capability to rapidly train other care providers, and it stretched the resources of this young nation. At the time, though, we were just trying to save the ailing Mozambicans who were flooding into our clinic. The epidemic had become a trial by fire for us all.

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The man from the *mato* stayed at the Central Hospital in Beira for more than a week, and a combination of intravenous solutions followed by oral rehydration gradually restored his strength. Then one day he walked out of the hospital with his family. We saved many others as well. But we couldn't save everyone. Many of the ailing people lived far from the hospital, and slow access to transport and care meant that an estimated 5 percent of those stricken with cholera died, many of them deep in the countryside.

Epidemics had previously been events I'd studied in historical and medical textbooks, but now they were a dreadful reality. However, after the cholera epidemic abated, I was struck by just how much could be done to stem the tide of an outbreak with early warnings, rapid diagnoses, and relatively basic training of health care personnel. During the epidemic, the services we set up to rapidly diagnose and treat cholera patients had saved hundreds of lives.

We had far less success stopping a devastating man-made scourge. Just a few weeks after we began working at the Central Hospital of Beira, the first of what would be thirty-five young Zimbabwean refu-



**FIGURE 5.** Dr. Paul Epstein conducting a public health survey in a refugee camp at the border area of Mozambique and Zimbabwe, 1985. (Photo courtesy of Paul Epstein)

gees, most of them under twenty-five years of age, wound up at our hospital, bleeding from multiple orifices.

At the time, Ian Smith's all-white Rhodesian army was fighting to retain control of that country, and they occasionally pursued fleeing Zimbabweans, some of whom were fighting for their country's independence, across the border into Mozambique. The young men and women we encountered had been staying in a refugee camp several hundred miles from Beira. Given how much they were bleeding, we initially suspected they were suffering from one of the viral hemorrhagic fevers—Ebola, Lassa, or Marburg—that were newly emerging in Africa. But that was not the case, and we—and other infectious disease experts we consulted—were at first bewildered about the cause of their ailments.

We organized a ward for these desperately ill young people and infused them with blood provided by other Zimbabweans and Mozambicans, but over the next two weeks, fifteen of the thirty-five died. After the last victim, a handsome young man, succumbed in front of me, I excised a small sample of fatty tissue from his abdomen. A toxicological investigation revealed the cause of this macabre disaster. The man's fatty tissue

had been contaminated by warfarin, a blood anticoagulant commonly used as a rat poison. It turned out that members of the Rhodesian intelligence forces, aided by foreign mercenaries, had deliberately impregnated the Zimbabweans' clothing with rat poison.

That event was our initiation into the darkest reaches of biological and chemical warfare. Through both the epidemic and the poisonings, however, Andy and I gained a new appreciation of the interwoven environmental and social determinants of health (figure 5). The lessons learned have stayed with me and helped shape my views on how to cope with and prevent the mounting health problems associated with a changing climate.

### THE ROOTS OF DISEASE

I returned from Mozambique in 1980 with a strong desire to better understand the field of public health. I was acutely aware that, while individual health care was essential and needed to be distributed to all corners of the globe, public health measures and social interventions were needed to prevent the ills afflicting large populations. After returning to Massachusetts, I worked as a primary care doctor at a neighborhood health center in Boston for a while, then at Cambridge Hospital, a teaching hospital affiliated with Harvard Medical School. Most days I worked at the associated East Cambridge Neighborhood Health Center, located in a neighborhood populated by Portuguese-speaking people from the Azores, Portugal, the Cape Verde Islands, and, later, Brazil.

In 1981, I enrolled in a master's program at Harvard's School of Public Health. Over the next two years, I was exposed to ideas and people who influenced me deeply and helped shape my approach to medicine, science, and international public health policy. One significant encounter occurred in a classroom in an eleven-story brick building at the Harvard School of Public Health. There, Richard Levins stood at a blackboard, speaking quickly and sketching a diagram as a small group of graduate students, most from or with experience in developing countries, leaned forward in our seats and focused intently. Levins was and still is a professor of population sciences at the school. A self-described ex-tropical farmer turned ecologist, biomathematician, philosopher of science, and political theorist, Levins was one of the founders of modern ecology. Of solid build and with a bushy beard, Levins resembled a modern-day Charles Darwin. And like Darwin, Levins was a scientific leader far ahead of his time.

The diagram Levins had sketched on the blackboard represented a scenario involving a factory worker and his foreman. The diagram consisted of a pair of circles with arrows pointing from one circle to another; one circle was the factory worker and the other was the foreman. The foreman was pressuring the employee to work harder and faster and threatening to fire the employee if he didn't. The worker's adrenaline surged, causing his blood pressure to rise. Chronically elevated blood pressure could have placed this worker at risk for heart and kidney disease.

Then Levins drew another circle—the union organizer—who stepped forward to protect the worker's rights. The foreman backed off, and the man's blood pressure settled back to normal. Then Levins modified the diagram again. The union had been weakened by social and political factors; the worker was under chronic stress and experienced high blood pressure repeatedly. By using examples like this, Levins taught how both social and environmental conditions can profoundly influence human physiology and health. In laying out the specific pathways and mechanisms by which this occurs, Levins provided a powerful intellectual tool that sheds light on the root causes of individual and global distress.

I had signed up for Levins's seminar soon after beginning my training at Harvard. I'd heard high praise for the man and soon joined a fellow physician classmate who'd also worked in Mozambique to seek out Levins's counsel and teachings. Levins attracted many students like us who had lived and worked in developing countries, an experience that creates a breed unto itself. In the seminar, we discussed emerging issues such as integrated pest management, an approach to farming that minimizes the use of toxic chemicals. We discussed sustainable development—half a decade before an influential United Nations report, *Our Common Future*, popularized that term. For graduate students like me, Levins's methods offered useful tools to help tackle complex real-world systems, and he set an example as a thoughtful, rigorous, ethical, and independent thinker. Dick became a friend and a scientific mentor—a central figure who helped me understand the world and what it would take to transform it.

In the 1950s, Levins and his wife, Rosario Morales, a poet, had farmed for five years in rural Puerto Rico, growing vegetables that included lettuce, bush beans, snow peas, and Chinese cabbage. There he learned firsthand through hard work how the richness of the soil and a diversity of plants provided natural resistance to pests and microorganisms that plague farmers worldwide. After returning to the mainland, Levins

earned a doctorate in evolutionary biology at Columbia University. His early work established the importance of maintaining corridors that link wildlife habitats in order to sustain large and genetically diverse populations of animals—an idea that is applied widely today in designing wildlife refuges and conserving rare and endangered species.

While Levins was making his mark as an ecologist and biomathematician in the 1960s and 1970s, infectious disease declined in North America and in Europe, having been successfully suppressed with vaccines, insecticides, and antibiotics. Scientists concluded that we had passed through what was termed “the epidemiological transition,” in which the main scourges of society went from acute infectious disease to chronic illness. “Public health assumed that we’d licked it,” Levins recalled recently. Harvard’s health experts were so convinced of this that in the 1980s its public health school abolished its department of microbiology and decided to focus almost exclusively on the chronic diseases of developed modern societies, including heart disease, stroke, and cancer.

But Levins never believed the battle was won. His evolutionary biology training had taught him that pathogens such as bacteria and parasites are highly resourceful creatures. For example, some one-celled parasites switch their overcoats—their outer membranes—several times as they course through our bodies, thereby evading our immune responses. Many bacteria have evolved resistance to antibiotics. By the late 1970s, such knowledge led Levins to suspect that fast-growing, easily adapting pathogens that cause infectious diseases would not give up without a fight.

By the 1980s, and in spite of the epidemiological transition, it was clear to most epidemiologists that dozens of infectious diseases, including HIV/AIDS, tuberculosis, and Ebola, were emerging or reemerging. Levins searched for clues to why so many U.S. and European researchers had gotten it wrong. He concluded that they had based their assessment on just several decades of disease trends in North America and Europe. They had neglected to consider how infectious diseases have waxed and waned through history. They had also neglected to consider how microbes regularly evolve antibiotic resistance, or how mosquitoes and other insect carriers of disease evolve pesticide resistance. They had assumed wrongly that the vaccines and antibiotics that vanquished infectious disease in the developed world would be available widely in the developing world. And they hadn’t appreciated that sunny projections for economic development in many countries masked widening inequities and growing impoverishment, which often lead to malnutri-

tion, which in turn lowers immune defenses. The source of the error was a “narrowness in the field,” Levins concluded.

### A SCIENCE OF THE WHOLE

The narrowness of thinking that Levins encountered pervades much of modern science and leads to inaccurate assessments and prescriptions in many fields. The narrowness itself stems from a perennial challenge with which every scientist must grapple: many phenomena we’d like to understand are highly complex and have multiple, interacting causes. For the last three centuries, many scientists have tried to overcome that challenge by simplifying, using an approach called reductionism. The codification of this approach is often credited to the seventeenth-century French philosopher René Descartes, whose work helped launch the rise of modern science. In his *Discourse on the Method* (1637), Descartes provided reductionism’s central metaphor. The natural world works like a machine, he wrote. More broadly, the central tenet of reductionism and the Enlightenment that followed was that by studying pieces of the world and reducing them to basic laws, we could unravel the marvels of the whole.

Over the centuries, this reductionist approach to science has revealed a great deal about complex phenomena, and that understanding has led to technologies that have transformed our lives. In medicine, William Harvey, a seventeenth-century doctor and physiologist, dissected animals and discovered that veins had valves and that the heart pumped blood through our arteries—insights that revealed, with remarkable accuracy, how blood circulated through the human body. In biology, Rosalind Franklin isolated DNA from cells and bombarded it with X-rays, creating images that helped James Watson and Francis Crick determine that DNA is shaped like a double helix—a finding that paved the way for modern biotechnology. And today’s nanoscientists conduct experiments on individual molecules and use what they learn to build microscopic machines that promise to revolutionize batteries, solar energy collectors, and medicine. Reductionism has taken hold so widely that, for many people, its analytical, mechanistic approach has become synonymous with science.

There is another powerful but less well-known scientific approach, however, that plays a vital role in addressing some of today’s global issues, including climate change. It has its roots in biology rather than physics, and it uses concepts derived from the study of life rather than the study of machines. The approach is known as systems theory, and it

was pioneered in the first half of the twentieth century by a renowned biologist and philosopher named Ludwig von Bertalanffy.

Bertalanffy was born in 1901 in Atzgerdorf, Austria, a small village near Vienna, to a distinguished and scholarly family that traced its roots to sixteenth-century Hungarian nobility. He trained in both philosophy and biology at the University of Vienna in the early 1920s, then launched his career as a biologist by investigating how animals develop from a few simple embryonic cells into complex creatures with many types of interacting tissues and organs.

When Bertalanffy began his work, a debate was raging in biology. In the late nineteenth and early twentieth centuries, one school of biologists proposed that every process of living organisms, from metabolism to development, could ultimately be explained completely using only the laws of physics and chemistry. The way to gain that understanding was via a reductionist approach: take organisms apart into their components, literally or conceptually, and then understand the parts and use that knowledge to comprehend the whole. For example, reductionists believed that complete knowledge of the human body could ultimately be obtained by completely understanding the workings of human cells.

Other reputable biologists believed this approach would never work in living beings because they were fundamentally different from machines. To support that conclusion, these biologists cited several properties of life that no machine possessed. For example, organisms, unlike machines, become progressively more complex as they develop from embryos to adults and as they evolve over millennia into complex life-forms. And organisms, unlike machines, can grow, adapt to circumstances, reproduce, and even regenerate missing parts. Organisms were so different from machines that some of these biologists invoked an ancient idea first attributed to Aristotle: that each living creature possesses an intangible life force that directs its mechanistic forces.

Ludwig von Bertalanffy didn't buy either explanation. Classical physics and chemistry did not seem able to explain all the properties of living organisms. But the idea of an intangible life force was vague and useless, he believed, and would do nothing to advance a scientific understanding of living organisms.

Instead, Bertalanffy believed every living organism could be thought of as an open system. In science, the term *system* has a specific meaning: it's a collection of interrelated parts that function together via driving processes. An open system takes in matter and energy from outside itself, uses that flux of matter and energy to maintain itself, and releases waste

matter and energy to the environment. Such systems are omnipresent. The flame of a lit candle is a classic example: it takes oxygen from the air and matter from the wick and the wax, then releases heat to the environment and uses this flux of matter and energy to maintain itself. Similarly, all life-forms take in matter (nutrients from food, water, oxygen from air) and energy (the calories stored in food), and they release matter (bodily wastes, exhaled carbon dioxide) and energy (heat) to their surroundings.

In a crucial insight, Bertalanffy realized that every open system, living or not, has properties characteristic of life. He sought to define and describe those common properties with a unified theory that explained open systems. To do that, he drew ideas from philosophy, several fields of biology, and physics.

From the then-new science of ecology, Bertalanffy borrowed the essential concept of networks. In the 1920s, pioneering ecologists had realized that most real-world forests and tide pools, indeed all biological communities, actually consist of food webs: interconnected networks of species whose relationships are determined by whom one eats, whom one helps, and with whom one peacefully coexists. This led to a view of systems as “an integrated whole whose essential properties arise from the relationship between its parts,” as Fritjof Capra put it in his book *The Web of Life*, an illuminating exposition of nonreductionist science. This emphasis on relationships and connections differentiates systems theory from a mechanical world view. Both are useful.

Bertalanffy also understood that the whole of a biological community or any complex system is more than the sum of its parts. A system at any level of organization—whether a cell, a tissue, an organ, or an entire biological community—exhibits properties and behaviors that its component parts do not.

From physiology, Bertalanffy realized that open systems could maintain a steady state by regulating the functions of their parts. Physiologists call this concept homeostasis. For example, the body keeps blood sugar levels relatively constant by adjusting the levels of two hormones, insulin and glucagon, that control the release of sugar from the liver and its uptake into muscle and other tissues. Similar stabilizing mechanisms keep blood pressure, body temperature, and the saltiness of our body fluids relatively constant, within healthy limits. Since all open systems maintain themselves in steady states, Bertalanffy posited that they all had analogous stabilizing mechanisms.

From cybernetics, a science developed in the 1940s to understand and control how machines process information, Bertalanffy and others

added the idea of self-regulation by feedback—the act of sending information about the outcome of a process or activity back to its source. Feedback mechanisms are described as *positive* if an increase in one part of the system stimulates an increase in another. A suckling baby, for example, stimulates its mother to produce more milk. *Negative* feedbacks, in contrast, are self-correcting, dampening, and balancing; thus they help to maintain homeostasis. A thermostat provides a negative feedback: when it gets too cool, the heater kicks on; when it gets too warm, it shuts off.

From cybernetics, Bertalanffy and others drew the pivotal idea of feedback loops—circular sequences of feedback mechanisms in which component A influences component B, which influences component C, and so on, until the final component in the chain influences component A. Negative feedback loops in our endocrine and nervous systems steady our warm body temperature, our blood sugar level, and more, thereby maintaining our health. Positive feedback loops, in contrast, amplify change, quickly turning small changes into big ones. Examples include a nuclear chain reaction and a mob that’s escalating out of control. The terms we use for positive feedback loops reflect their volatility: *chain reactions* or *vicious cycles*.

The Earth’s climate system contains both negative feedback loops that help stabilize the climate and positive feedbacks that destabilize it. Our global economic system also contains both types of feedback loops: the financial sector integrates feedback information about the state of our world and responds by deciding where to best invest its capital, which maintains stability. But investors also feed on each other’s irrational exuberance, creating bubbles, or feed on each other’s panic, accelerating a crash.

As the example of a financial crisis illustrates, the central concepts of systems theory—input and output, networks, homeostasis, and feedbacks—apply equally well to social systems, including those of our families, congregations, corporations, communities, and the community of nations. Each of these systems, taken alone, is composed of a web of relationships among its members, each has its own ways of maintaining stability, and each receives input from the world outside itself.

Bertalanffy realized this early on, which in the 1940s led him to propose systems theory as a universal scientific framework, a way to unify the natural and social sciences. Other scientific heavyweights, including Massachusetts Institute of Technology mathematician Norbert Wiener and anthropologist Margaret Mead, contributed to its development in

the mid-twentieth century. Today systems thinking is influential in the fields of biology, education, psychotherapy, technology, and economics—and climate science. Thanks in large part to decades of work by Levins, it is also on the rise in epidemiology, ecology, and public health.

Using systems thinking, scientists now have tools to consider entire systems too complex to analyze using reductionism alone. “Someone must dare to look at the whole,” writes physicist Murray Gell-Mann, founder of the Santa Fe Institute, in the introduction to his fascinating book *The Quark and the Jaguar*. Systems science allows us to do just that, and it has framed my thinking along my scientific and experiential journey.

### AN EPIDEMIC OF EPIDEMICS

After 1976, forty diseases new to medicine surfaced, including HIV/AIDS, Ebola, and a new hantavirus. Other long-quiescent diseases like cholera resurged and spread, as I had witnessed in Mozambique. The resurging infectious diseases began invading every medical practice. Why, in the middle of the epidemiological transition to diseases of affluence, were microbes reasserting themselves?

As Levins suggests, we can look to medical history for clues. Major epidemics have often followed periods of decaying infrastructure and dissolving social fabric. In A.D. 541, for example, as Emperor Justinian was presiding over the dissolution of the Holy Roman Empire, the bubonic plague swept through Constantinople (today, Istanbul), killing an estimated ten thousand people per day at its peak—so many that survivors ran out of grave space and stacked bodies in the open. The plague then spread throughout Europe to China, killing forty million people in numerous waves over the following two centuries. The plague died out, then reemerged in the early 1300s as peasants from the European countryside pushed into cities that were built for far fewer of them, leading to overcrowding, shortages of drinking water, and poor sanitation. The Black Death, as the plague was then known, killed 30 percent of Europe’s population in half a decade.

Such pandemics (epidemics that spread through multiple regions) have transformed history. The Plague of Justinian led people to abandon cities en masse and settle into isolated fortresslike rural communities, thus helping to usher in the Feudal era. The Black Death led ultimately to protests against the old church order, to Protestantism, and to the Reformation. Smallpox, plague, typhus, and other diseases, sometimes introduced intentionally, contributed to the decimation of native peoples

throughout the Americas between the sixteenth and nineteenth centuries, helping European colonists take control over new territories.

Astute observers of health and history have perceived the deep connections between disease and social order. Dr. Rudolf Virchow was a nineteenth-century pathologist and activist who pioneered the study of social medicine, which examines how social, cultural, and economic conditions affect health and disease. “Epidemics,” he wrote, “are like sign-posts from which the statesman of stature can read that a disturbance has occurred in the development of his nation.”

Virchow, a contemporary of John Snow, was active in the protests spurred by the rash of urban epidemics. These protests had a positive result, as civic leaders responded by installing sanitation systems and drinking water plants and pipes. These changes to the infrastructure helped quell infectious diseases, which made cities safer and became the critical driver of economic development. Infectious disease declined steadily, with a bit of help from antibiotics, which were first employed in the late 1930s. The decline continued until the mid-1970s, when the first sign of an uptick in more than a century was seen.

By the 1980s, it was clear that infectious disease had returned with a vengeance. We had not just two or three simultaneous epidemics but dozens of new diseases, occurring in humans, other animals, and plants: an epidemic of epidemics. As a physician and a public health practitioner, I had begun to study the environmental and social origins of individual diseases. But was this new raft of infectious ills—occurring worldwide—a symptom of a more fundamental global change?

In 1991, a devastating cholera epidemic gave me an epiphany. On January 29 of that year, the first cases of severe diarrheal disease appeared in the coastal district of Chancay, Peru, a port city near Lima. Health officials raced to the city to investigate, soon isolating the bacterium *Vibrio cholerae* from the stool of those who’d fallen ill. These were the first cases of cholera in the Americas in more than a century, and the sickness simultaneously appeared in two other port cities along Peru’s 1,200-mile coastline. From there, it spread to other port cities and inland up streams and rivers, including the Amazon, throughout South and Central America. A massive epidemic was underway.

## CLIMATE AND CHOLERA

My experience confronting cholera in Mozambique made me particularly curious about the causes of the Latin American epidemic. I soon came

across the groundbreaking research of Rita Colwell, a tenacious and innovative microbiologist then at the University of Maryland, Baltimore County, who later became the head of the National Science Foundation. By then Colwell had been investigating the underlying causes of cholera epidemics for more than two decades.

When she began her work in the 1960s, several harsh realities were apparent to modern research scientists. Cholera was caused by the bacterium *Vibrio cholerae*, and people were infected when they drank water contaminated with the bacterium. Cholera bacteria passed into the drinking water when fecal discharge from cholera-infected people was spread by poor sanitation and mixed with water supplies. Many microbiologists considered the case closed.

But a great puzzle remained. Cholera epidemics waxed and waned, raging some years, then disappearing for decades or centuries at a time. Where did the cholera bacteria hide between outbreaks? Or, in the scientific vernacular, where was the “reservoir”?

From the beginning, clues pointed to the sea. The seven major cholera epidemics that have occurred in history all began on or near continental coastlines. Likewise, the first victims have tended to be fishermen and other seafaring people. Even more telling, historical accounts of the outbreaks often linked them to the arrival of ships from areas where cholera was endemic. In the early 1960s, when Colwell began her work, most scientists had put aside this “ancient” history. Colwell, however, had not.

For her doctoral research at the University of Washington in the early 1960s, Colwell had studied the salt requirements of several harmless bacterial cousins of *V. cholerae* that thrive in open oceans as well as in the less salty waters of estuaries, bays, and salt marshes. Colwell’s early career took a turn for the better when a colleague suggested that she look for *V. cholerae* in the same bodies of water in which she was searching for the non-disease-causing bacteria. In 1969, the young microbiologist searched for and found *V. cholerae* in, of all places, the Chesapeake Bay.

“This was not something people wanted to know,” Colwell recalled wryly. Infectious cholera bacteria were not supposed to be floating in the Chesapeake Bay, or any other large body of water—certainly not one frequented by commercial fishermen. The National Marine Fisheries Service of the National Oceanic and Atmospheric Administration (NOAA), which was providing her grant money at the time, promptly cut off her funding.

Colwell rebounded with financial support eight times larger from

National Sea Grant, another NOAA program, which supports coastal research. Colwell went on to pursue her cholera research for years, ultimately opting to work in the most cholera-prone region of the world: the low-lying Ganges River Delta in Bangladesh. There, large cholera epidemics erupt as if on cue from September through December, following the seasonal monsoons, and smaller epidemics occur with equal regularity between March and May.

Colwell chose to study Ganges delta water near Matlab, a small city just forty-five kilometers (twenty-eight miles) from the sprawling capital city of Dhaka. In one now-famous experiment, she began by pulling fifty-two water samples from the river delta. Into those samples, she added antibodies that had a fluorescent chemical attached and that bound specifically to *V. cholerae*, thereby helping to visualize the bacteria under the microscope. The results were stunning. All but one of the fifty-two water samples had tiny glowing particles in them, indicating the presence of *V. cholerae*. Perhaps most astonishing was the fact that the particles were less than one-fifteenth the size of the typical *V. cholerae* bacteria. And yet, Colwell was able to culture *V. cholerae* from seven of the positive samples.

Colwell concluded from this and other confirming experiments that *V. cholerae* could exist in the ocean and in estuaries in a tiny and dormant but hardy state. Colwell's colleagues were not swayed—a situation common for those who make paradigm-shifting discoveries. Most refused to accept that these miniature microbes were actually alive and capable of causing disease. One called her work “rubbish”; others mocked her, dubbing the dormant microbes “Colwell's ghosts.”

Despite such derision, Colwell pressed on. She knew that benign, or noninfectious, marine *Vibrio* bacteria hitched a ride on minute marine animals called zooplankton that have shells made of a hard, carbohydrate-based substance called chitin. By sampling water from ponds and rivers in and around Matlab for three years, Colwell proved that infectious *V. cholerae* also hitched a ride on zooplankton and sustained themselves by feeding on the chitin in the zooplankton's shells. Had Rita Colwell discovered cholera's reservoir?

To see if cholera bacteria from seawater could cause disease, Colwell undertook another remarkable study—done with extreme care because of the toxic potential and conducted with medical treatment available promptly if needed. She enlisted human volunteers to swallow water containing the tiny dormant form of *V. cholerae*. The results were, once again, stunning. Colwell was able to isolate infectious cholera bacteria

from her volunteers' stool samples. Seemingly, in one fell swoop, Colwell had solved one of the great mysteries of this ancient disease: the location of the *V. cholerae* reservoir. She bolstered that study with later work that showed that *V. cholerae* could hide out in a dormant state for years in the plankton in estuaries, swamps, and coastal oceans yet remain fully capable of infecting people when they drank water or ate shellfish that harbored the plankton.

Colwell's team obtained other evidence that bolstered the case for the ocean–cholera connection. When seawater warmed and its nitrogen and phosphorus levels were heightened, dormant cholera bacteria emerged from hibernation and became infectious. Under the same conditions, algae bloomed, followed after a lag by zooplankton, which fed on the algae. Meanwhile, monsoon-driven floods could flush cholera-carrying zooplankton into Bangladesh's inland waterways. The result was a kind of perfect storm, if in microcosm: as zooplankton were carried inland, the cholera bacteria they carried became infectious and would then infect people who drank unpurified water, which led to epidemics. In fact, annual algal blooms in coastal waters near Bangladesh were followed, after a lag, by cholera epidemics.

Almost as if to vindicate Rita Colwell's years of scientific dedication, the Peruvian cholera epidemic of 1991 began almost simultaneously in three distant port cities. If the disease had appeared in a single city, its appearance might have been explained by a traveler carrying the bacteria. But since the outbreaks began in widely separated harbors nearly simultaneously, cholera was most likely coming from the sea. This fact, and the fact that the cholera epidemic occurred during an El Niño, a large and periodic climatic event that warms nearshore waters, suggested a link between climate and cholera.

Over fifteen months, half a million people in nineteen South American countries contracted cholera and almost five thousand died. The death rate was much lower than in the Mozambique epidemic I experienced, because of accessible public health services and the coordination of the Pan American Health Organization, but cholera has persisted in Peru ever since.

My appreciation for Rita Colwell's revolutionary cholera research, and the drama of the Latin American cholera epidemic of 1991, against the backdrop of my time in Mozambique, set me on a new path. Global warming, I suspected, could threaten human health in ways that scientists had yet to fully anticipate.