CHAPTER 1

Human, Remote, Autonomous

LATE IN THE NIGHT, HIGH ABOVE THE ATLANTIC OCEAN IN THE long, open stretch between Brazil and Africa, an airliner encountered rough weather. Ice clogged the small tubes on the aircraft's nose that detected airspeed and transmitted the data to the computers flying the plane. The computers could have continued flying without the information, but they had been told by their programmers that they could not.

The automated, fly-by-wire system gave up, turned itself off, and handed control to the human pilots in the cockpit: thirty-two-year-old Pierre Cedric Bonin and thirty-seven-year-old David Robert. Bonin and Robert, both relaxed and a little fatigued, were caught by surprise, suddenly responsible for hand flying a large airliner at high altitude in bad weather at night. It is a challenging task under the best of circumstances, and one they had not handled recently. Their captain, fifty-eight-year-old Marc Debois, was off duty back in the cabin. They had to waste precious attention to summon him.

Even though the aircraft was flying straight and level when the computers tripped off, the pilots struggled to make sense of the bad air data. One man pulled back, the other pushed forward on his control stick. They continued straight and level for about a minute, then lost control.

On June 1, 2009, Air France flight 447 spiraled into the ocean, killing more than two hundred passengers and crew. It disappeared below the waves, nearly without a trace.

In the global, interconnected system of international aviation, it is unacceptable for an airliner to simply disappear. A massive, coordinated search followed. In just a few days traces of flight 447 were located on the ocean's surface. Finding the bulk of the wreckage, however, and the black box data recorders that held the keys to the accident's causes, required hunting across a vast seafloor, and proved frustratingly slow.

More than two years later, two miles deep on the seafloor, nearly beneath the very spot where the airliner hit the ocean, an autonomous underwater vehicle, or AUV, called Remus 6000 glided quietly through the darkness and extreme pressure. Moving at just faster than a human walking pace, the torpedo-shaped robot maintained a precise altitude of about two hundred feet off the bottom, a position at which its ultrasonic scanning sonar returns the sharpest images. As the sonars pinged to about a half mile out either side, the robot collected gigabytes of data from the echoes.

The terrain is mountainous, so the seafloor rose quickly. Despite its intelligence, the robot occasionally bumped into the bottom, mostly without injury. Three such robots worked in a coordinated dance: two searched underwater at any given time, while a third one rested on a surface ship in a three-hour pit stop with its human handlers to offload data, charge batteries, and take on new search plans.

On the ship, a team of twelve engineers from the Woods Hole Oceanographic Institution, including leader Mike Purcell, who spearheaded

the design and development of the searching vehicles, worked in twelve-hour shifts, busy as any pit crew. When a vehicle came to the surface, it took about forty-five minutes for the engineers to download the data it collected into a computer, then an additional half hour to process those data to enable a quick, preliminary scroll-through on a screen.

Looking over their shoulders were French and German investigators, and representatives from Air France. The mood was calculating and deliberate, but tense: the stakes were high for French national pride, for the airliner's manufacturer, Airbus, and for the safety of all air travel. Several prior expeditions had tried and failed. In France, Brazil, and around the world, families awaited word.

Interpreting sonar data requires subtle judgment not easily left solely to a computer. Purcell and his engineers relied on years of experience. On their screens, they reviewed miles and miles of rocky reflections alternating with smooth bottom. The pattern went on for five days before the monotony broke: a crowd of fragments appeared, then a debris field—a strong signal of human-made artifacts in the ocean desert. Suggestive, but still not definitive.

The engineers reprogrammed the vehicles to return to the debris and "fly" back and forth across it, this time close enough that onboard lights and cameras could take pictures from about thirty feet off the bottom. When the vehicles brought the images back to the surface, engineers and investigators recognized the debris and had their answer: they had found the wreckage of flight 447, gravesite of hundreds.

Soon, another team returned with a different kind of robot, a remotely operated vehicle (ROV), a heavy-lift vehicle specially designed for deep salvage, connected by a cable to the ship. Using the maps created by the successful search, the ROV located the airliner's black box voice and data recorders and brought them to the surface. The doomed pilots' last minutes were recovered from the ocean, and investigators could now reconstruct the fatal confusion aboard the automated airliner. The ROV then set about the grim task of retrieving human remains.

The Air France 447 crash and recovery linked advanced automation and robotics across two extreme environments: the high atmosphere and the deep sea. The aircraft plunged into the ocean because of failures in human interaction with automated systems; the wreckage was then discovered by humans operating remote and autonomous robots.

While the words (and their commonly perceived meanings) suggest that automated and autonomous systems are self-acting, in both cases the failure or success of the systems derived not from the machines or the humans operating on their own, but from people and machines operating together. Human pilots struggled to fly an aircraft that had been automated for greater safety and reliability; networks of ships, satellites, and floating buoys helped pinpoint locations; engineers interpreted and acted on data produced by robots. Automated and autonomous vehicles constantly returned to their human makers for information, energy, and guidance.

Air France 447 made tragically clear that as we constantly adapt to and reshape our surroundings, we are also remaking ourselves. How could pilots have become so dependent on computers that they flew a perfectly good airliner into the sea? What becomes of the human roles in activities like transportation, exploration, and warfare when more and more of the critical tasks seem to be done by machines?

In the extreme view, some believe that humans are about to become obsolete, that robots are "only one software upgrade away" from full autonomy, as *Scientific American* has recently argued. And they tell us that the robots are coming—coming to more familiar environments. A

new concern for the strange and uncertain potentials of artificial intelligence has arisen out of claims that we are on the cusp of superintelligence. Our world is about to be transformed, indeed is already being transformed, by robotics and automation. Start-ups are popping up, drawing on old dreams of smart machines to help us with professional duties, physical labor, and the mundane tasks of daily life. Robots living and working alongside humans in physical, cognitive, and emotional intimacy have emerged as a growing and promising subject of research. *Autonomy*—the dream that robots will one day act as fully independent agents—remains a source of inspiration, innovation, and concern.

The excitement is in the thrill of experimentation; the precise forms of these technologies are far from certain, much less their social, psychological, and cognitive implications. How will our robots change us? In whose image will we make them? In the domain of work, what will become of our traditional roles—scientist, lawyer, doctor, soldier, manager, even driver and sweeper—when the tasks are altered by machines? How will we live and work?

We need not speculate: much of this future is with us today, if not in daily life then in extreme environments, where we have been using robotics and automation for decades. In the high atmosphere, the deep ocean, and outer space humans cannot exist on their own. The demands of placing human beings in these dangerous settings have forced the people who work in them to build and adopt robotics and automation earlier than those in other, more familiar realms.

Extreme environments press the relationships between people and machines to their limits. They have long been sites of innovation. Here engineers have the freest hand to experiment. Despite the physical isolation, here the technologies' cognitive and social effects first become apparent. Because human lives, expensive equipment, and important missions are at stake, autonomy must always be tempered with safety and reliability.

In these environments, the mess and busyness of daily life are temporarily suspended, and we find, set off from the surrounding darkness, brief, dream-like allegories of human life and technology. The social and technological forces at work on an airliner's flight deck, or inside a deep-diving submersible, are not fundamentally different from those in a factory, an office, or an automobile. But in extreme environments they appear in condensed, intense form, and are hence easier to grasp. Every airplane flight is a story, and so is every oceanographic expedition, every space flight, every military mission. Through these stories of specific people and machines we can glean subtle, emerging dynamics.

Extreme environments teach us about our near future, when similar technologies might pervade automobiles, health care, education, and other human endeavors. Human-operated, remotely controlled, and autonomous vehicles represent the leading edge of machine and human potential, new forms of presence and experience, while drawing our attention to the perils, ethical implications, and unintended consequences of living with smart machines. We see a future where human knowledge and presence will be more crucial than ever, if in some ways strange and unfamiliar.

And these machines are just cool. I'm not alone in my lifelong fascination with airplanes, spacecraft, and submarines. Indeed, technological enthusiasm, as much as the search for practical utility, drives the stories that follow. It's no coincidence that similar stories are so often the subject of science fiction—something about people and machines at the limits of their abilities captures the imagination, engages our wonder, and stirs hopes about who we might become.

This enthusiasm sometimes reflects a naïve faith in the promise of technology. But when mature it is an enthusiasm for basic philosophical and humanistic questions: Who are we? How do we relate to our work and to one another? How do our creations expand our experience? How can we best live in an uncertain world? These questions lurk barely below the surface as we talk to people who build and operate robots and vehicles.

Join me as I draw on firsthand experience, extensive interviews, and the latest research from MIT and elsewhere to explore experiences of robotics and automation in the extreme environments of the deep ocean and in aviation (civil and military) and spaceflight. It is not an imagination of the future, but a picture of today: we'll see how people operate with and through robots and autonomy and how their interactions affect their work, their experiences, and their skills and knowledge.

Our stories begin where I began, in the deep ocean. Twenty-five years ago, as an engineer designing embedded computers and instruments for deep-ocean robots, I was surprised to find that technologies were changing in unexpected ways the work of oceanography, the ways of doing science, the meaning of being an oceanographer.

The realization led to two parallel careers. As a scholar, I study the human implications of machinery, from ironclad warships in the American Civil War to the computers and software that helped the Apollo astronauts land on the moon. As an engineer, I bring that research to bear on present-day projects, building robots and vehicles designed to work in intimate partnership with people. In the stories that follow I appear in some as a participant, in others as an observer, and in still others as both.

These years of experience, research, and conversation have convinced me that we need to change the way we think about robots. The language we use for them is more often from twentieth-century science fiction than from the technological lives we lead today. Remotely piloted aircraft, for example, are referred to as "drones," as though they were mindless automata, when actually they are tightly controlled by people. Robots are imagined (and sold) as fully autonomous agents, when even today's modest autonomy is shot through with human imagination. Rather than being threatening automata, the robots we use so variously are embedded, as are we, in social and technical networks. In the pages ahead, we will explore many examples of how we work together with our machines. It's the combinations that matter.

It is time to review what the robots of today actually do, to deepen our understanding of our relationships with these often astoundingly capable human creations. I argue for a deeply researched empirical conclusion: whatever they might do in a laboratory, as robots move closer to environments with human lives and real resources at stake, we tend to add more human approvals and interventions to govern their autonomy. My argument here is not that machines are not intelligent, nor that someday they might not be. Rather, my argument is that such machines are not *inhuman*.

Let us name three mythologies of twentieth-century robotics and automation. First, there is *the myth of linear progress*, the idea that technology evolves from direct human involvement to remote presence and then to fully autonomous robots. Political scientist Peter W. Singer, a prominent public advocate for autonomous systems, epitomizes this mythology when he writes that "this concept of keeping the human in the loop is already being eroded by both policymakers and the technology itself, which are both rapidly moving toward pushing humans out of the loop."

Yet there is no evidence to suggest that this is a natural evolution, that the "technology itself," as Singer puts it, does any such thing. In fact there is good evidence that people are moving into deeper intimacy with their machines.

We repeatedly find human, remote, and autonomous vehicles evolving together, each affecting the other. Unmanned aircraft, for example, cannot occupy the national airspace without the task of piloting manned aircraft changing too. In another realm, new robotic techniques for servicing spacecraft changed the way human astronauts serviced the Hubble Space Telescope. The most advanced (and difficult) technologies are not those that stand apart from people, but those that are most deeply embedded in, and responsive to, human and social networks.

Second is *the myth of replacement*, the idea that machines take over human jobs, one for one. This myth is a twentieth-century version of what I call the iron horse phenomenon. Railroads were initially imagined to replace horses, but trains proved to be very poor horses. Railroads came into their own when people learned to do entirely new things with them. Human-factors researchers and cognitive scientists find that rarely does automation simply "mechanize" a human task; rather, it tends to make the task more complex, often increasing the workload (or shifting it around). Remotely piloted aircraft do not replicate the missions that manned aircraft carry out; they do new things. Remote robots on Mars do not copy human field science; they and their human partners learn to do a new kind of remote, robotic field science.

Finally, we have *the myth of full autonomy*, the utopian idea that robots, today or in the future, can operate entirely on their own. Yes, automation can certainly take on parts of tasks previously accomplished by humans, and machines do act on their own in response to their environments for certain periods of time. But the machine that operates entirely independently of human direction is a useless machine. Only a rock is truly autonomous (and even a rock was formed and placed by its environment). Automation changes the type of human involvement required and transforms but does not eliminate it. For any apparently autonomous system, we can always find the wrapper of human control that makes it useful and returns meaningful data. In the words of a recent report by the Defense Science Board, "there are no fully autonomous systems just as there are no fully autonomous soldiers, sailors, airmen or Marines."

To move our notions of robotics and automation, and particularly the newer idea of autonomy, into the twenty-first century, we must deeply grasp how human intentions, plans, and assumptions are always built into machines. Every operator, when controlling his or her machine, interacts with designers and programmers who are still present inside it—perhaps through design and coding done many years before. The computers on Air France 447 could have continued to fly the plane even without input from the faulty airspeed data, but they were programmed by people not to. Even if software takes actions that could not have been predicted, it acts within frames and constraints imposed upon it by its creators. How a system is designed, by whom, and for what purpose shapes its abilities and its relationships with the people who use it.

My goal is to move beyond these myths and toward a vision of situated autonomy for the twenty-first century. Through the stories that follow, I aim to redefine the public conversation and provide a conceptual map for a new era.

As the basis for that map, I will rely throughout the book on *human*, *remote*, and *autonomous* when referring to vehicles and robots. The first substitutes for the awkward "manned," so you can read "human" as shorthand for "human occupied." These are of course old and familiar types of vehicles like ships, aircraft, trains, and automobiles, in which

peoples' bodies travel with the machines. People generally do not consider human-occupied systems to be robots at all, although they do increasingly resemble robots that people sit inside.

"Remote," as in remotely operated vehicles (ROVs), simply makes a statement about where the operator's body is, in relation to the vehicle. Yet even when the cognitive task of operating a remote system is nearly identical to that of a direct physical operator, great cultural weight is attached to the presence or absence of the body, and the risks it might undergo. In the most salient example, remotely fighting a war from thousands of miles away is a different experience from traditional soldiering. As a cognitive phenomenon, human presence is intertwined with social relationships.

Automation is also a twentieth-century idea, and still carries a mechanical sense of machines that step through predefined procedures; "automated" is the term commonly used to describe the computers on airliners, even though they contain modern, sophisticated algorithms. "Autonomy" is the more current buzzword, one that describes one of the top priorities of research for a shrinking Department of Defense. Some clearly distinguish autonomy from automation, but I see the difference as a matter of degree, where autonomy connotes a broader sense of self-determination than simple feedback loops and incorporates a panoply of ideas imported from artificial intelligence and other disciplines. And of course the idea of the autonomy of individuals and groups pervades current debates in politics, philosophy, medicine, and sociology. This should come as no surprise, as technologists often borrow social ideas to describe their machines.

Even within engineering, autonomy means several different things. Autonomy in spacecraft design refers to the onboard processing that takes care of the vehicle (whether an orbiting probe or a mobile robot) as distinct from tasks like mission planning. At the Massachusetts Institute of Technology, where I teach, the curriculum of engineering courses on autonomy covers mostly "path planning"—how to get from here to there in a reasonable amount of time without hitting anything. In other settings autonomy is analogous to intelligence, the ability to make human-like decisions about tasks and situations, or the ability to do things beyond what designers intended or foresaw. Autonomous underwater vehicles (AUVs) are so named because they are untethered, and contrast with remotely operated vehicles (ROVs), which are connected by long cables. Yet AUV engineers recognize that their vehicles are only semiautonomous, as they are only sometimes fully out of touch.

The term "autonomous" allows a great deal of leeway; it describes how a vehicle is controlled, which may well change from moment to moment. One recent report introduces the term "increasing autonomy" to describe its essentially relative nature, and to emphasize how "full" autonomy—describing machines that require no human input—will always be out of reach. For our purposes, a working definition of autonomy is: a human-designed means for transforming data sensed from the environment into purposeful plans and actions.

Language matters, and it colors debates. But we need not get stuck on it; I will often rely on the language (which is sometimes imprecise) used by the people I study. The weight of this book rests not on definitions but on stories of work: How are people using these systems in the real world, experiencing, exploring, even fighting and killing? What are they actually doing?

Focusing on lived experiences of designers and users helps clarify the debates. For example, the word "drone" obscures the essentially human nature of the robots and attributes their ill effects to abstract ideas like "technology" or "automation." When we visit the Predator

operators' intimate lairs we will discover that they are not conducting automated warfare—people are still inventing, programming, and operating machines. Much remains to debate about the ethics and policy of remote assassinations carried out by unmanned aircraft with remote operators, or the privacy concerns with similar devices operating in domestic airspace. But these debates are about the nature, location, and timing of *human* decisions and actions, not about machines that operate autonomously.

Hence the issues are not manned versus unmanned, nor human-controlled versus autonomous. The questions at the heart of this book are: *Where are the people? Which people are they? What are they doing? When are they doing it?*

Where are the people? (On a ship . . . in the air . . . inside the machine . . . in an office?)

The operator of the Predator drone may be doing something very similar to the pilot of an aircraft—monitoring onboard systems, absorbing data, making decisions, and taking actions. But his or her body is in a different place, perhaps even several thousand miles away from the results of the work. This difference matters. The task is different. The risks are different, as are the politics.

People's minds can travel to other places, other countries, other planets. Knowledge through the mind and senses is one kind of knowledge, and knowledge through the body (where you eat, sleep, socialize, and defecate) is another. Which one we privilege at any given time has consequences for those involved.

Which people are they? (Pilots . . . engineers . . . scientists . . . unskilled workers . . . managers?)

Change the technology and you change the task, and you change the nature of the worker—in fact you change the entire population of people who can operate a system. Becoming an air force pilot takes years of training, and places one at the top of the labor hierarchy. Does operating a remote aircraft require the same skills and traits of character? From which social classes does the task draw its workforce? The rise of automation in commercial-airline cockpits has corresponded to the expanding demographics of the pilot population, both within industrialized countries and around the globe. Is an explorer someone who travels into a dangerous environment, or someone who sits at home behind a computer? Do you have to like living on board a ship to be an oceanographer? Can you explore Mars if you're confined to a wheelchair? Who are the new pilots, explorers, and scientists who work through remote data?

What are they doing? (Flying . . . operating . . . interpreting data . . . communicating?)

A physical task becomes a visual display, and then a cognitive task. What once required strength now requires attention, patience, quick reactions. Is a pilot mainly moving her hands on the controls to fly the aircraft? Or is she punching key commands into an autopilot or flight computer to program the craft's trajectory? Where exactly is the human judgment she is adding? What is the role of the engineer who programmed her computer, or the airline technician who set it up?

When are they doing it? (In real time . . . after some delay . . . months or years earlier?)

Flying a traditional airplane takes place in real time—the human inputs come as the events are happening and have immediate results. In a spaceflight scenario, the vehicle might be on Mars (or approaching a distant asteroid), in which case it might take twenty minutes for the vehicle to receive the command, and twenty minutes for the operator to see that the action has occurred. Or we might say that craft is landing

"automatically," when actually we can think of it as landing under the control of the programmers who gave it instructions months or years earlier (although we may need to update our notions of "control"). Operating an automated system can be like cooperating with a ghost.

These simple questions draw our attention to shifts and reorientations. New forms of human presence and action are not trivial, nor are they equivalent—a pilot who risks bodily harm above the battlefield has a different cultural identity from one who operates from a remote ground-control station. But the changes are also surprising—the remote operator may feel more present on the battlefield than pilots flying high above it. The scientific data extracted from the moon may be the same, or better, when collected by a remote rover than by a human who is physically present in the environment. But the cultural experience of lunar exploration is different from being there.

Let's replace dated mythologies with rich, human pictures of how we actually build and operate robots and automated systems in the real world. The stories that follow are at once technological and humanistic. We shall see human, remote, and autonomous machines as ways to move and reorient human presence and action in time and in space. The essence of the book boils down to this: it is not "manned" versus "unmanned" that matters, but rather, where are the people? Which people? What are they doing? And when?

The last, and most difficult questions, then, are:

How does human experience change? And why does it matter?

NOTES

CHAPTER 1: HUMAN, REMOTE, AUTONOMOUS

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4 **"only one software upgrade away":** "Terminate the Terminators," *Scientific American* 303, no. 1 (July 2010): 30.

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CHAPTER 2: SEA

24 **The Skerki D survey:** Robert D. Ballard et al., "The Discovery of Ancient History in the Deep Sea Using Deep Submergence Technology," *Deep-Sea Research* I 47 (2000): 1591–1620.

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29 **"It was fortunate that Alvin was there":** Frank Taylor interview with Robert Ballard, April 27, 2000, Woods Hole, MA, Woods Hole Oceanographic Institution Archives.

29 **much of the scientific community:** Ballard and Hively, *The Eternal Darkness*, 158

29 **Ballard developed methods:** Frank Taylor interview with ANGUS group, February 27, 2002, Woods Hole, MA, Woods Hole Oceanographic Institution Archives.

29 **"And the nimble little white submarine":** Ballard and Hively, *The Eternal Darkness*, 49.

30 **"We asked Holger and Fred how to proceed":** Ibid., 186.

32 **a computer connection to the ship's control system as well:** Frank Taylor interview with ANGUS group, February 27, 2002. Woods Hole Oceanographic Institution Archives, 13.

32 **"We found running the sled":** Ibid., 14.

33 **In team member Steve Gegg's words:** Ibid., 21.

37 **Ballard split away from the *Alvin* group:** Ballard and Hively, *The Eternal Darkness*, 233.

38 **"He was very much interested in social issues":** Author interview with Dana Yoerger, Woods Hole, MA, August 2011.

41 **"an improbable kite of white steel":** Ballard and Hively, *The Eternal Darkness*, 8.

42 **"Our scanning human eyes":** Ibid., 9, 240–41.

45 **"the *Alvin* group lost some of its popular glamour":** Ibid., 295

46 **"*Alvin* became a different machine":** Author interview with Will Sellars, Woods Hole, MA, August 2011.

46 **"We went from [testing in] ten feet of water":** Frank Taylor interview with Martin Bowen, October 2001, Woods Hole, MA, Woods Hole Oceanographic Institution Archives, 35.

46 **the cook on *Atlantis II* made a special cake for Ballard:** Ballard and Hively, *The Eternal Darkness*, 297.

46 **"bureaucratic inflexibility":** Ibid., 301, 312.

47 **"When the *Alvin* pilot turned on":** Frank Taylor interview with Martin Bowen, October 2001, Woods Hole, MA, Woods Hole Oceanographic Institution Archives, 35.

47 **"in the portholes you'd see an eight-story building":** Ibid., 40.

48 **"all I could see was that big gaping hole":** Author interview with Dudley Foster, Woods Hole, MA, August 2011.

49 **"I was in that vehicle's eye":** Frank Taylor interview with Martin Bowen, October 2001, Woods Hole, MA, Woods Hole Oceanographic Institution Archives, 38–39.

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49 **"As we sat inside *Alvin*":** Ibid., 43.

50 **Will Sellars was amazed:** Author interview with Will Sellars, Woods Hole, MA, August 2011.

50 **The *Alvin/Jason Jr.* combination was the feature of a new *National Geographic*:** *National Geographic* cover, December 1986.

51 **after *Titanic*, it was never used again:** Martin Bowen and I rebuilt *Jason Jr.* and redid its internal electronics in 1991, in preparation for an expedition to the Galapagos. Unfortunately, the barge carrying *JJ*, and all of our equipment, sank while being towed to the islands. *JJ* sits today in a crate, inside a shipping container, three miles down in the South Pacific. Ironically, the only piece of equipment likely to be undamaged is *JJ* and its titanium pressure housing.

55 **"It's a ballet":** Frank Taylor interview with Martin Bowen, October 2001, Woods Hole, MA, Woods Hole Oceanographic Institution Archives, 45.

56 **"You become overwhelmed with input":** Author interview with Will Sellars, Woods Hole, MA, August 2011.

56 **"With robots you could have a whole gallery of experts":** Frank Taylor interview with Martin Bowen, October 2001, Woods Hole, MA, Woods Hole Oceanographic Institution Archives, 44.

57 **"I just starting mapping things in my own head":** Ibid., 67.

60 **"People would say, ROVs?":** Ibid.

60 **Another member of the team recalled:** Interviewee unattributed by request.

61 **"And you find people that go":** Author interview with Will Sellars, Woods Hole, MA, August 2011.

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ROBOTICS AND THE MYTHS OF AUTONOMY

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