ABUNDANCE INSTITUTE

# Nanotechnology

## A PRIMER FOR POLICYMAKERS

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## Historical Context

Throughout history, there have been technological revolutions which have substantially changed the human condition. Some happened slowly, such as the development of agriculture, which enabled the growth of cities and civilization. Some happened faster, such as the adoption of the printing press, which over a few centuries enabled science and modern machinery. More recently, the invention of computers and digital communications has drastically changed our way of life in a few decades.

There is a clear pattern to these technological revolutions: they have been coming faster. There is good reason to believe that another one is coming soon. An examination of the earlier ones can help us understand what kind of effects it may have on our way of life and on the shape of our society.

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## The Industrial Revolution

Before the 18th century, there were strict limits to what people could make. Producing enough food for everyone required roughly 90 percent of the workforce to be farmers.[2] It took three months of skilled labor to make a single woolen tunic.[3]

Today, only about 3 percent of the workforce consists of farmers, and the amount of labor involved in making woolen tunics amounts to a few hours per tunic, including the appropriate share of materials, production machinery, and transportation in the entire supply chain.[4] We are literally hundreds of times as rich as our ancestors who lived before the Industrial Revolution.[5]

How did this happen? The usual answer is "steam engines"—but the story is not so simple.

First there was science, aided and spread by the printing press. The Renaissance physicist Evangelista Torricelli discovered that one could produce a force by creating a vacuum.[6] This knowledge was used to invent what are called *low-pressure steam engines*, in which the condensation of steam is used to create a vacuum, drawing a piston into a cylinder. Such engines were large, inefficient, and not very powerful. Originally they burned so much coal that they could be used only right next to a coal mine to pump water out of the mine.[7] But by the end of the 18th century, experience and further innovation had made them smaller and efficient enough to replace wind and watermills in many industrial applications, including spinning and weaving and, notably, metalworking.

The advance of metalworking allowed for a second revolution in steam engines: high-pressure ones, in which the steam pushed the piston directly.[8] These were sufficiently smaller and lighter than their predecessors to be used on vehicles, and they were efficient enough that their fuel could be carried as well. They made the 19th century the age of the railroad and the steamship.

But, just as importantly, they drove the development of ever more complex and precise machinery, which could reduce the amount of labor needed to do and to make many things,

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[2] Marian L. Tupy and Ronald Bailey, "The Changing Nature of Work," Human Progress, March 1, 2023, https://humanprogress.org/trends/the-changing-nature-of-work/.

[3] Lars Pilø, "The Reconstruction of the Lendbreen Tunic," *Secrets of the Ice*, June 29, 2016, https://secretsoftheice.com/funn/2016/06/28/reconstruction/.

[4] Men's Mid-Length Single Breasted Wool Blend Top Coat Casual Solid Stand Collar Winter Coats Classic Lightweight Overcoat, $41.99 - $44.99, https://www.amazon.com/Mid-Length-Breasted-Blend-Coat-Lightweight/dp/B0CNNYSBC7.

[5] Marian L. Tupy and Ronald Bailey, "Global Income Is Rising," *Human Progress*, March 1, 2023, https://humanprogress.org/trends/global-income-is-rising/.

[6] Singer, Holmyard, Hall, et. al, ed.: A History of Technology: Volume IV: The Industrial Revolution. p. 169. Oxford University Press, London, 1958.

[7] "The Industrial Revolution (1712 to 1850)," *The Rise of Coal in Britain* (blog), accessed February 15, 2024, https://riseofcoalinbritain.wordpress.com/the-industrial-revolution-1712-to-1850/.

[8] John H. Lienhard, "High-Pressure Steam Engines," episode 109 of *The Engines of Our Ingenuity* (Cullen College of Engineering, University of Houston), accessed February 15, 2024, https://engines.egr.uh.edu/episode/109.

including machinery that was even more complex and precise. By the end of the 19th century the power, precision, and range of products available would have been virtually incomprehensible by the standards of antiquity. And that, in turn, meant that the wealth, standard of living, and quality of life of the average person was improved to an extent that would have been almost unimaginable just a few generations before.

Before the year 1500 or so, as far back as scholars can make reasonable estimates, the growth rate of the entire world economy was about 0.06 percent, which means that it would have taken over 1,000 years for the economy to double in size. After the Industrial Revolution, the growth rate rose to about 3 percent, which means that the economy was doubling every 25 years: a completely different growth mode.[9]

## The Automotive Age

In fact, the personal automobile, perhaps the defining technology of the 20th century, is singularly missing from predictions made in the 19th century by pundits such as Jules Verne and H. G. Wells. The basic form and capabilities of the machine were understood well enough—after all, Karl Benz had invented the automobile by 1886.[10] But it seemed impossible for 19th century dreamers to grasp the potential for enormous productive capacity in the form of mass manufacturing, which meant that every family might have a car.

Meanwhile, the continuing improvement in engines' power-to-weight ratio had other implications. Inventors who attempted flying machines had long been derided by leading scientists. Because of this, there was no great rush by investors to encourage and support the development of such machines. As a case in point, the Wright brothers' first flight was in 1903, but they were not awarded a patent until 1906.[11] They initially tried to sell the airplane to the US Army but were turned down. It was not until their demonstration flights at Le Mans, France, in 1908 that the public at large realized that the airplane was a real thing. Then investment in aviation took off with a vengeance.[12]

## The Atomic Age

To some extent, the so-called Atomic Age witnessed the opposite trajectory: the benefits of our new understanding of the energy in the nuclei of atoms were substantially overpromised. Nuclear power, and a few other fairly minor applications such as smoke detectors and PET scans, have not made nearly as thoroughgoing a change in the average person's life as the family car.

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[9] Robin Hanson, "Long-Term Growth as a Sequence of Exponential Modes" (working paper, George Mason University Department of Economics, Fairfax, VA, December 2000).

[10] Suzanne Deffree, "Karl Benz Drives the First Automobile, July 3, 1886," EDN, July 3, 2019, https://www.edn.com/karl-benz-drives-the-first-automobile-july-3-1886/.

[11] "Starting the Business," Collection: Wilbur and Orville Wright Papers at the Library of Congress, accessed February 15, 2024, https://www.loc.gov/collections/wilbur-and-orville-wright-papers/articles-and-essays/collection-highlights/starting-the-business/.

[12] "A History of the Airplane," Wright Brothers Aeroplane Company, accessed February 15, 2024, https://www.wright-brothers.org/History_Wing/History_of_the_Airplane/History_of_the_Airplane_Intro/History_of_the_Airplane_Intro.htm.

One of the reasons for the mismatch between expectations and reality is the strong association between nuclear weapons and anything else nuclear. This association was likely unavoidable given the origin of modern nuclear science as a top-secret weapons program and the role of nuclear weapons at the end of World War II. Because of this, however, nuclear research has tended to be "born secret" (that is, designated as classified as soon as it exists), and it has been subject to extreme regulatory control as a consequence. Furthermore, the association in the public mind of anything nuclear with weapons has been capitalized upon by political opportunists, with the result that purely civilian nuclear technology is essentially stymied.[13]

## The Intellectual Revolution

This conflation of nuclear and weaponry was not a necessary outcome, however. Another secret World War II–era technology, the computer, was reinvented several times. It never suffered the overregulation that stifled nuclear technology, even though the US imposed military export restrictions on supercomputers throughout the rest of the century.[14]

Instead, the government's relationship with the developing technology stands as a major success story, as contrasted with nuclear research. ARPA (later DARPA) funded research in artificial intelligence, the ARPANET, and ultimately the internet.[15] Spin-off development from the space program brought us computers using transistors and integrated circuits to replace the "giant brains" of the 1950s, which had relied on vacuum tubes.[16]

Circa 1970, a PDP-10, the workhorse computer of AI research at the time, cost a million dollars.[17] It had a million bytes of memory and could process a million instructions per second.[18] Today, you can buy a Raspberry Pi microcomputer for less than a hundred dollars that has 8,000 million bytes of memory and can process 10,000 million instructions per second.[19] Because of inflation, the Pi is not in real terms 10,000 times cheaper than the PDP-10: it is 100,000 times cheaper. This is a revolution in abundance to rival the Industrial Revolution itself.

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[13] This holds true in spite of help from the Department of Energy: see Timothy Gardner and Manas Mishra, "NuScale Ends Utah Project, in Blow to US Nuclear Power Ambitions," *Reuters*, November 9, 2023, https://www.reuters.com/business/energy/nuscale-power-uamps-agree-terminate-nuclear-project-2023-11-08/. See also Sam Batkins, Philip Rossetti, and Dan Goldbeck, "Putting Nuclear Regulatory Costs in Context," American Action Forum, July 12, 2017, https://www.americanactionforum.org/research/putting-nuclear-regulatory-costs-context/.

[14] John Markoff, "Export Restrictions Fail to Halt Spread of Supercomputers," *The New York Times*, August 21, 1990, A1.

[15] United States. Defense Advanced Research Projects Agency, and United States. Department of Defense. Office of the Secretary of Defense. *DARPA: 50 Years of Bridging the Gap*. Faircount LLC, 2008.

[16] Charles Fishman, "How NASA Gave Birth to Modern Computing—and Gets No Credit for It," *Fast Company*, June 13, 2019, https://www.fastcompany.com/90362753/how-nasa-gave-birth-to-modern-computing-and-gets-no-credit-for-it.

[17] "DEC PDP-10: KI-10 (DECSYSTEM-10)," Living Computers Museum + Labs, accessed February 15, 2024, https://livingcomputers.org/Computer-Collection/Vintage-Computers/Mainframes/DEC-PDP-10-KI-10-(DECsystem-10).aspx.

[18] The PDP-10 was referred to by its afficionados as "a meg and a mips." Digital Equipment Corporation. *PDP-10*. Promotional Material. Maynard, MA: Digital Equipment Corporation, 1969.

[19] "What Is a Raspberry Pi?," *Opensource.com*, accessed February 15, 2024, https://opensource.com/resources/raspberry-pi.

# Moore's Law

Carver Mead, a professor of engineering at the California Institute of Technology, invented the term Moore's Law to describe the remarkable trend line in electronics that made the exponential increase in computing possible.[20] Gordon Moore and Mead were collaborators in 1960; Moore had asked the question to which Mead found the answer: the smaller (and closer together) you make transistors, the faster, cooler, and cheaper they can be. If you want more powerful and efficient computers, put more and smaller transistors on a chip. The race was on. It remained only, over the following decades, to discover how to fabricate such increasingly intricate chips.

Mead credits some of the inspiration to his collaborator and fellow Caltech professor Richard Feynman, whose 1959 talk "There's Plenty of Room at the Bottom" is often regarded as the inspirational spark of nanotechnology. Indeed, today's computer chips fall under the definition of nanotechnology put forward by the National Nanotechnology Initiative (NNI), as does practically all of molecular biology.[21] Thus it was appropriate for President Clinton to announce the formation of the NNI on the steps of Caltech.

# Artificial Intelligence

Artificial intelligence is a technology with a history similar to that of aviation in that for a substantial period, the general opinion of the experts was that it either was impossible or would require centuries to develop. Indeed, in the 1970s, it was the general opinion *among AI researchers* that the technique that eventually prevailed, deep learning in neural networks, was a waste of time.[22] AI had its Le Mans moment with the release of ChatGPT, and interest and investment in AI has skyrocketed.

Much more than early researchers realized, the basis for AI's success is Moore's Law and the literally astronomical power of today's computers. If instead of buying a Raspberry Pi, the hobbyist's hobbyhorse, for 100,000 times less money than a PDP-10, you spent the 10 million that is today's equivalent of the PDP-10's cost, you could buy 500 Nvidia A100s and have 10,000 times the estimated power of the human brain.[23] This is a fair description of the systems that are used to train today's AI.

Even so, AI is in its infancy, as aeronautics was in 1910. In computers, where Moore's Law and the progress of nanotechnology are essentially the same thing, this means that the

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[20] "The 40th Anniversary of Moore's Law with Gordon Moore" *computerhistory.org*, accessed February 15, 2024 https://www.computerhistory.org/collections/catalog/102695277.

[21] "About Nanotechnology," National Nanotechnology Initiative, accessed February 15, 2024, https://www.nano.gov/about-nanotechnology.

[22] Author's personal experience.

[23] Kif Leswing, "Meet the $10,000 Nvidia Chip Powering the Race for A.I.," *CNBC*, February 23, 2023, https://www.cnbc.com/2023/02/23/nvidias-a100-is-the-10000-chip-powering-the-race-for-ai-.html.

price of AI will drop precipitously while its capability and sophistication increase. The implications for nanotechnology, and for technology generally, are profound. The cost of engineering complex systems seems likely to decline.

## The Biotechnology Revolution

The NNI is a big tent in which a host of scientific fields congregate, brought together by its definition of nanotechnology as anything dealing with matter at scales smaller than a few hundred nanometers. These include studies as diverse as materials science, surface physics, and macromolecular chemistry. The NNI also includes molecular biology.

The essence of life, and the difference between living and inert matter, was in antiquity regarded as some kind of magic. It has taken us a long time to realize that living tissue is instead a system of machines with specific physical functions. It wasn't until 1628, for example, that William Harvey published his discovery that the heart is a pump powering the recirculation of the blood.[24]

Since the 1950s, it has become clear that individual living cells are extremely complex machines—machines at the molecular level. They have powers that do seem magical compared to those of the comparatively simple machines of our macroscopic experience. But that is because they are so incredibly complex. The human DNA in one cell encodes about as much information as 3000 full-length books.[25] There are more working parts in a housefly than in a Boeing 747.

Over the past few decades, we have developed tools to create or modify a broad swath of this cellular machinery, but attaining complete mastery of the mechanism will require considerably more knowledge. An analogy may be enlightening: the information in DNA is essentially software in an extremely obscure programming language. With modern techniques such as CRISPR, we have the ability to read from, or write into, the 3000 volumes, but a lot of what we find there looks like gibberish and we have little idea what effect our changes to the code will have.

## Atomic Precision

We do understand one extremely important thing, however: the magical properties of life, its ability to do amazing chemical transformations, its ability to grow and reproduce and to move and sense the physical world, are all due to the fact that the machinery of life is atomically precise. An organism's DNA describes each molecular machine in such a way that any two of them are *exactly* the same, atom for atom. The mechanism is digital, like the information in a computer. There is a bond between these two atoms—or there is not. This atom

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[24] Stanley G. Schultz, "William Harvey and the Circulation of the Blood: The Birth of a Scientific Revolution and Modern Physiology," *Physiology* 17, no. 5 (October 2002): 175–80, https://doi.org/10.1152/nips.01391.2002.

[25] Brown TA. Genomes. 2nd edition. Oxford: Wiley-Liss; 2002. Chapter 1, The Human Genome. https://www.ncbi.nlm.nih.gov/books/NBK21134.

is carbon—or it is not. The digital nature of matter at the atomic scale is a big part of the secret of reproduction: it is easy to copy digital information exactly, as DNA is copied.[26]

And reproduction is, in turn, the secret to abundant production, as in the Industrial Revolution, when steam engines powered machine tools which built more steam engines. Recall that the Industrial Revolution shifted the world to a growth rate of 3 percent per annum, which means a doubling time of about 25 years.[27] But the doubling time for a digital, atomically precise machine system such as the *E. coli* bacterium is 20 minutes.[28] Bacteria are simple compared to most life, but still complex compared to our macroscopic machines. Their DNA blueprint might be estimated as equivalent to 10 volumes.

In nanotechnology, as with life, the secret is atomic precision, where dealing with matter is pushed into the digital domain. But we also benefit from the transistor trick: the smaller the faster. Even though it is made of floppy proteins that move through water, the ATP synthase machine in the bacterium, a kind of electric motor, can turn at up to 39,000 rpm.[29] If we built a electric motor out of strong materials and ran it in a vacuum, it could turn at something like 200 billion rpm. The ATP synthases in your body produce your body weight in ATP every day. What if they ran a million times faster?

Speeding up one motor doesn't imply a concomitant speedup in the whole industrial system containing it. Often some other part of the system is unable to use its output at the increased rate. Such bottlenecks are especially common when interfacing revolutionary technology to existing manufacturing systems. Don't expect microsecond doubling times, or even 20 minute ones. But the doubling time for Moore's Law is about a year and a half. Since we do that in the real world with existing technology, it probably accounts for most of the bottlenecks. What if we could get our capital stock, our economy—the abundance of everything we build—to grow at Moore's Law rates?

It was a glimpse of such a possibility that so excited Feynman in 1959 and Eric Drexler a couple of decades later. Feynman was ahead of his time; he couldn't get traction for the idea in an age when the transistor radio was only two years old. It had been nearly forgotten by the time Drexler independently rediscovered it and named it "nanotechnology" while studying the technological possibilities of recombinant DNA, for which Paul Berg had won the Nobel Prize in 1980.[30] In that environment, it did get traction.[31] Drexler proceeded to get his

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[26] "Nucleic Acids Book", *Biotage,* https://atdbio.com/nucleic-acids-book/Transcription-Translation-and-Replication.

[27] Hanson, "Long-Term Growth as a Sequence of Exponential Modes."

[28] Amie R. Tuttle, Nicholas D. Trahan, and Mike S. Son, "Growth and Maintenance of *Escherichia coli* Laboratory Strains," *Current Protocols* 1, no. 1 (January 2021), https://doi.org/10.1002/cpz1.20.

[29] BioNumbers, "Maximal Velocity (Vmax) of ATP Synthase at 45°C" (ID 104893, accessed February 15, 2024), https://bionumbers.hms.harvard.edu/bionumber.aspx?id=104893&ve.

[30] "Paul Berg: Facts," Nobel Prize website, accessed February 15, 2024, https://www.nobelprize.org/prizes/chemistry/1980/berg/facts/.

[31] K. Eric Drexler, "Molecular Engineering: An Approach to the Development of General Capabilities for Molecular Manipulation," *Proceedings of the National Academy of Sciences* 78, no. 9 (September 1981): 5275–78, https://doi.org/10.1073/pnas.78.9.5275.

MIT PhD studying it in great detail. What follows borrows heavily from calculations in his dissertation.[32]

## Traction and Misuse of Nanotechnology

Out of every billion words printed in English in 1985, just one was "nanotechnology."[33] By 1995, 111 were; and by 2005, the number had increased to 1,357. Now, nearly 20 years later, the word *nanotechnology* appears at approximately the same rate. The early growth in usage of the term was almost entirely due to the efforts of Drexler and associates at the Nanotechnology Study Group at MIT and to the publication of *Engines of Creation*, a popularization of the above ideas regarding an atomically precise mechanical technology.[34]

The ideas and technology are extremely compelling once one realizes that they imply changes in capability at least as profound as those ushered in by the Industrial Revolution. A substantial number of scientists and engineers, this author among them, began to study them intensely during the 1990s. Learned, peer-reviewed journals with the word *Nanotechnology* in their titles began to appear by the turn of the century.[35]

It was in this environment that President Clinton, in an address at Caltech in which he quoted Feynman about putting individual atoms where we wanted them, announced the formation of the National Nanotechnology Initiative. Unfortunately, the resulting political dogfight for funding has distorted the term *nanotechnology* into near meaninglessness. *Nanotechnology* has come to be used as a buzzword that adds virtually nothing to the understanding of the extremely diverse discoveries, inventions, and analyses it has been used to describe.

A single example should suffice. In the January 2024 issue of the journal *Nature Nanotechnology*, we find a paper called "Urease-Powered Nanobots for Radionuclide Bladder Cancer Therapy."[36] The word *nanobot* occurs 165 times in this paper. What the paper describes is a preparation of a monodispersant colloid (an ultrafine powder with particles all the same size) with enhanced dispersion characteristics due to some chemical properties that interact with the urea in the kidney. (The principle is similar to the soap-powered paper toy boats we made as children.) The powder can be used as a carrier for radioactive substances, which will preferentially settle toward a tumor and can be used for imaging or radiotherapy.

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[32] K. Eric Drexler, *Nanosystems: Molecular Machinery, Manufacturing, and Computation* (New York: Wiley, 1992).

[33] Google Books Ngram Viewer ("nanotechnology," accessed February 15, 2024), https://books.google.com/ngrams/graph?content=nanotechnology&y2019&smoothing=0.

[34] K. Eric Drexler, *Engines of Creation: Challenges and Choices of the Last Technological Revolution* (New York: Anchor Doubleday, 1986). In subsequent editions the subtitle was changed to "The Coming Era of Nanotechnology."

[35] See, e.g., J. S. Hall, "Architectural Considerations for Self-Replicating Manufacturing Systems," *Nanotechnology* 10, no. 3 (1999): 323–30.

[36] Cristina Simó et al., "Urease-Powered Nanobots for Radionuclide Bladder Cancer Therapy," *Nature Nanotechnology* 2024, https://doi.org/10.1038/s41565-023-01577-y.

Make no mistake, this is excellent work and may well shorten diagnoses and treatments, saving lives. But it is a misnomer to refer to the particles as robots! This is pure chemistry: mixing, stirring, and heating reagents (and running them through centrifuges) in a modification of the Stöber process invented in 1968.[37] The particles were not built by, and most certainly do not constitute, self-replicating factories. There is no sense in which this development, valuable though it may be, portends a phase change in the way everything is made. But "nanotechnology" is by now such a universally applied buzzword that it is probably impossible for it to regain its former precision and descriptiveness.

## Capabilities of Nanotechnology

Because the word *nanotechnology* has become a buzzword, in this primer I shall use the acronym APM, meaning "atomically precise machinery" or "atomically precise manufacturing," to refer specifically to technology that, like molecular biology, uses processes that result in exactly the intended arrangement of atoms and bonds. Before the advent of the NNI, this was just what the word *nanotechnology* meant: essentially a technology that, given any arrangement of atoms, can transform it into any other arrangement of the same atoms. (I use the word *any* guardedly, in the same sense as one would say that a machine shop can cut any shape in steel or a printer can print any software program. The range of outputs is not infinite but covers an extremely broad spectrum of useful products. In particular, the system must be able to make all of the parts that comprise the system itself.)

There is a surprisingly large portion of current technology that can be described as rearranging atoms. For example, our food and our waste stream, including exhaled carbon dioxide, is composed of not only the same types of atoms but the same individual atoms! A technology capable of rearranging them would replace agriculture, animal husbandry, and much of the food processing and preparation industry. All chemical and drug synthesis, light manufacturing, even laundry services can be viewed as merely rearranging atoms.

APM is distinguished from *bulk technology*, which I use to describe any technology that is not atomically precise, including much of what is currently termed *nanotechnology* merely because it deals with objects 100 nanometers or less in size. A 100-nanometer cube of salt contains approximately 76,000,000 atoms.[38] Dealing with matter at this scale without atomic precision is like building with Lego blocks when your smallest tool is a dump truck. All you can make is heaps. There are many more optimal structures and more complex systems you could make if you could only use your hands and put each block in a specific place.

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[37] Wikipedia, s.v. "Stöber process," last modified February 1, 2024, https://en.wikipedia.org/wiki/Stöber_process.

[38] "Computational Chemistry Comparison and Benchmark DataBase Release 22" National Institute of Standards and Technology, accessed April 30, 2024, https://cccbdb.nist.gov/exp2x.asp?casno=7647145&charge=0.

There is much valuable scientific and technological work being done in the study of matter at the nanoscale. But only atomically precise, self-replicating machinery[39] has the potential to enable an economic phase change of Industrial Revolution proportions. What follows is a description of the capabilities to be expected of a mature, well-developed, atomically precise, self-replicating, machine-phase (using gears, shafts, bearings, etc., instead of floppy protein molecules in solution) manufacturing technology: APM. These capabilities have been studied over the past three decades with detailed quantum-level computer modeling, and we have very high confidence that they will work essentially as designed.

They are not available today, however. What is currently described as “nanotechnology” is extremely imprecise and primitive in comparison. It constitutes incremental progress, not revolutionary progress. Thus, an overview of the existing work and latest results from the labs, while scientifically fascinating and occasionally economically valuable, would be a poor guide to the ultimate capabilities of APM.

## Manufacturing

Current manufacturing practice requires vast factories because the processes used to fabricate modern devices and materials are very complex, and there are significant economies of scale that come with handling large quantities of raw materials and large numbers of products. But an APM factory can be much more complex still.

For comparison, a bacterium, with 10 million working parts, is more complex than a car, which has a mere 30,000. Similarly, a desktop APM 3D printer could contain more working parts, internal supply chains, and different synthesis procedures than the entire world economy does today. Given the appropriate atoms as raw material, it could produce essentially anything that can be manufactured, grown, cultivated, cultured, processed, or made in any other way today, and plenty of things that cannot.[40] The salient constraints are product size, energy, and the quantity and quality of feedstocks.[41]

Among the most world-changing of the possible products such a printer could make is more APM 3D printers. Suppose you had just one APM 3D printer capable of printing another one within the space of a day. Assuming negligible time to set up the new printer, power it, and provide it with raw materials, on the second day each printer would make another and you would have a total of four. You would have 8 the third day, 16 the fourth day, 32 the fifth. At the end of the first week you would have 128 printers; at the end of the second week, 16,384; at the end of the third week, two million; at the end of the fourth week, a quarter of a billion. At the end of five weeks, if you hadn’t run out of raw materials or energy, you would have four 3D printers for each person on Earth.

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[39] See, e.g., Robert A. Freitas Jr. and William P. Gilbreath, eds., *Advanced Automation for Space Missions*, NASA Conference Publication 2255, 1982; and Robert A. Freitas Jr. and Ralph C. Merkle, *Kinematic Self-Replicating Machines* (Georgetown, TX: Landes Bioscience, 2004).

[40] Drexler, *Nanosystems*, 411–41.

[41] K. Eric Drexler, personal communication.

Enough raw materials for a very wide range of products could be had from the air (carbon, hydrogen, oxygen, and nitrogen) and a handful of dirt from which the next 10 or so elements, used in trace amounts, can be extracted. This is essentially how green plants work: the bulk of the material in a plant comes from the carbon dioxide in the air, the soil essentially supplies "vitamins" and water, and the energy comes from sunlight.[42] It would be more expeditious, however, to provide the nanofactory with a piped nutrient stream and a connection to the power grid.

Once you have your nanofactory, what could it make for you? The possibilities are endless, but each product will have to be designed, its construction planned out, and specifications published in a form that will allow you to choose between them. It would obviously be possible for an online repository to offer a browsable catalog of downloadable designs for consumer items. Food, clothing, and other household items could be fabricated by a kitchen-counter-sized nanofactory, vehicles and so forth by a garage-sized one. However, the rapid progress in generative artificial intelligence suggests that it might be possible for tomorrow's nanofactories to produce bespoke designs based on a consumer's verbal instructions.

## Robotics

The current state of the art in robotics is probably much more advanced than the general public realizes. Given a tractable environment and a well-specified task, today's robots are quite capable, and they are getting better fast.

With the rapid miniaturization of electronics has come equally remarkable progress in sensor technology. Consider that a typical pocket telephone now has vision, hearing, balance, and the ability to feel fingertips on its screen. With APM, these become quite adequate for the senses of a humanoid robot. Current technology is not as capable in the area of *actuators*; motors and the accompanying mechanisms that are at the same time as fast, as powerful, as versatile, as lightweight, and as compliant as the human hand are lacking, although we can do better at any single one of these characteristics by itself.[43]

With APM, the situation reverses. A typical human consumes about 200 watts as a baseline but is capable of five times that during vigorous exercise. The muscles of an average man weigh about 30 kilograms and the bones 10.[44] This amounts to a peak capacity of roughly 30 watts per kilogram for the muscles. APM electric motors could have a capacity of 100 billion watts per kilogram.[45] Human bones have a strength of 200 megapascals; nanoengineered structures

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[42] "Photosynthesis, Nutrients, Soil & Basic Plant Information," Smithsonian Environmental Research Center, accessed February 15, 2024, https://serc.si.edu/node/39150.

[43] Wei Liang et al., "Comparative Study of Robotic Artificial Actuators and Biological Muscle," *Advances in Mechanical Engineering* 12, no. 6 (2020), https://doi.org/10.1177/1687814020933409.

[44] "Human Bones, Joints and Muscles Facts," Winston Medical Center, accessed February 15, 2024, https://www.winstonmedical.org/human-bones-joints-and-muscles-facts/.

[45] Drexler, *Nanosystems*, 339.

can have a strength of 50 gigapascals: 250 times as strong.[46] APM could make robots the same size and strength as humans but weighing less than a pound, batteries not included.

This property will affect virtually all APM-made machines: when atoms are arranged optimally, the material can be much stronger and much lighter than natural materials. Motors can be extremely powerful and yet microscopically, invisibly small. There can be many, many more of them than we could afford to put into our macroscale machines. They will be built into the fabric of any object, which will simply change shape, like your body but with greater flexibility and strength, to accomplish its ends.

## Construction

The raw productive power of APM lies in the fact that a one-kilogram nanofactory can make one kilogram of product in an hour (consuming about a kilowatt of power).[47] Nanofactories allocated to construction could produce robots, vehicles, building materials (also lighter but stronger than their conventional counterparts), and then more nanofactories. The robots would assemble the materials into infrastructure and transportation systems and lay power and communication lines, keeping the nanofactories supplied. The growing system would be something like building a city from scratch by sending in a battalion of SeaBees to lay roads, build factories, and move personnel and materiel where they were needed. The difference is in the nano-based system the personnel would be made in the factories too!

One would of course need a blueprint for the entire development in advance. But if this were properly done, doubling time could be considerably shorter than a day. If it could be held to four hours—which is enough time for a nanofactory to make another nanofactory, a human-sized robot, and quite a lot of infrastructure supplies—there would, at the end of a week, be a billion well-equipped robots. This is enough industrial potential to rival that of any nation.

## Energy

Virtually all the energy humans use is solar energy. Virtually none of the power we use is solar power. The difference is crucial.

Millions of years ago, green plants used energy from sunlight to separate carbon and hydrogen from carbon dioxide and water, respectively, ultimately storing the separated elements in what we call fossil fuels. We burn fossil fuels to reclaim that energy, recombining carbon and hydrogen with oxygen from the air. Unlike fossil fuels, however: oxygen is continually replenished by contemporary green plants. Also unlike fossil fuels, life on Earth is finely adapted to the proportions of oxygen (and other gases) in the atmosphere, which means we are limited to using any fuel to the rate oxygen is produced. This is the often overlooked

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[46] Drexler, 256. See also chap. 7.1, "Strength of Human Bones," in Lawrence Davis, *Body Physics: Motion to Metabolism* (Corvallis: Open Oregon Educational Resources, 2020).

[47] Drexler, *Nanosystems*, 441.

second half of the energy equation. APM will let us easily and efficiently replicate this process and produce as much hydrocarbon fuel as we like from air and water. The only hitch is that the process still requires energy. Fossil fuels represent an accumulation of millions of years of sunlight. Fossil fuels are called a primary energy source, but that is a terminological inexactitude. Sunlight was the primary energy source. Chemical fuels make an excellent on-demand power source.

If we pave over the Earth with solar cells, we get non-dispatchable power, and we tamper with the often overlooked second half of the energy equation—solar cells do not produce oxygen, and they shade the green plants that do. APM can solve both problems at once: a nanoengineered "plant" could both produce fuel and release oxygen. Your lawn could be a mat that is indistinguishable from grass except that it never needs mowing and it delivers both fuel and pure water to your house.

On a sunny and windy day, an acre of such grass could produce a gallon of gasoline in about a minute. The wind is necessary to replenish the carbon dioxide that would be extracted, which forms the limiting factor. Alternatively, a non-carbon fuel such as ammonia could be produced, again storing energy at rates on the order of a megawatt per acre.

APM will completely revolutionize the way we use fuel. Since mankind discovered fire, we have extracted energy in the form of heat and light from chemical fuels by combustion. This is quite inefficient for many purposes: a candle produces 80 watts of heat and 13 lumens of light; an LED produces 8,000 lumens from the same power.[48]

Similarly, only about 20 percent of the energy in gasoline becomes useful motion in your car.[49] There are fundamental physical (thermodynamic) limits to the fraction of heat energy that can be converted into useful work. But the limit doesn't hold if the fuel doesn't burn. Devices such as a fuel cell, or the Krebs cycle in your own cells, convert the chemical potential energy of a fuel directly to electricity without thermalizing it.[50] This can be considerably more efficient.

## Transportation

Hydrogen is very light, which makes it promising as a fuel for aircraft. A liter of liquid ammonia, $NH_3$, actually contains more hydrogen atoms than a liter of liquid hydrogen. Ammonia is widely produced and transported today. Both hydrogen and ammonia produce only environmentally null effluents when they are used as fuels—that is, their waste materials

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[48] Anthony Hamins, Matthew Bundy, and Scott E. Dillon, "Characterization of Candle Flames," *Journal of Fire Protection Engineering* 15 (November 2005): 265–85; "Watts to Lumens Calculator," Calculator Site, accessed February 15, 2024, https://www.thecalculatorsite.com/energy/watts-lumens.php.

[49] "Where the Energy Goes: Gasoline Vehicles," US Department of Energy, accessed February 15, 2024, https://www.fueleconomy.gov/feg/atv.shtml.

[50] Drexler, *Nanosystems*, 397–98.

are already components of the atmosphere. But hydrogen and ammonia are problematic to handle as fuels, at least with current technology.[51]

Hydrocarbons are even more energy-dense and even more widely handled.[52] Glucose (essentially corn syrup) is what your body uses, is safe and easy to handle, and contains enough energy to be a perfectly viable automotive fuel.[53] Corn oil is similar.[54]

APM could make a fuel cell for any of these, although internally such fuel cells would look like factories combining atoms in complex processes. Because they would not thermalize the energy, they could be nearly 100 percent efficient; your electric car with an APM gasoline fuel cell would get 129 miles per gallon.

## A Second Atomic Age?

Nuclear fuels constitute a vast store of potential energy, the only widely used form that does not come ultimately from the sun. Unfortunately our current methods of using them are primitive and inefficient: producing heat in enormous structures to turn steam engines. The physics we know already allows for much more compact and efficient methods if APM is used. To be clear, APM could not manipulate nuclei directly, but it would let us process fuels one atom at a time. This would allow for cheap isotopic separation and selective transmutation. Continuous reconstruction and decontamination of mechanisms at the molecular scale is what enables the remarkable resistance of the bacterium *Deinococcus radiodurans* to intense radioactivity; APM could do the same for our machines (and, to a lesser extent, for our bodies).[55]

NASA has already sponsored designs for reactors to be used on space probes—reactors that would be of appropriate size and power for a home.[56] The huge roadblock is cost (and, of course, regulation). But the cost reductions that accompany another industrial revolution could easily make such reactors affordable.

## The Final Frontier

APM could easily produce spacecraft economically enough to enable widespread private ownership, much as the previous Industrial Revolution enabled the proliferation of automobiles. Furthermore, future spacecraft could be made significantly safer than current-day rockets.

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[51] Stephen T. Miller, Seth A. Levine, and Ilsa H. Luther, “What Will Fuel the Energy Transition: A Comparison of Hydrogen and Ammonia—Is There a Clear Winner?,” *National Law Review*, October 5, 2023, https://www.natlawreview.com/article/what-will-fuel-energy-transition-comparison-hydrogen-and-ammonia-there-clear-winner.

[52] US Energy Information Administration Glossary, s.v. “Hydrocarbon,” accessed February 15, 2024, https://www.eia.gov/tools/glossary/index.php?id=Hydrocarbon.

[53] Wikipedia, s.v. “Glucose,” last modified January 28, 2024, https://en.wikipedia.org/wiki/Glucose.

[54] T. Balamurugan, A. Arun, and G. B. Sathishkumar, “Biodiesel Derived from Corn Oil—a Fuel Substitute for Diesel,” *Renewable and Sustainable Energy Reviews* 94 (October 2018): 772–78, https://doi.org/10.1016/j.rser.2018.06.048.

[55] Feng Liu, Nuomin Li, and Yongqian Zhang, “The Radioresistant and Survival Mechanisms of *Deinococcus radiodurans*,” *Radiation Medicine and Protection* 4, no. 2 (June 2023): 70–79, https://doi.org/10.1016/j.radmp.2023.03.001.

[56] Lee Mohon, “Kilopower,” NASA, December 12, 2017, https://www.nasa.gov/directorates/stmd/tech-demo-missions-program/kilopower-hmqzw/.

It seems virtually certain that spacecraft will become the default mode of long-distance travel on Earth. This would put every location on Earth within one hour's travel time of every other location.[57] It would also place the territory and natural resources of the solar system within our reach.

## Environment

As mentioned previously, a technology that is capable of rearranging atoms arbitrarily is one that is capable of converting the waste stream of humanity into a supply of food, fresh air, clothing, and consumer items without resort to the natural processes that we are forced to utilize today: fertilization, crop growth, carbon dioxide uptake and oxygen release, and the life cycle of food animals, all powered by sunlight. With APM, the equivalents of these processes could be done directly, powered by any energy source available, and more quickly and in a much more self-contained way. With APM, the carrying capacity pathway through nature can be short-circuited, and humans need have no environmental impact at all. *No environmental impact at all.*

Most industrial processes that do chemical processing have become cleaner over time, but there is also a strong trend toward more processing.[58] APM will most likely accelerate both trends. It will be possible in most cases to eliminate industrial effluents entirely and to restore the natural world to its original state with minimal effort. In the extreme, we could restore the entire Earth to purely natural conditions while housing the entire human race within enormous skyliners that never land and ocean liners that never dock. (This primer takes no position on the desirability of such a step; I mention it merely to help delineate the range of possibilities.)

## Nanomedicine

Genetic engineering may well allow us to improve our bodies by eliminating design inefficiencies, inherited diseases, and susceptibility to various natural diseases. But APM could augment or replace biological mechanisms with mechanical ones considerably better, stronger, and faster.

*Respirocytes*, artificial red blood cells, could use pressure tanks instead of absorbent hemoglobin to transfer oxygen, allowing you to hold your breath for four hours.[59] Your blood chemistry could be continually monitored and maintained. Artificial leukocytes[60] (white blood cells) could give you immunity to a new disease by downloading a firmware upgrade. APM lenses

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[57] Thomas Burghardt, "Preparing for 'Earth to Earth' Space Travel and a Competition with Supersonic Airliners," *National Science Foundation*, December 26, 2020, https://www.nasaspaceflight.com/2020/12/earth-to-earth-supersonic-airliners/.

[58] "National Overview: Facts and Figures on Materials, Wastes and Recycling," US Environmental Protection Agency, last updated November 22, 2023, https://www.epa.gov/facts-and-figures-about-materials-waste-and-recycling/national-overview-facts-and-figures-materials.

[59] Robert A. Freitas Jr., "Exploratory Design in Medical Nanotechnology: A Mechanical Artificial Red Cell," *Artificial Cells, Blood Substitutes, and Immobilization Biotechnology* 26 (1998): 411–30.

[60] Robert A. Freitas Jr., "Microbivores: Artificial Mechanical Phagocytes Using Digest and Discharge Protocol," *Journal of Evolution and Technology* 14, no. 1 (April 2005): 55–106, https://www.jetpress.org/volume14/freitas.pdf.

in your eyes could give you telescopic and microscopic vision; a replacement retina could see in the infrared and ultraviolet.

A second skin, invisibly thin, could insulate you from virtually any temperature extreme on Earth; one only a few millimeters thick could form a wearable robot—a powered exoskeleton providing armor and enhanced strength. It could even form an artificial gill, allowing you to breathe underwater.

Artificial nerves implanted among the natural ones will first be a research tool, allowing us to study the dynamics of the brain in detail. Once the brain is better understood, we will be able to monitor, augment, supplement, or substitute any desired portions of mental function. Completely realistic virtual experience should be possible, as well as memory enhancement and various forms of telepathy, including communication with other humans and with machines. You will never get lost, either geographically or in thickets of the most complex mathematics.

Ultimately cancer and the aging process itself will be understood and cured;[61] APM will be an essential tool in both processes.

## Dangers Associated with Nanotechnology

I do not wish to convey the impression that a mature APM system will suddenly be developed within the next few years. Basic atomically precise synthesis of individual parts may appear within a decade, but the advanced general manipulation and fabrication capabilities described in the previous section, including billion-part self-replicating nanofactories, will take longer to emerge. Getting to the high level of technological maturity from where we are today will probably require at least two or three decades of focused research and development, as well as public or private funding at the multi-billion-dollar level. Nevertheless, the emergence of a mature APM technology is absolutely inevitable.

The policy issues that will arise as a result of this are immense and promise to have a pervasive impact on virtually everything, from poverty to war. So it is imperative to initiate serious policy discussions sooner rather than later. To paraphrase what Schrödinger said about quantum mechanics, anyone who is not deeply disturbed about nanotechnology has failed to understand it.

### Accidents

Any self-reproducing technology comes with the danger of unconstrained growth. APM mechanisms designed to replicate in the biosphere would compete with natural organisms and would likely

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[61] Robert A. Freitas Jr., “Comprehensive Nanorobotic Control of Human Morbidity and Aging,” in *The Future of Aging: Pathways to Human Life Extension*, ed. Gregory M. Fahy et al. (Dordrecht, Germany: Springer, 2010).

displace them by means of greater efficiency and fecundity. Mechanisms designed as predators would quickly extinguish the biological prey in their niche.

## War

War changed drastically with the advent of mechanization during the Industrial Revolution; the level of death and destruction wreaked by the major wars of the 20th century was unprecedented. Any power possessing APM could create, within a few weeks, machinery equivalent to all the armies, navies, and air forces of today's world. The capabilities of individual weapons could considerably exceed those of even the most sophisticated modern systems. Once APM robots have been designed, there will be no need to recruit and train human soldiers.

Together, these facts mean that any organization or entity with a fairly small minimum design capability will be the military equivalent of the great superpowers of today. A large population and preexisting industrial base will no longer be necessary to a power aiming to conduct a war.

## Unintended Consequences

Side effects from the widespread use of air-breathing synthesizers might include drawing down the carbon dioxide in the atmosphere. This could be catastrophic in two ways: first, green plants would starve; and second, because the climate response to carbon dioxide is logarithmic, reductions have a greater cooling effect than increases have a heating effect.[62]

Radical abundance comes with its own dangers related to the removal of constraints on our activities currently imposed by our relative poverty (compared to the wealth we would command in a APM economy). When everyone can afford a domestic staff of a thousand robots, there will be a pseudo population explosion. When anyone can wear a suit that makes Siberia as comfortable as southern California, or live in the oceans, there will be people everywhere

## Unknown Unknowns

It has been quipped that while God created men and women, Samuel Colt made them equal. It would be closer to the truth to name James Watt and Henry Ford. It was the Industrial Revolution that allowed the elimination of slavery and the emancipation of women. It also was responsible for significant cultural changes, however—changes that would have been viewed with alarm by our ancestors. We might similarly view with alarm some of the changes APM will allow. How will culture and character differ in a world where you can send a text to your bloodstream telling it to raise or lower its alcohol levels? Or where, instead of 140-character tweets, your social media offers five-minute trysts indistinguishable from physical reality? Extreme body modification seems virtually inevitable, although with APM it would be easier to reverse than it is today.

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[62] Yi Huang and Maziar Bani Shahabadi, "Why Logarithmic? A Note on the Dependence of Radiative Forcing on Gas Concentration," *JGR Atmospheres* 119, no. 24 (December 2014): 13,683–89, https://doi.org/10.1002/2014JD022466.

### Failure to Act

APM makes it possible for a relatively small group to wield the kind of power that only great nations possess today. There are many more such groups than the existing superpowers, and their motivations are diverse. If nations such as the US fail to develop APM in a timely manner, we will have disarmed ourselves in an increasingly dangerous world. At the same time, we will continue to live in what would be viewed as extreme poverty, scientific ignorance, and medical misery by the people of a post-APM world.

## Policy Recommendations

Around the turn of the century it was an open question among the leading researchers in the field whether APM or artificial intelligence would arrive first.[63] Today we know the answer is AI, and this development encourages us to draw some instructive parallels. AI has been funded at reasonable levels since the 1960s, but the breakthroughs did not come from those efforts. Instead, maverick researchers pushing a machine learning technology well outside the mainstream were largely responsible for the breakthroughs.

Then, once it was widely appreciated that AI actually worked, private investment skyrocketed.[64] The field has quickly become the fastest-growing segment of the tech sector. Expect the same thing to happen with APM.

### Distinguish APM and Nanoscale Science

The NNI represents one of the greatest failures of our scientific funding establishment. When President Clinton inaugurated it, he quoted Feynman's description of manipulating matter atom by atom. But today the NNI refers to those engaged in nanotechnology as studying the properties of matter at scales of between 1 and 100 nanometers. This excludes single atoms.[65]

What happened was that the NNI and its relatively modest budget was captured by established scientific actors in existing, well-positioned political structures.[66] In the process Feynman's original idea was not only ignored but actively disparaged.[67] Any attempt to work in the field as originally conceived became dangerous to a researcher's funding even for unrelated activities.

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[63] See, e.g., J. S. Hall, "Is AI Near a Takeoff Point?," *Nanotechnology Perceptions* 2, no. 1a (March 2006): 57–61.

[64] "AI Investment Forecast to Approach $200 Billion Globally by 2025," Goldman Sachs, August 1, 2023, https://www.goldmansachs.com/intelligence/pages/ai-investment-forecast-to-approach-200-billion-globally-by-2025.html.

[65] A single cubic nanometer of diamond contains about 125 carbon atoms; see "About Nanotechnology," National Nanotechnology Initiative.

[66] K. Eric Drexler, *Radical Abundance: How a Revolution in Nanotechnology Will Change Civilization* (New York: PublicAffairs, 2013), chap. 13.

[67] One example is the Drexler-Smalley debate: https://en.wikipedia.org/wiki/Drexler–Smalley_debate_on_molecular_nanotechnology. Another is a similar but more congenial in-person debate between me and Richard Jones, Britain's leading nanotechnologist at the time, on August 24, 2005, at the University of Nottingham as part of a Surface Science Summer School. See "Nanotechnology under the Microscope," *Phys.org*, August 17, 2005, https://phys.org/news/2005-08-nanotechnology-microscope.html.

The study of matter on the scale of nanometers is quite valuable, and indeed it should be funded at levels significantly higher than what Americans spend annually on Halloween costumes for dogs.[68]

However, it shouldn’t be called nanotechnology, and there shouldn’t be a campaign against the study of actual, atomically precise nanotechnology—that is, APM.

## Abjure Crippling Regulation

Nanomachines that can sustain operation and reproduce in the natural environment should not be built, even as supposedly well-contained gain-of-function experiments. Strong and effective regulation is not only proper but critical to the survival of the biosphere. On the other hand, impeding the efforts of well-intentioned actors carries the danger of enhancing the relative capabilities of malevolent ones who are beyond our control.

APM as described here *will be developed*. The laws of physics clearly allow it, and the state of the art is creeping inexorably toward it. The only significant question is who will get it first.

## Adopt Strategic Funding Directions and a Focus

The model that has worked best for the development of breakthrough technologies is to fund goals rather than specific approaches. Examples include mail-carrying aircraft,[69] microelectronics, and reusable rocket boosters. Natural experiments include the Industrial Revolution itself: It happened in England, which had no major national research and development program, and not in France or Germany, which did have such programs.[70]

But I should also note that before we can fund goals such as the specific applications described in this primer, we must first develop the basic manufacturing technology capable of controllably and reliably building atomically precise 3D objects at the 10–1,000 atom size level. (Note that basic atom-by-atom mechanosynthesis has already been demonstrated experimentally in multiple labs over the past 20 years.) Once this goal is accomplished, we can expect a “Cambrian explosion” of research and development, much like the one currently happening in AI, to produce the full panoply of applications described in this paper. APM will explode in a thousand different directions.

Thus it would seem that funding the development of a threshold, entry-level manufacturing capability is of greatest immediate importance to the field. It is not yet clear what is the optimal form for this funding to take—public or private, direct or via prizes, or a full-court press. But it is vital that it should happen in one way or another.

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[68] Gita Sitaramiah, “Americans Are Spending $700M on Halloween Costumes. For Our Pets,” *The Seattle Times*, October 30, 2023, https://www.seattletimes.com/business/americans-are-spending-700m-on-halloween-costumes-for-our-pets/.

[69] See, e.g., chap. 10 (“The Mailwing”) in Frank Kingston Smith, *Legacy of Wings: The Harold F. Pitcairn Story* (New York: Aronson, 1981).

[70] J. Storrs Hall, *Nanofuture: What’s Next for Nanotechnology* (Amherst, NY: Prometheus, 2005), 40–41.

### Open the Frontier

Perhaps the clearest example of a project APM would benefit is space travel. Space travel with current technology is far too expensive to permit any significant proportion of humanity to live anywhere but Earth, but APM will change that.

The machines we invent today to maintain a healthy body weight and prevent cancer may well be used tomorrow to adapt to prolonged weightlessness and resist the higher levels of radiation outside Earth's magnetic field. Closed-cycle life support and food technologies developed in aid of lunar or Martian colonies might well aid in preserving the natural environment on Earth. The list of such dual-use technologies seems practically limitless, and fertilization can go both ways. The challenges of space travel might provide an attractive focus.

The world dodged a bullet with COVID-19, but as technological capabilities grow everywhere—especially in biotech—we need an outlet for aggressive development, an insurance policy for humanity, and a platform from which to repair the Earth, should it come to that. Mature APM would allow humanity to live comfortably throughout the solar system. We would be much more resilient as a species. We could preserve the Earth as a park and take our fights outdoors.

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