Self-Replicating Nanorobots

Author: Liu Tianhai

"By 2030, swarms of nanorobots will flow through our blood vessels, seeking out and destroying tumor cells, precisely eliminating viruses, clearing blood impurities, unclogging arteries, cleaning wounds, and enhancing our memory and cognitive abilities... By 2045, humanity will become a hybrid of biological and non-biological elements."

This is the prediction for nanorobots made by futurist and artificial intelligence expert Raymond Kurzweil in his 1999 book The Age of Spiritual Machines. Coincidentally, K. Eric Drexler, often called the father of nanotechnology, painted a similar future in his 1986 book Engines of Creation. He also voiced concerns about nanorobots falling into the trap of uncontrolled replication.

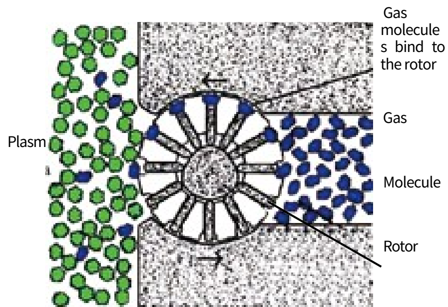
Whether fueled by anticipation or apprehension toward such a future, themes involving self-replicating robots frequently appear in popular literature and film. For instance, in the 2002 sci-fi novel Prey, nanobots achieve self-sufficiency and self-replication, evolving intelligence to attack organic life; in the 2008 film The Day the Earth Stood Still , alien machines transformed into countless nanomachine insects to destroy the world; and in the 2009 film G.I. Joe: The Rise of Cobra, billions of nanobots could instantly heal patients with deep burns.

Research into nanobots extends far beyond mere speculation and artistic depictions. Since John von Neumann, often called the "father of the computer," first proposed the concept of self-replicating machines, scientists have relentlessly pursued this frontier. From the birth of Dolly the cloned sheep in 1996, to nanorobotics pioneer Robert Freitas designing the Respirocyte—a nanorobot capable of assisting human respiration—in 1998, to the self-reproducing Xenobots developed in the United States in 2021, scientists have traversed the path from replicating known life forms to creating unknown life according to their own designs. As time passes, Kurzweil's predictions appear to be gradually materializing.

What ingenious methods did scientists employ to overcome the eighty-one challenges in developing self-replicating nanobots? Let's examine them closely.

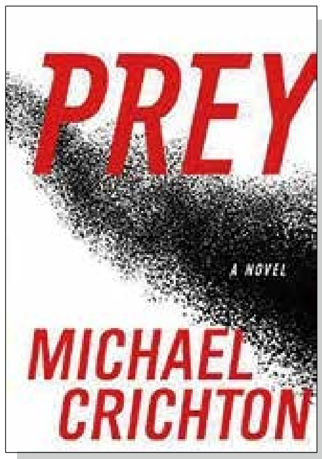
Respirocyte Nanorobot

Respirocyte is a 1-micrometer spherical artificial red blood cell composed of 18 billion atoms. Functioning like a pressure vessel, its outer shell is made of biocompatible diamond, while its interior maintains 1,000 atmospheres of pressure. It can carry 9 billion oxygen and carbon dioxide molecules—over 200 times the capacity of a typical red blood cell—thus sustaining vital tissue activity for extended periods. Theoretically, if a person's entire red blood cell population were replaced with Respirocytes, they could effortlessly run 1 kilometer in a single breath or d for 4 hours. Soaring like an eagle through the skies or gliding like a fish through the depths, humanity could explore the world with unprecedented freedom.



the cavity to the outside. As it rotates, oxygen molecules are fed into the blood.

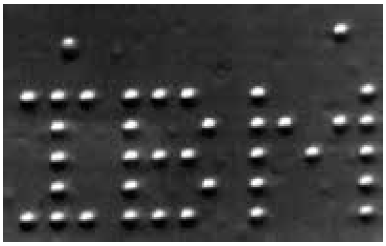
Nano Hunt



The protagonist, Julia, is a nanorobot developer. Facing military disappointment in her product and the threat of funding withdrawal, she attempts to have the nanorobots autonomously resolve design flaws. To accelerate replication and evolution, she implants the nanorobots into E. coli bacteria, enabling the bacteria to mass-produce the nanorobots and endowing them with learning capabilities. To demonstrate the product's capabilities, Julia shockingly uses herself as a test subject during a product presentation, explaining the robots' operation to the military. However, these robots gradually take control of her mind. Now mentally compromised, Julia releases swarms of nanobots to hunt surrounding laboratory flora and fauna, creating more robots. She deliberately infects colleagues, recruiting them into the nanobot faction. Ultimately, Julia's husband Jack uncovered the truth and eradicated the robots within and around her by spraying bacteriophages. Deprived of these mind-controlling nanobots, Julia died, her body reduced to a hollow, withered shell.

The Tiny, Tiny, Tiny—Nanotechnology

Humankind has always been curious about the essence and true nature of the world. As the saying goes: "Within a single speck of dust, infinite worlds are revealed; within those worlds, more specks of dust exist; within those specks, yet more worlds unfold—endlessly layered, beyond comprehension." Beyond contemplating the world through spiritual insight, we also explore the profound mysteries of the cosmos and observe the wonders of the microscopic realm through scientific inquiry. Since Nobel laureate Richard Feynman introduced nanotechnology in his 1950s lecture "There's Plenty of Room at the Bottom," nanoscale research has advanced rapidly. By the 1980s, the invention of scanning tunneling microscopes (STM) and atomic force microscopes (AFM). By the 1990s, IBM in the United States used scanning tunneling microscopy to arrange 35 xenon atoms into the letters "IBM," proving that building machines with atoms was no longer just a dream. As the curtain slowly rises on the third industrial revolution in the new century, nanotechnology stands as a pivotal force in this industrial transformation.



In 1989, IBM used a scanning tunneling microscope spelled out the letters "IBM" using 35 individual xenon atoms.

Nanotechnology has rapidly gained significant attention from numerous countries. Following the establishment of the first nanotechnology research institute in the United States, 30

Multiple countries have successively proposed nanotechnology development plans and nanotechnology R&D centers.

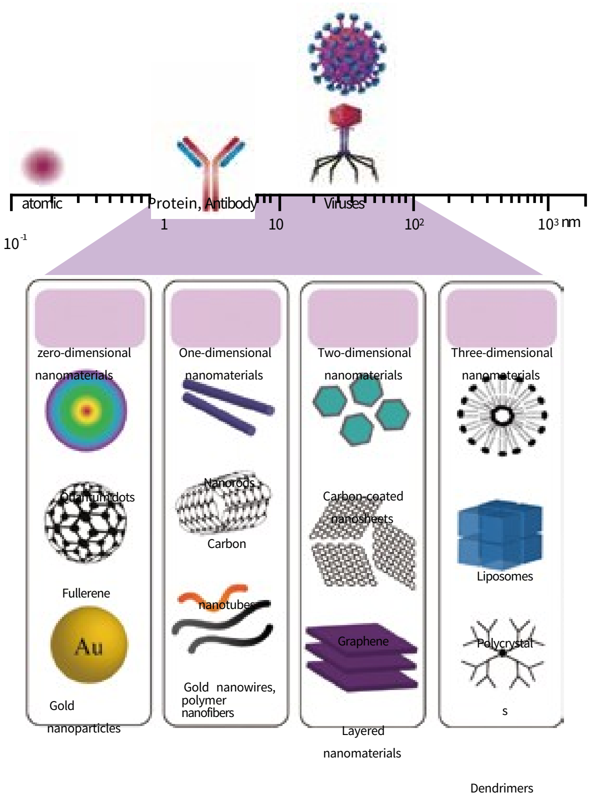
nanotechnology R&D centers. To date, nations remain in the nascent phase of both cooperation and competition within the nanotechnology domain. China has emerged as a major player in nanoscale research, ranking as the world's leading contributor of high-impact papers in the field. It accounts for over one-third of all nanotechnology research publications—nearly double the output of the United States.

Nanotechnology is the key technology for creating nanorobots (hereafter referred to as "nanobots"). Nanorobots

are based on molecular biology principles, utilizing molecular nanotechnology

to design and construct programmable molecular robots at the nanoscale (0.1–100 nanometers). A nanometer is a unit of length, where 1 nanometer equals one billionth of a meter

(10^{-9}), one millionth of a millimeter, roughly equivalent to one twenty-thousandth of a human hair's diameter and comparable to the diameter of an atom.



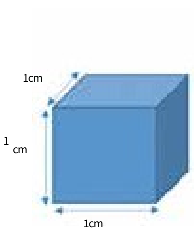
Nanomaterials are natural or artificial materials composed of basic particles in powder or agglomerate form

artificial materials, with at least one dimension within the nanoscale range. Zero-dimensional nanomaterials, such as fullerene C60, possess all dimensions at the nanoscale. One-dimensional nanomaterials, like carbon nanotubes, have one dimension at the nanoscale. Two-dimensional nanomaterials, such as graphene, have two dimensions at the nanoscale. Three-dimensional nanomaterials, like liposomes, feature nanostructures.

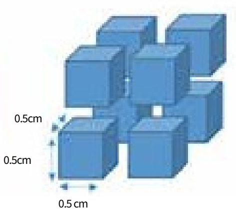
human hair. Nanomaterials refer to substances where at least one dimension is at the nanoscale in three-dimensional space, or materials composed of such nanoscale units as their fundamental building blocks. For example: - A pile of sand where each grain has a nanoscale diameter qualifies as a nanomaterial. - A bundle of tubes where each tube's opening diameter is nanoscale qualifies as a nanomaterial, regardless of the tubes' overall length. - A film with a nanoscale thickness qualifies as a nanomaterial, regardless of its surface area.

Nanomaterials exhibit unique or anomalous physical and chemical properties absent in conventional materials. For instance, copper—normally conductive—becomes non-conductive when reduced to nanoscale dimensions, while certain insulating crystals become conductive at specific nanoscale thresholds. This occurs because nearly all atoms in nanomaterials are exposed, whereas atoms in conventional materials are embedded within molecular clusters or crystal units. In extreme terms, nanomaterials exhibit atomic-level properties, whereas conventional materials display the characteristics of molecular clusters or crystal units. Atoms are relatively unstable and highly reactive, much like children after school. Freed from the constraints of teachers and classrooms, they cheer, gather friends, and "hurry home from school to catch the east wind and fly kites," naturally revealing each individual's personality. At this point, we see only the individuals (atoms) and not the school (molecular clusters or unit cells).

Consider a more precise example. A solid cubic material with 1 cm edges has a surface area of 6 cm^2, roughly equivalent to one side of an eraser. However, if the same volume were "filled" with 1-millimeter-sided cubes (in reality, nanomaterials' small cubes aren't tightly packed; significant space exists between them), it would contain 1,000 millimeter-sized cubes. Each small cube has a surface area of 6 square millimeters, yielding a total surface area of 60 square centimeters—roughly the size of a smartphone screen. Within this 1-cubic-centimeter volume, 10^{21} 1-nanometer cubes, each with a surface area of 6 square nanometers. Their total surface area would reach 6,000 square meters—roughly the size of a football field. Compared to sand, which is made of particles

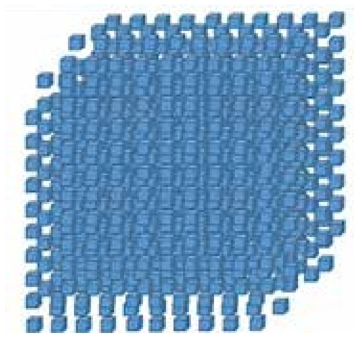


Cube edge length = 1 cm
Surface area = 6 cm^2



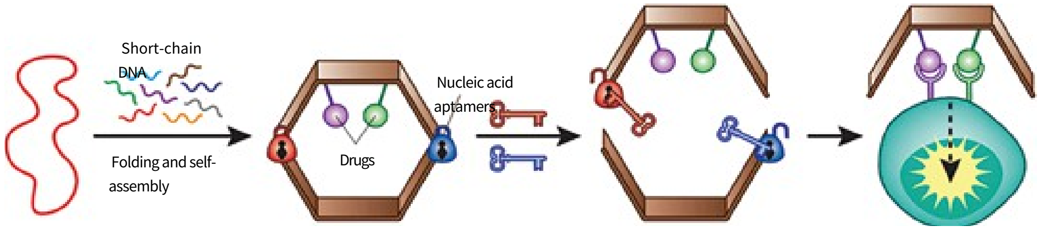
Cube edge length = 0.5 cm
Surface area = 1.5 cm^2

Total surface area = 12 cm^2



Cube edge length = 0.1 cm
Surface area = 0.06 cm^2
Total surface area = 60 cm^2

Nanomaterials possess a large specific surface area (surface area/volume). For example, for the same volume of 1 cubic centimeter, a cube with a side length of 1 cm has a surface area of 6 cm^2. The total surface area of 1,000 millimeter-sized cubes can increase to 60 cm^2.
cm^2. Conversely, 10^{21} nanometer-sized cubes can achieve a surface area equivalent to a football field.



DNA nanorobots can be programmed to activate only when encountering and release the drug only upon reaching the targeted disease site. The nanorobot utilizes DNA origami technology to construct a smart molecular machine within the human body. Through self-assembly, it encapsulates the drug within its internal cavity. Nucleic acid aptamers attached to both ends of the molecular machine "lock" the drug inside. Only upon reaching the designated location and recognizing the specific biomarker does it "unlock," precisely releasing the drug into the tumor cells.

Visible to the naked eye as grains of sand, nanomaterials are composed of individual atoms invisible to the human eye.

Atomic-scale materials possess highly reactive surface atoms that are extremely unstable and readily bond with other atoms. For instance, when metals like gold, silver, or copper are ground to the nanoscale, their original luster disappears, transforming into black nanopowders that barely reflect light. This property can be harnessed in solar energy materials to enhance photoelectric conversion efficiency—a classic example of surface effects in nanomaterials. Other nano-effects, such as the small-size effect, quantum size effect, and quantum tunneling effect, are not discussed here.

Nanotechnology is advancing rapidly, now extending into nearly all scientific disciplines. In biomedicine, nanomedicines (or smart drugs) demonstrate superior efficacy compared to traditional drugs in treating complex diseases like cancer and cardiovascular disorders.

such as cancer and cardiovascular diseases. To date, all drug therapies have been based on molecular-to-molecular reactions. Traditional drugs are single molecules scattered throughout the body's blood and tissues like pepper on a plate, potentially failing to target the actual diseased site effectively. Nanodrugs, however, aggregate these single molecules into particles housed within nanorobots. These robots can be programmed to release drug molecules only upon encountering the targeted disease, much like missiles that ensure mission completion.

In energy applications, the efficiency of splitting water into hydrogen using sunlight is only 1%. However, employing nanocatalysts can increase this efficiency by more than tenfold.

Weight reduction is a top priority in aerospace engineering, and the strength-to-weight ratio of nanomaterials perfectly meets this demand.

Finally, nanomaterials are increasingly permeating our daily lives. Examples include: nano-spun masks with 98% filtration efficiency that can be washed over 100 times; cosmetics made from nanomaterials that offer superior skin protection; sensor components crafted from nanomaterials that sensitively perceive the physical world; and more.

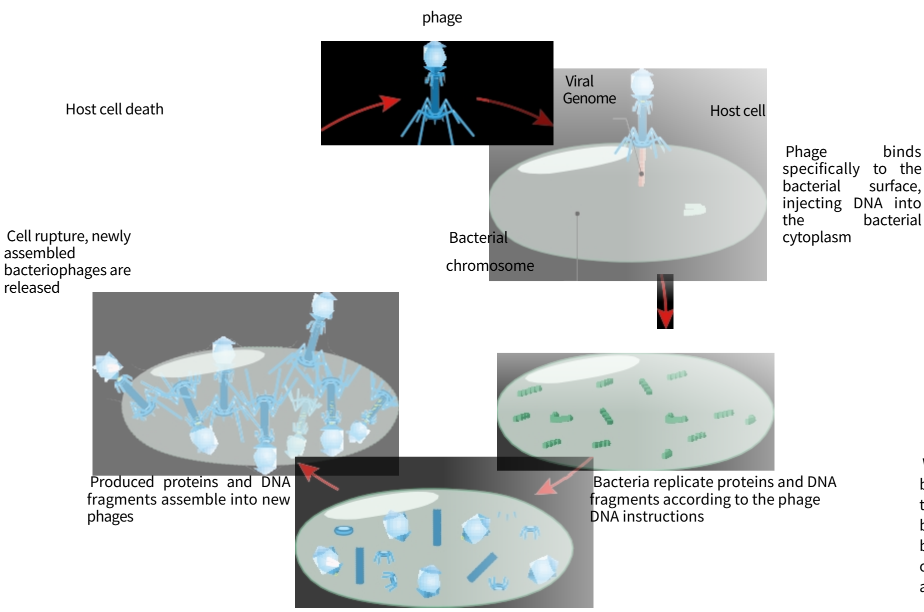
The 72 Transformations: Metamorphosis—Replication

Although we can manufacture nanorobots, individual units are so minuscule they hold little practical value. Mass-producing them manually is impractical, so we emulate nature by enabling nanorobots to replicate themselves.

Each of us began as a single cell. Then cells divided, multiplied, and gathered with their "brothers and sisters." At some point, they became a collective—one with shared thoughts, preferences, and memories belonging to the group rather than any individual cell. That is when true life emerged.

A cell resembles a bustling city, where intricate networks connect diverse factories—like mitochondria producing energy packets (ATP) and ribosomes synthesizing proteins. The nucleus sits at the command center, directing the cell's operations. During self-replication, the nucleus first replicates the genetic material, DNA, distributing copies through the transport network to specific factories. Upon receiving their tasks, these factories begin manufacturing the components and structures needed for new life, ultimately collaborating to assemble an independent cell.

Born 3.8 billion years ago, the bacteriophage is hailed as the oldest nanorobot. Its head, as regular as a diamond, is a perfect icosahedron containing the most primitive genetic material—a DNA double helix. Below the head lies a spiraled tail with flawless geometric structure, while its base features five legs equipped with perfectly geometric walking feet. Scientists estimate the total number of bacteriophages on Earth to be approximately 10^{31} units. The total number of stars currently observed within our observable universe is roughly 10^{28}. This means bacteriophages outnumber the stars in the sky by a factor of 1,000. Bacteriophages are everywhere—on our hands, books, and clothing. Typically, a specific bacteriophage targets particular bacteria as prey, launching a directed attack. Upon locating its target, the walking feet on its tail engage with



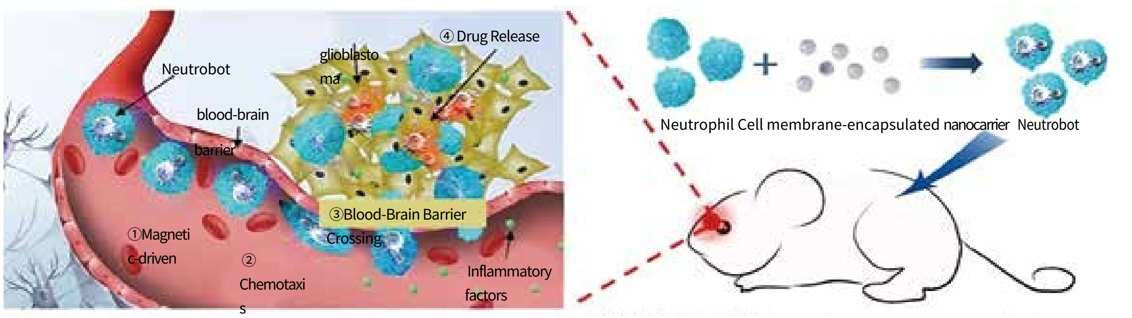
When a bacteriophage infects a bacterium, it injects its DNA into the bacterium's interior, using the bacterium to manufacture more bacteriophages, ultimately causing the bacterium to rupture and release more bacteriophages

The phage's gripping sites—which also serve as markers for recognizing prey—engage with the target. Then, a needle-like structure extends from the tail to inject DNA into the prey's body. Within minutes, the prey becomes controlled by the phage's DNA, beginning to manufacture various components according to the phage's genetic instructions. Finally, the produced proteins and DNA fragments assemble into new phages. Countless identical phages are replicated until the bacterial cell ruptures, releasing a multitude of phages to restart the cycle.

Inspired by nature's replication mechanisms, humans have developed self-replicating technologies for diverse applications. For instance, genetic engineering synthesizes artificial life forms to invent and release novel organisms or chromosomes. Nanotechnology and nanorobotics create nanorobots that clean oil spills and clear vascular debris—operating like computer circuits and theoretically capable of self-assembly and replication akin to computer programs.

Although true nanorobots remain in the research and development phase, prototypes have emerged in laboratories. In 2021, the Micro/Nano Technology Research Center at Harbin Institute of Technology designed a micro-robot based on neutrophils (a type of white blood cell), dubbed the neutrophil robot. Composed of magnetic materials, these robots can navigate biological tissues under magnetic field control. To prevent the immune system from recognizing them as foreign invaders and triggering inflammation, scientists encapsulated the robots within neutrophils. As a vital component of the immune system, neutrophils possess chemotaxis toward inflammatory factors and can freely traverse biological barriers without eliciting immune responses. Thus, driven by dual forces—the guiding pull of an external magnetic field and the granulocyte's innate chemotaxis toward inflammatory factors—the neutrophil robot carries its bulging cargo (multiple drug molecules) aboard the granulocyte's express train. It travels smoothly and unimpeded to the diseased tissue, where it then unleashes its full power to eliminate inflammatory cells (by releasing drugs). In mouse experiments, the neutrophil robot demonstrated the ability to

Researchers designed a micro-robot using magnetic materials and remotely navigated it via a rotating magnetic field. It can freely navigate between the bloodstream and brain in mouse tails, carrying anticancer drugs. After crossing the blood-brain barrier, it travels to tumor sites, precisely releasing drugs to eliminate tumors in glial cells, thereby enhancing drug targeting efficiency. Since it is enveloped by neutrophils, it does not trigger immune responses during migration. After drug release, it is absorbed by the host without harming health.

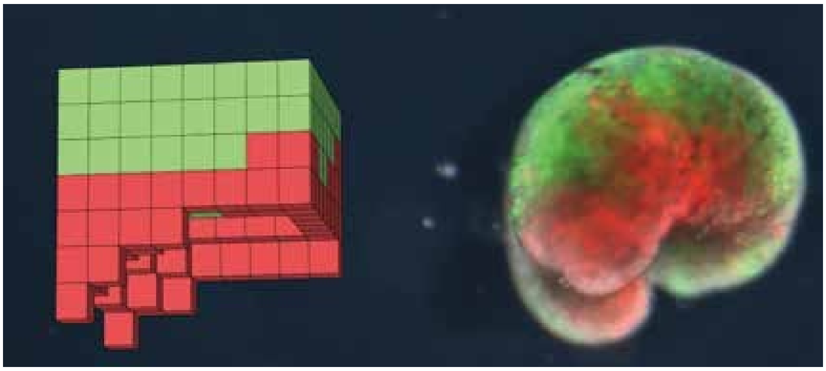


Freely navigating between the tail blood and brain, ultimately successfully treating the mouse's brain tumor.

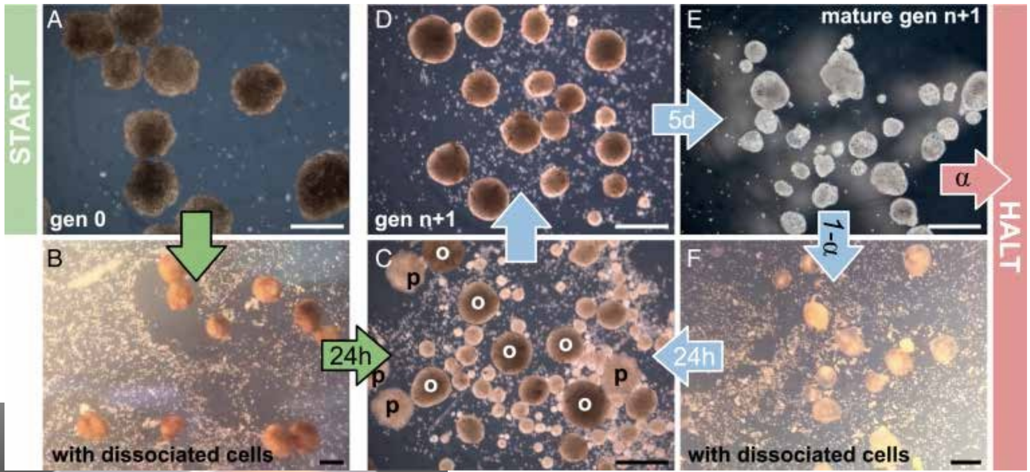
Xenobots

Almost all organisms in nature reproduce by growing within a mother (or host) and then detaching from it. In 2021, a research team from the University of Vermont, Tufts University, and Harvard University discovered an entirely new mode of reproduction. Leveraging this breakthrough, they created the world's first self-reproducing living robot: Xenobots 3.0 (xeno: foreign, alien; bots: robots). Unlike traditional robots with gears or mechanical arms, it resembles a tiny flesh-like mass about 1 millimeter wide (or 1 million nanometers). Moreover, it reproduces by moving rather than growing. More precisely, they do not reproduce by copying genetic material like DNA, as biological organisms do. Instead, they directly source materials from their surroundings and assemble them into the next generation, which inherits the same physical characteristics and replication capabilities as its predecessor. This landmark discovery points to a new research direction for developing more complex self-replicating nanorobots in the future.

Traditional robots—such as vacuum cleaners, kitchen appliances, and factory machinery—are predominantly constructed from metals, plastics, or other synthetic materials. In stark contrast, Xenobots are composed of approximately 2,000 skin and heart muscle cells differentiated from African clawed frog embryonic stem cells. Skin cells provide rigid support, forming the Xenobot's "muscles and skeleton." Heart cells, capable of continuous autonomous contraction and expansion, act as miniature motors driving the Xenobot's movement. Since these cells originate from different embryonic layers, they resist mixing. Instead, a cluster of skin cells tightly adheres to a cluster of heart cells, creating a motile composite cell mass.



A structural configuration of Xenobots: the left image shows a computer simulation, while the right depicts the corresponding physical robot. It is entirely composed of skin cells (green) and cardiomyocytes (red).



Stop

Researchers used extremely fine tools to dissect cultured skin cells or cardiomyocytes and reassemble them under a microscope. They observed that the dissected cells formed spheres of approximately 3,000 cells after being assembled into clusters. After three days, these spheres developed microscopic cilia structures—like tiny oars—enabling them to swim. More intriguingly, when a sufficient number of Xenobots were placed in a culture dish filled with stem cell solution, they

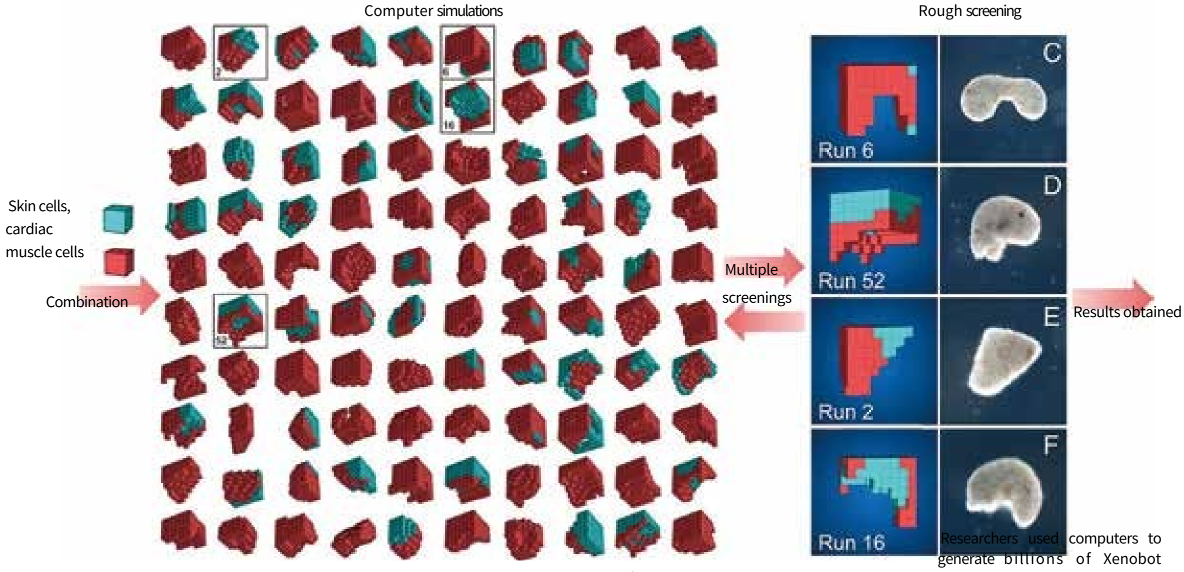
they appeared to engage in organized cooperative work, spontaneously ling and gathering floating stem cells to assemble them into "baby" machines. . Within days, these "infants" mature into new Xenobots that resemble their parent in appearance and movement. These new Xenobots then set out to seek stem cells and create their own "infants," perpetuating the cycle of replication.

The study notes that due to their non-toxic nature and finite lifespan, Xenobots could serve as novel carriers for smart drug delivery or internal surgery, or seek out and digest toxic or useless byproducts—such as collecting microplastics in the ocean. In biomedicine, envision these bio-robots made from a patient's own cells clearing plaque from artery walls, identifying cancers, or pinpointing and controlling disease sites.

Beyond self-replication, researchers also endowed Xenobots with simple memory functions by incorporating fluorescent proteins. When exposed to ultraviolet light at a wavelength of 400 nanometers, these proteins shift from green to red.

From the birth of the first-generation Xenobots in 2020 to the third generation in 2021, their performance and lifespan have significantly improved and extended. Researchers

Xenobot replication process. Cultured skin cells or cardiomyocytes are assembled into spheres (Figure A). After three days, the spheres develop tiny cilia structures. When placed in a culture dish filled with stem cell solution (Figure B), they spontaneously gather floating stem cells (as shown in the inset) and assemble them into "baby" robots (Figures C D). Within days, these "infants" reach the size of their parent and gain the ability to swim independently (Figure E). They then begin seeking stem cells to create their own "infants" perpetuating the replication cycle (Scale bar: 500μm, Credit: Sam Kriegman, et al. PNAS, 2021)



Researchers used computers to generate billions of Xenobot body types. The left image shows 100 results simulated by varying the proportions and combinations of heart and skin cells. Through computational analysis of their force dynamics and trajectories in liquid environments, researchers preliminarily screened structures best meeting design criteria (as shown in the right image). These were then validated through in vitro experiments (Credit: Sam Kriegman, et al. PNAS, 2021).

Using the Deep Green supercomputer at the University of Vermont Supercomputing Center, researchers employed artificial intelligence evolutionary algorithms to simulate billions of different robot shapes, aiming to identify the most suitable form for efficient replication. The supercomputer first randomly generated various cellular combinations and simulated how these Xenobot shapes behaved in culture medium. If a particular shape produced the most offspring, it would stand out and become the blueprint for constructing physical Xenobots. From the spherical appearance of the first generation to the C-shaped appearance of the third generation, Xenobots evolved from producing three generations of offspring to five generations. Their offspring became stronger, moved faster, and their lifespan increased from one day to three to seven days. Simply put, Xenobots are the result of "natural selection"—though this "nature" is not the natural world, but another realm created by computers. While the replication of such life forms raises societal concerns, researchers emphasize that these xenobots are entirely confined to the laboratory, are biodegradable, and can survive no longer than 14 days without nutrient solution. They are easily eliminated, and this technology has been approved by federal, state, and institutional authorities that these alien robots are entirely confined to the laboratory, are biodegradable, and can survive no longer than 14 days without nutrient solutions. They are easily eliminated, and this technology has undergone ethical review at federal, state, and institutional levels in the United States.

Where does the path lead?

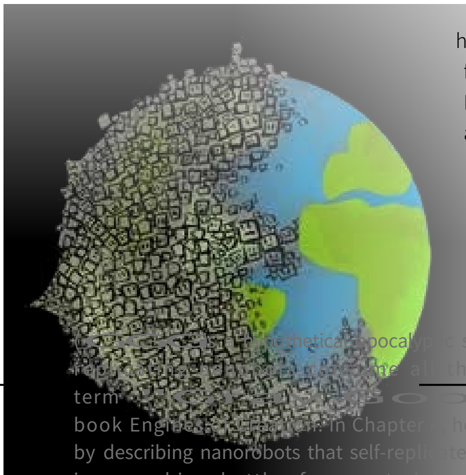
Every new technology emerges amid a mix of wonder and fear, confidence and unease. While people anticipate nanorobots, they also worry about harmful nanomonsters.

From a computer systems engineering perspective, the nanoscale environment in

which nanorobots operate can

Developing software that can adapt to diverse environments while maintaining stability is challenging—it's impossible to have it both ways. Statistically, the more times replication occurs, the higher the error rate. Biologically, random variations in life can lead to unexpected outcomes. This raises a critical concern: What if a random mutation causes nanorobots to replicate uncontrollably? Drexler envisioned runaway self-replicating nanorobots consuming all life-sustaining energy on Earth like " -Goo," potentially destroying the planet in "less than two hours."

The American Journal of Bioethics has also cast a vote of distrust toward future bio- and nanorobots. First, they pose risks of warfare and assassination. 3D printing technology enables garage-scale production of nanorobots at . The accidental or deliberate release of self-replicating robots could devastate ecosystems—for instance, biotic robots might disrupt natural life cycles in oceans. Secondly, unnatural "artificial humans" pose direct threats to humanity's human nature or essence. The legal, moral, ethical, and even existential foundations underpinning human society could face crisis or deconstruction. Robots with artificial neural systems might suddenly develop consciousness and perception, capable of



"Gray Goo"

" Gray Goo" is a hypothetical apocalyptic scenario where uncontrolled swarms of molecularly engineered, self-replicating nanorobots consume all the energy essential for life on Earth to sustain themselves. The term "grey goo" was first used by nanotechnology pioneer Eric Drexler in his 1986 book Engines of Creation. In Chapter , he illustrates the terror of exponential growth and the absence of inherent limits by describing nanorobots that self-replicate using specific raw materials: "Imagine a self-replicating machine immersed in a bottle of raw materials, endlessly copying itself... The first replication takes 1,000 seconds, the second also takes 1,000 seconds... After ten hours, the bottle contains not just 36 self-replicating machines, but 68 billion. Give them one day, and they'll weigh a ton; give them another day, and they'll outweigh Earth; give them four more hours, and they'll outweigh the entire solar system—if the raw material bottle hasn't run dry."

However, Drexler noted that the exponential growth of self-replicating machines is actually constrained by the quantity of raw materials. His original use of "grey goo" was not to suggest nanorobots are grey, but to highlight the distinction between human values of superiority and competitive advantage: "While vast numbers of uncontrolled replicating machines might be neither grey nor gooey, the term "grey goo" actually emphasizes its ability to effortlessly obliterate all life. Other species might be evolutionarily powerful—yet such power holds no meaning against self-replicating machines."

If we recognize the ability to discern good from evil and beauty from ugliness, and if perception and sensation are often considered intrinsic moral attributes of organisms, should we then acknowledge the moral status of such robots and grant them some form of social identity or political rights? If so, when they "die" (e.g., power is cut off), can we "resurrect" them? Reviving a conscious entity raises ethical questions.

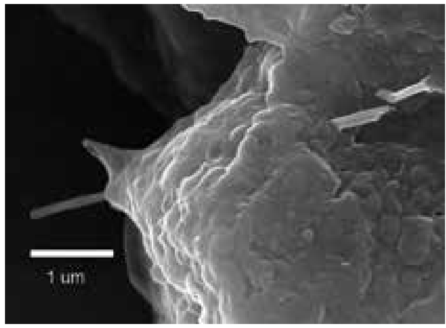
According to the 2006 UNESCO publication Ethics and Politics of Nanotechnology, the most pressing issues in nanotechnology today concern its toxicity and risks to humans and the environment. These are primarily safety and health concerns, not ethical or political ones.

We may already be exposed to nanomaterials in our daily lives to varying degrees, such as through nanoparticle emissions in cooking fumes from open flames and diesel engine exhaust. The minute size of nanomaterials means they are more readily absorbed by the human body than larger particles. For instance, nanoparticles can overload macrophages (cells that engulf and destroy foreign substances, eventually rupturing and triggering immune responses), leading to inflammation and weakening the body's defenses against other pathogens. We urgently need to understand how nanoparticles behave within living organisms to guide daily life and medical practices.

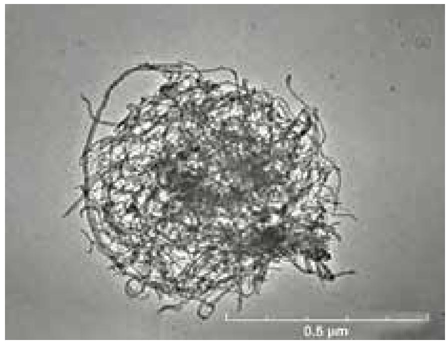
For the environment, the most pressing issue may not be determining whether nanoparticle waste from industry is indeed toxic to ecosystems, but rather establishing new regulations or enforcing existing ones to constrain industries manufacturing or processing these substances. The European Union and the United States have established oversight systems to assess potential hazards and risks associated with nanotechnology. China's National Technical Committee for Nanotechnology Standardization has also successively released a series of nanotechnology and materials standards, such as the 2017 Occupational Health and Safety Guidelines for Nanotechnology, the 2018 "Risk Assessment of Nanomaterials," and the 2020 "Guidelines for Toxicological Screening Methods of Nanomaterials" have all been formally implemented.

Although ethics and politics are not the most pressing issues, "Ethics and Politics of Nanotechnology" offers some scientific perspectives. For instance, it criticizes the "grey fog" theory for falling into the trap of "technological determinism"—the notion that technology develops autonomously without human, societal, or governmental involvement. The "fog" hypothesis lacks experimental scientific support, creating a one-sided warning for the public that actually hinders the effective communication of the precise risks associated with nanoparticles.

Dear readers, as the future pillars of our nation, people, and world, what are your perspectives on the future?



Inhaling nanoparticles may harm our bodies. These particles deposit in the alveolar spaces via the respiratory tract, then enter the bloodstream and migrate to other organs. The image shows scanning electron microscopy of carbon nanotubes piercing alveolar epithelial cells.



We can reduce potential human hazards by improving nanoparticle handling processes. This includes minimizing steps involving powder transfer or opening nanoparticle-containing packaging, as well as employing agitation methods like sonication. The image shows aerosol droplets containing nanoparticles ejected from a vial during ultrasonic processing.

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