

Simulation is a fundamental component of planetary intelligence. This is the conclusion of the infinity mirror project... "Infinity Mirror" is an account of how simulation technologies emerged from the interplay between military strategy, video game development, GPUs, artificial intelligence, medical modeling, and Earth System Science.

Organised as a multi-part research and design project, it begins by arguing that simulations are critical epistemic tools and integrates the capacity for self-representation and feedback into current discussions about what "planetary intelligence" might be.

Witnessing the diffusion of simulation tech within fields such as education and manufacturing, civil engineering and climate adaptation, "Infinity Mirror" anticipates the creation of ever-larger and more complex systems of representation, enshrining corrective loops within the technosphere analogous to those that regulate the biosphere, a maturation of techno-civilisation on Earth that may well be a feature of evolving planets everywhere.

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EDITORIAL

Infinity Mirror explores the evolution of simulation technologies and their role in shaping planetary intelligence. It delves into how simulations, initially developed for military strategy and video games, have become essential tools in climate science and global system modeling. It develops this history in five sections:

I. THE SIMULATION PARADOX

This section examines the dual nature of simulations: while they enhance our understanding and control over complex systems, they also introduce challenges. As simulations grow more intricate, they demand increasing computational resources, raising concerns about sustainability and unintended consequences.

II. PLANETARY INTELLIGENCE

The concept of *planetary intelligence* is introduced, suggesting that collective knowledge and simulations are integral to Earth's self-regulating systems. The idea posits that intelligence emerges not just from individual entities but from the planet's interconnected systems working in harmony.

III. WAR GAMES

This section traces the origins of simulation in military contexts, highlighting how war games have historically been used to predict outcomes and strategize. These practices laid the groundwork for modern simulations, influencing how we model and respond to various scenarios today.

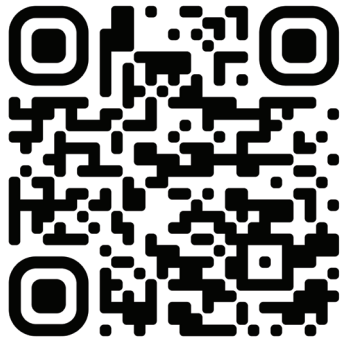
IV. WHOLE EARTH SIMULATION

Focusing on environmental modeling, this part discusses the development of comprehensive simulations that encompass Earth's entire ecosystem. Such models aim to predict climate patterns, ecological changes, and other planetary phenomena, aiding in proactive decision-making.

V. INFINITY MIRROR

The final section reflects on the culmination of simulation technologies, envisioning a future where simulations are so advanced they mirror reality itself. This infinity mirror concept raises philosophical questions about the nature of reality and our reliance on models to interpret the world.

Infinity Mirror project presents a comprehensive narrative on the progression of simulations from tools of warfare to instruments of planetary stewardship, emphasizing their profound impact on our understanding and management of Earth's complex systems.



Simulation is a fundamental component of planetary intelligence. This is the conclusion of the Infinity Mirror project: a history of simulation technology produced by the interplay between military strategy, video games, and earth system science.

During the Anthropocene's critical period (1950–2050), computing devices augmented with graphics processing units (GPUs) became the substrate on which a new kind of spatial intelligence was built, enabling the capacity to forecast, feedback, and modulate behaviors on a variety of scales.

Yet, as the size and complexity of target systems grew—from armies to landscapes and genomes, to the coupled systems of the whole Earth—so too did the sophistication of the hardware required to model them.

Over several decades, a machine was constructed and installed in low Earth orbit, an extraplanetary supercomputer capable of making “predictions born of experience” [1] and facilitating billions of distinct simulations at once.

In hindsight, the need for such a device might appear self-evident, a precondition for the continuation of life. But in the early days of simulation science in the twentieth and twenty-first centuries, it was far from obvious what was being built.

1 THE SIMULATION PARADOX

1.1 FEAR OF THE DOUBLE

Although the understanding of simulations as false or illusory was largely suppressed after World War II, a deep suspicion toward representation has left its mark on both science and art. Literary history abounds with faulty replicas and despicable twins, from the watery reflection of Narcissus to Dr. Jekyll's murderous alter ego and the seductive usurper in Fyodor Dostoevsky's *The Double*. They appear as living specters: likenesses that unearth painful truths for their real-life counterparts leading them to madness, solipsism, and death.

A splintered self is not always a hindrance. In the Tang Dynasty folk tale “The Divided Daughter,” the protagonist defies her parents' wishes by running off to live in the imperial capital with her lover. Five years later, when feelings of guilt drive her home again, the young woman's father explains that his daughter has been bedridden all this while and never left the house. The prodigal daughter enters her former bedroom and the two women become one—grateful for everything an indivisible self could never have experienced. [2]

Such misgivings in Western literature may well be an output of classical Western philosophy, with its tendency to boil over into full-blown existential paranoia. Plato's “Allegory of the Cave” ought not to have been taken literally but has been faithfully upgraded over the centuries—whether in the shape of René Descartes's *Deus deceptor* or the computational simulation of David Chalmers's *Reality+*.

Perhaps a greater understanding of what simulations are and do would decrease the likelihood of future philosophers assuming their imposition from outside. In

1. Frank et al., “Intelligence,” 47–61.
2. The appearance of a frightening imitation is a common trope in cinema. Christopher Nolan's *The Prestige* (2006), Denis Villeneuve's *Enemy* (2013), and Richard Ayoade's *The Double* (2013) weave contemporary concerns about identity, the unconscious, and the limits of perception into classic storylines inspired by Nikolai Gogol, Edgar Allan Poe, Ernst Theodor Amadeus Hoffmann, and others. However, the on-screen inheritor of Platonic–Cartesian skepticism may be the firmly established genre of simulation cinema—most obviously Rainer Werner Fassbinder's *Welt am Draht* (1973), which inspired *The Matrix* (1999), without which it would be hard to imagine *Westworld* (2016–2022) or *Ready Player One* (2018). Each is attuned to the possibilities of inhabitable computer simulations and the philosophy of universal computationism, as popularized in Nick Bostrom's 2003 paper, “Are You Living in a Computer Simulation?” (243–55). The paper assures us “it is not an essential property of consciousness that it is implemented on carbon-based biological neural networks inside a cranium: silicon-based processors inside a computer could in principle do the trick as well.”

Beyond Good and Evil (1866), Friedrich Nietzsche dismissed the theory that an operating system runs beneath our capacity to detect it: “It is, in fact, the worst proved supposition in the world.” Of the simulation hypothesis specifically, Nobel Prize-winning physicist Frank Wilczek soberly asked on Sean Carroll’s *Mindscape* podcast in January 2021: “If this is a simulated world, what is the thing in which it is simulated made out of?”

3. Bogost, *Unit Operations*.
4. Vallverdú, “What Are Simulations?,” 6–15.

1.2 WHAT ARE SIMULATIONS?

Simulations are a tool—a constructive apparatus that is most fruitful in situations where existing knowledge breaks down. More precisely, they are a dynamic reconstruction of a complex process or system which aids the user’s understanding of that system or process. Simulations are not flawed copies of a “more true” reality, but rank among the most effective strategies we have for increasing knowledge about the world. It is the “partitive nature” of simulations, however—the fact that someone must decide what to include and what to ignore—that has led to some anxiety toward them as an epistemic tool. [3]

The terms *model* and *simulation* are often used interchangeably. They are closely linked but are not quite the same. Model, from the Latin *modulus*, meaning “measure,” refers to an “informative representation of an object, person, or system.” [4] Models are “interpreted structures” whose purpose can be folded in with their ontology. It is a common mistake to assume that all models aspire toward verisimilitude, or realistic representation. But by their very nature models must target salient features selected according to the model maker’s purposes.

Simulations are best described as the execution of a single model, or multiple overlapping models, over time. You *build* a model, but you *run* a simulation. Both are ways of measuring, but models target the conceptualization or functional abstraction of real-world systems, whereas simulations are more focused on their implementation. A simulation can be disturbed, idealized, or incrementally transformed in order to record the shifting correspondence between it and the system it aims to represent. Noise and randomness can be introduced to create stochastic simulations with little knowledge of what the outcome will be.

Simulations are a crucial interpretative tool for capturing reality in a shared context. In this way they resemble other cognitive framing technologies as outlined in the table below—distinct categories we might be tempted to rank in terms of usefulness. Our instinctive bias as carbon-based intelligences might lead us to privilege *in vitro* experimentation over *in virtuo* computer simulations, seeing one as material and the other less obviously so. But they are equivalent, even if different. In fact they are often complementary.

In certain fields, a computer simulation is the only possible approach to discovery, such as when studying the origins of the universe, for example, or unpacking the formation of planetary systems from interstellar dust, neither of which can be recreated in a laboratory.

In *Reconstructing Reality* (2014), philosopher Margaret Morrison argues that there is no justification for epistemically privileging the results of experiments over knowledge accessed using idealizations, abstractions, and fictional models. One reason for this is that impossible mathematics can enable new discoveries. An infinite system is essential to explain phase transitions in statistical mechanics, for example. Likewise an infinite population improves results in genetics despite the fact that no such population could exist.

A simpler way to understand the significance of simulations in the modern world is to consider airline pilots. Each pilot is trained in a flight simulator containing software that is far more complex than the code onboard an actual airplane needs to be. Every nine months, pilots return to the airline’s training facilities to ensure their familiarity with the latest procedures, emergency situations, and aircraft systems. These expensive devices are built from physical, mathematical, and computational parts, the three categories into which most simulations can be placed.

1.3 THREE TYPES OF MODEL

John Reber was an amateur musical theater producer and schoolteacher in 1950s’ California who was anxious about the Bay Area’s fresh water supply. Despite a lack of expertise, he developed an ambitious plan to dam up the bay. Reber was no city planner, but he was influential and he knew how to generate funds and popular support. In 1957, fearing that the plan might actually be given the go-ahead, the US Army Corps of Engineers built a hydraulic scale model to test Reber’s plan, complete with pumps that simulated fluid dynamics including tides, currents, and even the salinity barrier where fresh and salt waters met. The model was 1:1000 scale horizontally, 1:100 scale vertically, and replicated the twenty-four tidal cycle just under once every fifteen minutes.

Although Reber died before seeing the results, the model indicated that damming up the San Francisco Bay would cause flooding and structural damage, as well as being

an enormous waste of resources. The Bay Area Model later became a museum: A remarkable example of a concrete or physical model like the many others that have aided scientific experimentation or determined future projects for centuries. [5]

The majority of scientific models fall into one of three categories: concrete, mathematical, or computational. There are also edge cases like “model organisms,” which are easy-to-handle analogs where biochemistry, gene regulation, and behavior is regular across the class under study (as in the use of yeast or *Escherichia coli* in microbiology, or mice as a stand-in for humans in mammal studies). More often than not they conform to one of the three groups. [6]

Examples of mathematical models might include the Lotka–Volterra model of predator–prey dynamics developed to anticipate how fish stocks in the Adriatic Sea would respond to increased fishing activity following World War I. An example of a well-known computational model is economist Thomas Schelling’s segregation model, which used a 51×51 square grid and a random distribution equilibrium to transform even a mild preference toward in-group neighbors into notable segregation even without economic or policy interventions.

Simulations remain closely tied to the purposes for which they were designed. At the same time there are features that commonly recur, such as whether they are stochastic, idealized, or deterministic (i.e., whether randomness, noise, or completeness is intentionally introduced). Specific simulations may be associated with distinct fields, such as Monte Carlo in finance, N-body simulations in astronomy, or reaction diffusion models in biochemistry.

1.4 SIMULATIONS AND SIMULATIONISM

Many simulations are used in search of ground truth, many others intentionally divert us from the truth. These other, parallel simulations may take place in virtual or augmented reality, in the form of game worlds or social simulations. They may take advantage of spectacular three-dimensional (3D) environments or the phenomenological superimposition of spatial computing. But there is no technological precondition for creating simulations capable of reshaping how society understands itself.

There are already thousands of cultural models which actively resist any incursion from fundamental or baseline reality. These closed worlds include everything from dictatorial or theocratic regimes to conspiratorial worldviews, or powerful nostalgias projected on the past. Any suite of aesthetic properties, value judgments, and moral suppositions that allow groups to cohere around a shared purpose—be that a nation, worldview, personality, or brand—runs the risk of fixity: a simulation too brittle to update itself.

This is perhaps the paradox at the heart of simulations. For every cosmological model that directs thought toward a deeper understanding of the universe, there is another in the world ready to distract us from it. Crucially, they most likely run on the same computers, processed using algorithms with a shared ancestry. It’s important to ask how parallel technologies can end up with such wildly different relationships to truth, especially in a technological landscape where simulations themselves become sovereign actors—the basis for human, machine, and planetary intelligences, and a core governance mechanism animating factories, designing cities, and deploying geotechnologies.

2 PLANETARY INTELLIGENCE

2.1 PLANETARY INTELLIGENCE AND AUTOPOIESIS

The Infinity Mirror project aims to illustrate the role of simulation as a fundamental aspect of planetary intelligence—to chronicle its artificialization and emergence from human behaviors in technical form, expanded and ultimately integrated at a planetary scale. Indeed, it was simulations in the form of global climate models that enabled us to foresee the looming crisis from the 1970s onward. Likewise there can be no response to climate change and other existential threats without including new models of Earth’s coupled systems as mechanisms to recognize and halt emerging threats.

It was the Russian Ukrainian mineralogist Vladimir Vernadsky who first argued that the sum of biological activity on Earth (the biosphere) should be considered a geological force with the power to change other systems with which it is inextricably coupled: the hydrosphere, cryosphere, lithosphere, and atmosphere. Later on, Vernadsky added another system—that of “cultural biogeochemical energy”—with equivalent power to bring about changes at a planetary scale.

Vernadsky adopted the term *noosphere* from the French Jesuit priest Pierre Teilhard de Chardin to describe the sum of collective cognition. The concept incorporates pre- and post-technological information processing, meaning it includes everything from organizational interactions among social insects to beavers constructing dams, and news updates spreading across social graphs to artificial neural networks.

5. In the 1760s, French naturalist and encyclopedia-maker Georges-Louis Leclerc, Comte de Buffon, started a series of experiments heating iron balls until they glowed white, then measuring how long they took to cool to room temperature. He didn’t use a thermometer for these experiments, relying instead on touch, yet his results were surprisingly accurate. Next, he heated and cooled different materials including sandstone, glass, and various rocks. He did so hoping to learn the age of Earth. Buffon believed that Earth indeed had a beginning, and it was originally a molten mass too hot for any living creature. It had to cool before it could support life. In 1778, he published *Les époques de la nature*, asserting that Earth was 74,832 years old, a 68,000-year increase on the Biblical chronology that had held since the Middle Ages.
6. In *Simulation and Similarity* (2013), 6, philosopher Michael Weisberg explains: “Roughly speaking, concrete models are physical objects whose physical properties can potentially stand in representational relationships with real-world phenomena. Mathematical models are abstract structures whose properties can potentially stand in relation to mathematical representations of phenomena. Computational models are sets of procedures that can potentially stand in relation to a computational description of the behavior of a system.”

An influential paper published in the *International Journal of Astrobiology* works on the assumption that intelligence is not a property of individuals as conventionally understood, but derives from collective behavior in the biosphere—not something that happens on a planet but to a planet. Astrophysicist Adam Frank, NASA astrobiologist David Grinspoon, and theoretical physicist-turned-astrobiologist Sara Walker, co-authors of this paper, go on to define planetary intelligence as “the acquisition and application of collective knowledge, operating at a planetary scale, which is integrated into the function of coupled planetary systems.” [7] Whether this takes place within biospheres or technospheres, without simulation this would be impossible.

Their paper adapts five possible properties required for a world to show cognitive activity operative across planetary scales. The last of these is autopoiesis—meaning “self-making” of “self-producing”—referring to a system’s capacity to establish “organizational closure” and maintain itself despite fluctuations and perturbations. They emphasize that “life is a process of maintaining an identity *from within*,” but that this unity is never static. The organism must “operationally reconstitute itself. It must continually create the conditions for its own existence via metabolism. If the dynamic falters or stops, the organism dies.”

2.2 MAJOR TRANSITIONS

Here it is useful to schematize the distinction between collective processes in the biosphere that are capable of exerting force on coupled planetary systems and anthropogenic forcing as a result of burning hydrocarbons (part of the general capacity of humans to act collectively and engineer their environment).

The biosphere represents a complex network of feedback loops that use signals such as incoming sunlight, or the abundance of a specific element, to modulate behaviors, curbing effects in service to a steady state. This learned behavior is dependent on knowledge born from many millions of years of trial and error—an evolutionary dynamic that contains and predates biotic life.

In a 2018 paper, Frank and colleagues proposed five classes of planet according to the degree of thermodynamic complexity exhibited in their coupled systems. [8]

Moving up the classes from I to IV, the energy available to do work increases with the addition of an atmosphere—and subsequent *thin* and *thick* biospheres—as disequilibrium between coupled systems rises. A speculative class V planet would be one that contains a technological civilization that has entered into a stable relationship with the other coupled systems of its host world, acting with intention to maintain and develop the biosphere from which it emerged and on which it depends for its continued existence.

In their 2022 influential paper, Frank et al. call this moving up the scale a transition from an “immature technosphere” to a “mature technosphere,” incorporating feedback loops and reducing forcing timescales, much in the way that Earth did when it transitioned from being an immature biosphere during the Archean (with insufficient feedbacks between life and geophysical coupled systems to exert strong co-evolution) to the Proterozoic era, when the biosphere began to exert strong forcing on the planet’s geophysical state, establishing full co-evolution of the entire system. [9]

According to geologist Peter Haff, technospheres refer to the activities of civilizational intelligence, a synthetic corona that metabolizes fossil fuels and includes “communication, transportation, bureaucratic and other systems.”[10] On a planet with an immature technosphere, this activity risks shifting coupled planetary systems into new dynamical states with no capacity to regulate them and guarantee the health of the civilization building the technology. By comparison, a planet with a mature technosphere contains feedback loops intentionally modified to ensure the maximum stable productivity of the full system.

A mature biosphere is more stable than an immature technosphere, yet only a mature technosphere can extend itself far enough in time to become significant to the search for extraterrestrial intelligence. “Contact inequality,” whereby the probability of contact is proportional to the age of the intelligence being detected, makes it likely that exo-civilizations will be older than those carrying out the search. As such we may be able to identify generic features in the evolution of intelligence that will prove relevant to astrobiology and the search for extraterrestrial intelligence. *Long-term* in this context does not refer to a geological era such as the Anthropocene, but rather a new *eon* that could stretch hundreds of millions of years into the future.

2.3 HOW EARTH BECOMES CLASS V

The arrival of a civilization capable of guaranteeing its own continuation is clear evidence for the existence of planetary intelligence. There was some evidence that by the year 2000, Earth was already well on its way. For example, the coordinated global response to chlorofluorocarbon use in the 1990s, or the growth of plane-

7. The use of the planet as the relevant scale for analysis in the context of an astrobiology paper is twofold. First, it enables the abstraction of historical dynamics on Earth that may prove to be generic, a useful benchmark for understanding evolutionary principles elsewhere in the universe. Second, it means recognizing that small tweaks in the DNA of microscopic organisms can cause changes that cascade upward and become significant enough in scale to change the weather. New states are created by upward causation, which in turn constrain and shape behaviors at lower levels. As such, the idea of a planetary boundary is neither a single ultimate region of activity nor a hierarchy of scales in any conventional sense. Instead we have a prismatic spheroid where both less and more are different. For more, see the original paper by Frank et al., “Intelligence,” 47–61.
8. Frank et al., “Anthropocene Generalized,” 503–18. The five classes of planet are an update of astrophysicist Nikolai Kardashev’s energy-harvesting measuring stick, the Kardashev scale, a rubric for classifying intelligent civilizations according to their ability to tap into the supplies of their planet, star, or galaxy of origin. Later adaptations of the Kardashev scale have ranked other features such as capacity to compute, to bounce back from natural disasters, or to engineer at ever smaller scales, from objects to genes and molecules, atoms and nuclei, quarks and leptons, and ultimately space and time.
9. The paper borrows the concept of “evolutionary transitions” from Eörs Szathmáry and John Maynard Smith’s *The Major Transitions in Evolution* (1995), which proposes a series of “changes in the way information is stored and transmitted” to account for an apparent increase in biological complexity in evolutionary lineages.
10. Haff, “Humans and Technology,” 126–36.

tary asteroid defense systems (of which NASA's double asteroid redirection test of deflection in 2022 was an example), might be ranked alongside nuclear arms treaties, vaccine development, and adaptation to natural disasters as examples of nascent planetary intelligence responding almost in tandem with emerging threats from within and without.

The response to anthropogenic climate change needed to be radically quicker than, say, Earth's recovery from an ice house state produced by microorganisms evolving to process trapped carbon and release it. Critically, some of the best models for network environment regulation were to be found in other evolved systems—including the human brain.

Simulations are vital tools for processing semantic information as it flows across the planet's geosphere, biosphere, and technosphere. [11] Much like the information networks of our own brains, they are sites of active inference in which new knowledge is assimilated and made accessible for utilization as part of a constantly shifting array of predictions.

2.4 THREE-DIMENSIONAL PREDICTION ENGINES

As it develops, the human brain constructs an incredibly complex model of the world. This model is the basis for all of our predictions, perceptions, and actions. When attempting risky maneuvers in a flight simulator, for example, a pilot creates new connections in their neocortex, a frame of reference they can call on should they ever need it (outside the simulator) in the future.

Our brains calculate the relative position of our bodies in the environment, but also the relative positions of other objects to each other, all of which is constantly on the move. A similarly spatialized process is at work for higher order concepts such as democracy, space flight, or envy, making thought a kind of movement. In each case, our world model—our expectations about the world—becomes the basis for planning. Comparison with sensory data causes the model to update automatically.

Predictive coding in neuroscience maintains that the reality we experience is built from mental models that we update when our best guesses miss the mark. This is why in functional magnetic resonance imaging, unexpected inputs lead to much higher rates of brain activity. Whether the scale is personal or planetary, *planning is an attempt to resolve ambiguities about the future and minimize errors*. The two are fundamentally linked. As cognitive philosopher Andy Clark has argued: "Minds are not merely what brains do. They are what brains create—distributed cognitive engines spanning brain, body, and world." [12]

The basis for predictive coding emerges in the microcircuitry of cortical columns: the 2.5-cubic millimeter cylinders that comprise the neocortex, the most recently evolved outer layer of the mammalian brain folded up inside the skull like a napkin in a wine glass. The columns consist of groups of neurons. Of the many billions in each human brain, just 2 percent of neurons are active at once. This 2 percent is everything you think and perceive.

Cells within columns are networked vertically, up and down, but also at great distance across the brain or down the spine across the nervous system. Crucially, cortical columns appear to operate the same regardless of which region (visual, touch) they are found, constituting a universal modeling toolkit (language, music, mathematics) that creates predictions. When a pattern of activity is recognized, dendrite spikes raise the voltage in a cell putting it into a predictive state. This is before the cell spikes, ensuring that the predictions we make are not experienced as hallucinations.

Although the precise evolutionary story of the neocortex remains the subject of some debate, neuroscientist and co-inventor of the Palm Pilot Jeff Hawkins argues it may have emerged from an increase in map-creating neurons in the much older hippocampus and entorhinal cortex in mammalian brains. These structures contain *grid cells* whose activity seeks to mirror minute details of their environment. In studies of rats moving through a maze, brain activity remained similar so long as they took the same route. When a new journey path opened up, a new pattern of activity (a new reference frame) was created, like arriving in a new city or entering an unfamiliar house. [13]

2.5 MAP MAKERS

In *A Thousand Brains* (2021), Hawkins argues that "it is as if nature stripped down the hippocampus and entorhinal cortex to a minimal form, made tens of thousands of copies, and arranged them side by side in cortical columns." To become an expert in any domain requires the creation of a highly detailed mental map. Within that map, or simulation, are multiple further simulations that we open a little like hyperlinks on the web.

Cortical columns enact a sensory-motor process according to the region through which sensory data arrive, but knowledge of objects is distributed by its relationship to other reference frames—similar to how neurons use many synapses and a

11. "In living systems, information always carries a semantic aspect—its meaning—even if it is something as simple as the direction of a nutrient gradient in chemo-taxis." Frank et al., "Intelligence," 6.
12. Clark, *Experience Machine*. Simulation technologies that artificialize this dynamic conform to what Richard Dawkins described as an "extended phenotype," extending the output of genes beyond protein synthesis or eye color to the changes they make to their environment.
13. The anecdotal parallel to this line of neuroscientific inquiry would be the "method of loci" or "memory palace," placing objects, words or symbols into a familiar environment, such as one's home, then mentally moving through that environment to recollect the new information. In his book *Moonwalking with Einstein* (2011), journalist Joshua Foer recounts his victory at the 2006 USA Memory Championship at which he memorized fifty-two cards in one minute and forty seconds despite having no real aptitude for remembering (the book opens with him forgetting his keys a year earlier). This suggests that learning new material is made easier by attaching information to an existing reference frame, but also that thinking itself evolves out of sensory-motor interactions between body and world.

network of neurons is never dependent on a single cell. Strokes can knock out multiple cortical columns and the brain will continue to function because it is a complex adaptive system. This is similar to how Adam Frank and colleagues predicted planetary intelligence would most likely be collective (rather than centralized) in nature because of how intelligence appears as a feature of eusocial species like ants, termites, or humans on Earth.

There is a limit to the number of objects a single cortical column can learn, but across the vast network of axons and synaptic terminals the number grows exponentially. Hawkins proposes that we alight on a single perception from the many ghost simulations contained in our brains through a process of voting.

Using its long-range connections, a column broadcasts what it thinks it is observing. Often a column will be uncertain, in which case its neurons will send multiple possibilities at the same time. Simultaneously, the column receives projections from other columns representing their guesses. The most common guesses suppress the least common ones until the entire network settles on one answer. [14]

Given that 90 percent of the neocortex—traditionally considered the seat of intelligence—maintains sub-perceptual processes like breathing or digestion, intelligence may be better understood as predictive monitoring and self-maintenance, making the conventional focus on *problem solving* an extension of this process.

It was in the conspiracy of neurons and brains that intelligence first became aware of itself. Yet it took a long time for theories of how they build and operate a model of the world to emerge, a crucial benchmark in the prehistory of the Infinity Mirror. Much as a child learns a model of the environment—locating possible threats and sources of nourishment—the planet's Anthropocene-era technosphere built many thousands of spatialized models, some critical, others less so, in the form of computer simulations. And just as with children, the ability to build those models within the twin arenas of competition and play, dynamics which would prove crucial to the character and function of the Infinity Mirror.

3 WAR GAMES

3.1 ALL BUT WAR IS SIMULATION

Conflict simulations have been in use since violence between humans first metastasized into war. The games chess and Go, for example, were both inspired by military simulations. However, the first victory in battle thought to be related to extensive simulation training was linked to the strategy board game Kriegsspiel—from the German meaning “war-game”—developed in 1811 for the new officer class of the Prussian Army.

Kriegsspiel does not exist to generate usable data but to train generals in a variety of hypothetical situations, enabling them to better analyze, interpret, and make decisions during battle. Although the game was offered for sale in France and Russia, nobody outside Germany took much interest until the Prussian Army's decisive victory in the Franco-Prussian War (1870–71), despite having no clear advantage in terms of munitions, soldiers, or experience. Instead, it was their cadre of officers that were praised: a generation of strategists raised with tabular calculations on a synthetic battlefield. [15]

In Kriegsspiel, outcomes are decided using calculation tables. Various mathematical procedures have been devised to predict everything from the effect of morale on outcomes to supply chain management. Two of the best-known procedures are Lanchester's Linear Law and Square Law formulated by the British engineer Frederick Lanchester in 1914. The Square Law is often known as “the attrition model” and suggests that the power of a modern military force is proportional to the square of its number of units (the Linear Law meanwhile was applied to pre-industrial combat using spears rather than long-range weapons). A later update was the Salvo Model, developed to represent naval combat as a series of salvos of missiles exchanged between opposing fleets. [16]

Throughout the 1900s, a greater number of variables—political, environmental, energetic—were incorporated into military simulations. In the United States, simulation practice and technology became enmeshed with state security and geopolitics, evolving in tandem with the development of a material substrate on which the necessary computations for predicting outcomes would be run: transistors and semiconductors. [17]

A permanent wargaming facility was created at the Pentagon in 1954 under the motto “All but war is simulation,” attributed to seventeenth-century samurai-philosopher Miyamoto Musashi who emphasized mental preparation and visualization in advance of combat. The American general Douglas MacArthur added his own spin, writing that “in no other profession are the penalties for employing untrained personnel so appalling or so irrevocable as in the military.” [18]

14. Hawkins, *A Thousand Brains*, 101.

15. IMBUID001—TABLES AND MATRICES: Each “IMBUID” represents an essential precursor to the Infinity Mirror, beginning here in the early days of simulation technology. In the case of Kriegsspiel, a set table is used to calculate combat outcomes. The game's map features different types of terrain—forests, mountains, rivers—each of which influence the effectiveness of a battalion. A unit's artillery, strengths, and relative position are disturbed by rolling dice, introducing a stochastic element to mimic the uncertainty of war. The game's umpire maintains a delay between orders being given and their implementation, recreating the communication issues of nineteenth-century warfare. In a sense, the umpire represents the “human computer” of the age: employed to carry out numerical procedures without deviating; producing and then working with mathematical tables for the insurance industry, agriculture, science, industry, and government. In the Netherlands, a (human-run) computer simulation was used to predict the effects of building the Afsluitdijk between 1927 and 1932. The majority of calculations related to the Manhattan project were carried out by uncredited “computers.”

16. IMBUID002—MATHEMATICAL FORMULAS: Calculations that approximate in numbers, from first principles, the behavior of objects, matter, and agents, are the foundation of the study of physics. They are not representations of any deeper reality, however, but extensions of intelligence's capacity to know its environment, no less real than any other type of thought.

17. IMBUID003—TRANSISTORS: The first Turing-complete, programmable electronic Numerical Integrator and Computer (ENIAC) was finished in 1945. The 27-ton machine was intended to calculate ballistic trajectories at far higher resolution than was possible using tables and human computers, though its actual first program simulated the potential for a fusion-powered, thermonuclear bomb. The ENIAC's vacuum tubes and crystal diodes were soon outpaced by the advent of point-contact, metal-oxide semiconductor field-effect transistor (silicon oxidation) and mesa transistor, which involved covering a block of germanium—another semiconductor material—with a drop of wax. The engineer Jay Lathrop, then with the US Army's Diamond Ordnance Fuze Laboratories in the 1950s, needed a transistor that would fit inside a mortar shell. The wax method was difficult to miniaturize so Lathrop and lab partner James Nall devised a method that involved turning microscope optics upside down. As Chris Miller, author of *Chip War* (2023), writes in Miller, “Chip Patterning Machines”:

Lathrop had spent years looking through microscopes to make some thing small look bigger. As he puzzled over how to miniaturize transistors, he and Nall wondered whether microscope optics turned upside down could let something big—a pattern for a transistor—be miniaturized. To find out, they covered a piece of germanium material with a type of chemical called a photoresist, which they acquired from Eastman Kodak, the camera company. Light reacts with photoresist, making it either harder or weaker. Lathrop took advantage of this feature and created a “mask” in the shape of a mesa, placing it on the microscope with upside-down optics. Light that passed through holes in the mask was shrunk by the microscope's lens and projected onto the photoresist chemicals. Where the light struck, the chemicals hardened. Where light was blocked by the mask, they could be washed away, leaving a precise, miniature mesa of germanium. A way to manufacture miniaturized transistors had been found.

The new process, photolithography, was patented in 1957. Nall was hired to work at Fairchild Semiconductors by Robert Noyce, who later went on to found Intel with Gordon Moore, and used lenses for the company's photolithography program bought in a San Francisco camera shop. This was the innovation that enabled chip fabricators to keep pace with the prediction that the number of transistors in an integrated circuit would double every two years, also known as Moore's Law.

18. PEO STRI, “History.”

The longest-standing pact between services of the US military is a 1950 agreement between the army and the navy about sharing training devices. In 1966, the agencies responsible for training soldiers moved to Orlando, Florida, where they introduced a synthetic flight training system for the Bell UH1 “Huey” helicopter—the workhorse of the air cavalry during the Vietnam War. [19] Around the same time the Naval Training Device Center introduced the multiple integrated laser engagement system (MILES), which used lasers and blank cartridges to enhance the realism of training and remained in constant use until the 2020s. The technology was not limited to the military, however. A similar system was released as a set of phaser guns by games manufacturer Milton Bradley to coincide with the release of *Star Trek: The Motion Picture* (1979), creating the market for recreational laser tag.

3.2 AMERICA’S ARMY AND UNREAL ENGINE

The production of military simulations gradually opened up to civilian researchers and private institutions. RAND Corporation, Harvard University, the National Defense University, and Massachusetts Institute of Technology each ran simulations for the Pentagon, which included modeling the Vietnam War, the fall of the Shah of Iran, and tensions between India, Pakistan, and China. In 1998, the US Army established a contract with the University of Southern California’s Institute for Creative Technologies in Los Angeles. The early success of RAND Corporation was connected to Hollywood by way of Herman Kahn’s “screenplay scenarios” which described how a nuclear exchange between the great powers might play out in qualitative as well as quantitative terms. The USC contract signified a desire to share technology between the entertainment world and the military, a pact that would be continued in the games industry.

The US Army and software company Epic Games worked together for eight years to produce the second generation of Epic Games’s graphics engine Unreal. The engine was launched along with the game it was designed to build: *America’s Army* (2002), a first-person tactical shooting game that provided a virtual experience of soldier training and deployment, and was designed at the Modeling Virtual Environments and Simulation Institute at the Naval Postgraduate School in Monterey, California.

The game was commissioned by Colonel Casey Wardynski, director of the Office of Economic and Manpower Analysis at West Point, New York, who told the *New York Times* its original aim was to cut one of the army’s biggest expenses—recruitment: “If the game draws 300 to 400 recruits, it will have been worth the cost.”

A 2008 study from the Massachusetts Institute of Technology found that “30 percent of all Americans ages 16 to 24 [years] had a more positive impression of the Army because of the game” and, even more surprisingly, “the game had more impact on recruits than all other forms of Army advertising combined.” [20] Counter to expectations, the game was a success with civilians, too, described as the “biggest surprise of the year” by IGN. [21] It was the first overt use of a video game as a recruitment and propaganda tool. [22]

After the invasions of Iraq and Afghanistan, training became more field-based. The motto became “train as you fight,” emphasizing the need to model complex urban and rural terrain to wage war against non-conventional armies. In 2007, the various commercial, military, and academic partners in Florida formally integrated as Team Orlando, presiding over an industry then worth \$4.8 billion. Orlando became home to the National Center for Simulation. It is also the home of the Interservice/Industry Training, Simulation and Education Conference (I/ITSEC), probably the largest simulation technology convention, where America advertises its innovations to the world with other NATO members as its primary customers.

In 2010, the US Air Force Research Laboratory built what was then the thirty-third largest supercomputer in the world by combining 1,760 Sony PlayStation 3s. The Condor Cluster was used for radar enhancement, pattern recognition, satellite imagery processing, and artificial intelligence research, and was the fastest interactive computer in the entire US Department of Defense for a time.

No combination of later consoles was able to rival the world’s fastest supercomputers, yet each progressive generation of video game consoles has forced innovation in the field. They did this consistently through huge economies of scale and manufacturing subsidies offered by console producers assuming software purchases and percentages of in-game economies would make up for early investment. Yet it was the arms race between console makers and chip designers, fueled by the public’s willingness to pay for improved graphics, that led to the improvements necessary to overcome various bottlenecks and dead ends across the military, science, and industry. This was the era of the GPU: a unique computational architecture that began a steep upward curve for simulation in all areas of life.

3.3 ORIGINS OF THE GPU

One of the first personal computers (PCs) to escape the laboratory and enter into mass production was the Datapoint 2200, which integrated Intel’s 8008 central processing unit (CPU). Intel’s previous logic chip, the 4004 CPU was the world’s

19. IMBULD004—HYBRID SYSTEMS: The first electronic flight simulator was built by Edwin Link in 1929, a chunky blue aircraft frame with an engine underneath that used pneumatic bellows to control pitch and roll and a small motor-driven device to produce turbulence. Link built the “Link Trainer” because his father, a piano maker, could not afford flight school for his son, yet the high number of casualties due to pilot error at the time led the US Air Corps to buy six of the devices for \$3,500 each. Many of the pilots heading into World War II were trained on them. The first computer image generation systems for simulation were produced by General Electric for the space program. Early versions produced a patterned “ground plane” image while later systems were able to generate images of 3D objects, enabling continuous viewing of 180 degrees. The interplay of calculated scenery in a loop with the onboard instruments and the human between them represents a specific type of hybrid simulation that incorporates physical or “concrete” testing features with computer modeling, and in this case a human-in-the-loop. For more, see the presentation “Brief History of Flight Simulation” by Ray L. Page, a former manager at Qantas.

20. Ederly et al., “Changing the Game,” 141.

21. Flatlife, “Evolution of Unreal Engine [1995-2023].”

22. *America’s Army* inspired tactics that soon became widespread, from crowd-sourcing stock market picks to recruitment for air traffic controllers (Federal Aviation Administration, “Level Up Your Career”). The game incorporated real-world data based on the latest armaments, vehicles, medical training (though this module was optional), and even set up disciplinary protocols for poor behavior. It cost \$7 million from a recruitment budget of \$3 billion and was continually developed with an additional \$3 million every year until the series was discontinued in 2022. According to Colonel Wardynski, the game generated interest from other agencies, which resulted in the development of a training version for internal government use only. In a 2005 blog post, Scott Miller, the game developer and publisher who created *Duke Nukem* in 1991 and worked on *America’s Army* in the early 2000s, wrote about furious disagreements and a run of resignations after the moonshot project turned out to be a runaway success and its history was gradually rewritten:

When the project was just a fly-by-night rogue mission, no one paid much attention to it. Once the Army figured out that the game was the single most successful marketing campaign they’d ever launched (at 1/3rd of 1% of their annual advertising budget), we suddenly came under a very big microscope . . . The Army is basically clueless when it comes to making games and they don’t know how to treat people, especially game developers. They had an A-level team, but I honestly don’t see them building another one (particularly since they weren’t the ones who built the first one). It’ll be interesting to watch what happens though. Essentially, there was a magic couple of years there where two totally alien cultures came together to do something cool.

first commercially produced microprocessor, commissioned by the Japanese office devices firm Basicom for use in electronic calculators. [23] Although the idea of a chip explicitly dedicated to computer graphics was popularized by the launch of NVIDIA's GeForce 256 in 1999—with the term itself reaching mainstream consciousness thanks to its use in relation to the original PlayStation five years before that—NVIDIA's frequent claim that theirs was the first specialized graphics accelerator is technically inaccurate.

The first playable computer games, *Bertie the Brain* (1950), *Tennis for Two* (1958), and *Space War* (1962), ran on systems that were custom-built. In the same way, arcade machine games such as *Computer Space* (1971), *Pong* (1972), and later *Space Invaders* (1978) housed their hardware in tall fiberglass cabinets and used video controllers hard-coded to output visuals for each specific game.

Like a gallery in any arcade, this was a demonstration of what was and could be possible, even if private ownership of such devices was beyond the reach of most households. The first home games consoles—the Magnavox Odyssey (1972) and Atari 2600 (1977)—appeared at a time when computers were still extremely expensive. Although the history gets a little difficult to parse, no home console seems to have had a purpose-built programmable graphics card until Nintendo's Famicom in 1983. [24]

A GPU is a computer chip with a variety of hardware-accelerated 3D rendering features, but in the early years the term GPU was more a change in marketing than any real difference from existing CPUs. The Commodore Amiga, released to the mass market in 1986, offloaded image processing to the processor TMS34010, developed by Texas Instruments in 1986. But it wasn't until intuitive graphical user interfaces such as Windows became popular that what we think of as GPUs today began to speciate and develop on a separate path.

That same year the Canadian company Array Technologies, Inc. (ATI) launched its Wonder series of video card add-ons for IBM PCs, which supported multiple displays and enabled users to switch resolutions. Yet, they still relied on the system's CPU for many core processing tasks. In the early 1990s, application programming interfaces like OpenGL (1992) and DirectX (1995) enabled programmers to write code for different graphics adapters, creating with it a standard software platform that could be used by games studios. CD-ROMs enabled greater data storage, and two games, *Virtua Racing* (1992) and *Doom* (1993), were among the standouts that pioneered 3D (or at least 2.5D) graphics for PC gamers, much as *Sonic the Hedgehog* (1991) and *Street Fighter 2* (1991) had done on the Sega Genesis and Super Nintendo did with the use of parallax scrolling, with a much richer color pallet and light-related techniques such as shadows.

By the time the original PlayStation was released in 1995, consumer PC gaming was going through a slump with graphics cards such as the S3 ViRGE jokingly referred to by gamers as a "graphics decelerator." The runaway success of Sony's console lit a fire that spread through the hardware market. The 3dfx Voodoo by San Jose's 3dfx Interactive, Inc., released in 1996, was the first to support a multi-GPU setup, a signal that maximizing resolution and frame rate by any means necessary would become holy grails for the industry.

3.4 GPUS IN ASCENDANCE

In 1999 NVIDIA released the first GPU in its GeForce series for domestic PC gaming. GeForce 256 was capable of processing complex visuals that included advanced lighting and rendering of individual pixels, though it was only with the release of GeForce 2 (NV15) in 2000 that game developers were able to catch up and make use of what NVIDIA co-founder Jensen Huang had hailed "the single largest chip ever built."

In 2002, 3dfx Interactive, Inc., went bankrupt after attempting the notoriously difficult process of fabricating its own chips, and was acquired by the "fabless" NVIDIA, leaving ATI and NVIDIA as the two most prominent companies in the field. To differentiate their product from that of their southern rival, Toronto-based ATI used the term "visual processing unit" and launched its rival to GeForce, the Radeon series, in 2000.

The launch of PlayStation 2 in 2000 and the Xbox in 2001 introduced standard definition, a resolution of 480 pixels, to home consoles, but the febrile competition between NVIDIA and ATI (who were acquired by Advanced Micro Devices, Inc., the creators of Athlon and Opteron processors, for around \$5.4 billion in 2006) meant that by the end of the first decade of the 2000s, PC gaming had comfortably dwarfed the next generation of consoles. By this point they were regularly sustaining 1,080 pixels, high-definition resolution at frame rates above 60 frames per second.

In 2006, NVIDIA released GeForce 8800GTX: an immense, energy-hungry card with 681 million transistors, a three-way linkable interface for the most ambitious gamers, and a core clock rate of 575 megahertz, which was faster than the CPUs it was commonly paired with. [25] A crossover moment had arrived.

23. IMBUID005—INTEL 4004: The first microprocessor, the 4-bit Intel 4004 CPU, was released to the market in 1971. It had been an under-resourced side project at Intel, whose primary concern at the time was producing memory chips. The company lacked specialists capable of patterning the logic gates to be imprinted on silicon. In the end they hired Italian-American engineer Federico Faggin who left his initials, "F. F.," on the design, an artist's signature transferred into mass production.

24. IMBUID006—PICTURE PROCESSING UNIT: The Japanese electronics giant Ricoh developed what it described as a "video co-processor" in the early 1980s and named it the picture processing unit (PPU), later incorporated in Nintendo's Famicom and the 1985 Nintendo Entertainment System. Up until that point the entire command center had been the CPU—essentially the brain of the machine, the intellectual property-controlled and most expensive part of the product. The major realization for Nintendo was that their system didn't need to be a universal machine that could run any kind of software. Nobody was planning to run payroll or inventory management on it. The device was to be used for gaming and gaming alone, meaning they could pair a cheaper CPU with a dedicated parallel chip for processing the background scenery and sprites (moving characters), which it did with the 8-bit, 256x240 pixel PPU.

25. IMBUID007—GEFORCE 8800GTX: The 128 processing streams (or cores) inside NVIDIA's GeForce 8800GTX allowed graphical tasks to be parallelized at greater efficiency than had been possible before. This enabled greater and more immersive gameplay but also opened the door to general-purpose GPU computing using graphics cards. A new paradigm in simulation capacity had emerged to support the insatiable hunger for better graphics and in-game physics, and was gradually appreciated and absorbed into other fields, mostly during the 2010s. Gaming produced the core technology behind complex modeling, advanced plasma physics, and machine learning, but also Bitcoin mining. In the early 2020s, the bull market and subsequent crash of cryptocurrencies, the expansion of remote work, factory shutdowns across Asia, and PC gamers trapped indoors due to the COVID-19 pandemic produced a worldwide shortage in what we might think of as a "simulation crisis." It meant the widespread understanding that an expanding virtual realm is not without cost—the energy and resources required to keep these worlds operational, but also the immense up-front investment to develop and manufacture the hardware on which they run.

After the exponential growth of resolution and frame rates in the 2010s, GPU specs began to plateau. The jump from a resolution of 1,080 to 4,000 pixels, for instance, is a 400 percent leap resulting in computational and energetic demands that were unjustifiable. Instead, in the 2010s, the same companies worked on software enhancements for the way lighting dynamics are calculated. They used deep learning to upscale resolution, improving visual output without requiring additional power or a quicker frame rate, pushing chip architecture towards diversification once again. [26]

The most popular NVIDIA cards of the early 2020s were 2021's RTX3090, marketed as the world's first 8,000-pixel GPU, and 2023's RTX4090. They each contain a distinct core dedicated to ray tracing and another for deep-learning super sampling that uses AI to upscale resolution. Advances in machine learning throughout the 2010s enabled chips that can predict what we want to see, which were in turn made possible by targeted AI research using GPUs originally designed for gaming. Generative AI and new hardware that was capable of running increasingly large models spread in tandem, transforming everything from how airplanes and ocean liners are designed, to scientific simulations of fusion reactions and cosmological models that demonstrate how galaxies "breathe in" gasses to create stars then let them fall away after those stars die. The ability to model complex, dynamic environments opened new possibilities for scientific knowledge but also raised the bar for training soldiers in the theatres of war. [27]

3.5 VIRTUAL BATTLE SPACE

The Czech games studio Bohemia Interactive was founded by brothers Marek and Ondřej Španěl under its original name, Suma, in 1985. The duo had developed an obsession with computers after Marek bought a Texas Instruments TI-99/4A in the early 1980s and released a hovercraft-based military simulator called *Gravon: Real Virtuality* in 1995.

After various dead ends, the studio found success with *Operation Flashpoint: Cold War Crisis* in 2001, a tactical shooting game set on a fictional archipelago whose islands were divided between the Soviet Union and the United States. The game sought to outdo competitors in terms of realism by 3D-scanning guns and even modeling individual eyeballs. It caught the attention of the US Army who began using a modded version of the game called *DARWARS Ambush!* to train soldiers—supported by US Defense Advanced Research Projects Agency funding.

Bohemia would later set up a special division called Bohemia Interactive Simulations (BISim) to cater to military training and simulation exclusively. In 2001 the studio signed an exclusive contract with the US Marines to develop the first edition of their *Virtual Battle Space* (VBS) series. Where a game like *Call of Duty* or *Counterstrike* might hone a player's motor skills and reaction times, VBS incorporated the latest ordnance, bringing game controls into alignment with existing weaponry. Deployed in enormous battle simulation centers in the US and overseas, soldiers sat side by side in monitor-filled rooms to practice the techniques, procedures, and outcomes they might encounter in the field. Much like Kriegsspiel it was an exercise in collective cognition enabled by simulation, establishing useful reference frames and teaching groups of humans how to think.

VBS3 became the entire army's "game for training" when it was released in 2014. Meanwhile, Bohemia Interactive continued to create games for civilian use. In 2012, the company fell into financial difficulties after two of the studio's staff, Martin Pezlar and Ivan Buchta, were arrested on suspicion of espionage and held for 129 days on the Greek island of Lemnos after they were caught taking photographs of military installations. If convicted, Pezlar and Buchta faced a twenty-year sentence, ruining morale at Bohemia and overshadowing the launch of *Carrier Command: Gaea Mission*, the studio's latest game. In the end, then Czech president Václav Klaus stepped in and Bohemia encouraged gamers to petition the Greek government, both of which contributed to their eventual release.

3.6 ONE WORLD TERRAIN

After the occupations of Iraq and Afghanistan, the US Army, whose capital injections had rescued Bohemia Interactive more than once, stressed the need to improve close combat training on the front line—which accounted for just 4 percent of all personnel but where 90 percent of total casualties occurred. The US's 2018 National Defense Strategy included a commitment "to provide a cognitive, collective, multi-echelon training and mission rehearsal capability" and combine "virtual, constructive and gaming training environments into a single Synthetic Training Environment (STE)." [28] The commitment was both inspired by and an accelerator of a game studio culture increasingly devoted to generating large open worlds that more fully embraced the firepower provided by banks of next generation GPUs.

Bohemia set to work on a specific aspect of the mission known as One World Terrain, which aspired to create "a realistic, common, accessible and automated 3D terrain data set for simulation and, potentially, mission command and intelligence systems, to conduct collective training, mission rehearsal and execution" that could

26. Ray tracing is a means of calculating light transport plotted across a grid system whose history dates back to the German draftsman Albrecht Dürer. The necessary computations can be expensive, which is why NVIDIA's RTX (the RT is for "ray tracing") GPU features dedicated ray tracing cores. Unreal Engine 5, released in 2020, incorporates Lumen, a dynamic global illumination and reflections system designed for next-generation consoles based on ray tracing to produce photorealistic effects. Deep-learning super sampling, meanwhile, uses a dedicated deep-learning chip to up-scale resolution while only rendering them at a fraction of the resolution perceived by the viewer.

27. In *Reconstructing Reality*, Morrison uses the example of the Large Hadron Collider and the discovery of the long-theorized Higgs particle in Peter Higgs's lifetime to explain how simulations contribute to experimental knowledge. She notes that the detected five-sigma signal (a result with a 0.00003 percent likelihood of being a statistical fluctuation) could only have been made through the use of simulation data—never mind the vast number of simulations that would have been required to produce the machine itself.

28. PEO STRI, "History."

leverage “game-streaming technologies enabled by new advances in fiber optic and 5G wireless networks.” [29] The result was *VBS4*, a step change in the series described by Bohemia as “a whole-earth virtual desktop trainer and simulation host that allows you to create and run any imaginable military training scenario,” [30] released to the United States and allied military customers at the start of 2020.

VBS4 is more of a game engine than a game. It was specifically designed for military simulation and training. It simulates the whole planet, opening with a giant blue-green orb that can be manipulated from space and altered down to individual patches of grass. It provides users a relatively straightforward interface with which to build battle spaces and to integrate terrain data “from any conceivable source.” In a 2019 interview with *PCMag*, Australian Army veteran and chief commercial officer of BLSim, Peter Morrison, described how the system incorporates drone-collected 3D data: “The military can fly a drone at a low level, and using photogrammetry, a highly realistic 3D model of a huge area can be constructed. Our users can quickly pull that data into the game and use it as the basis of training.” [31]

Trainees inhabit avatars in the simulation that they access either at their desktop or using devices such as headsets, vehicle cockpit simulators, advanced weapons simulators, and parachute harnesses. Senior military figures use mission planning tools and deploy enemy soldiers to test and assess tactics—much as the Prussian Army had done while playing *Kriegsspiel* 300 years before. What was so obviously different was the scale and resolution of these operations: from a handful of calculations to a simulation that aimed to stand in for the globe and to grant users video game-style controls over it.

In 2022, BLSim was acquired by British arms and aerospace manufacturer BAE Systems for \$200 million. In the press release accompanying the acquisition [32], BAE Systems noted that the global spend on military training simulation environments and related services was expected to surpass \$11 billion each year. *VBS4* is accessible through the cloud, enabling troops on deployment to simulate conditions in the next valley over by inputting tomorrow’s weather.

As with previous innovations, like MILES, no sooner is a technology unveiled it quickly diffuses throughout the economy. The overlap between physics engines, collision detection, scene graphing, and network structure developed in tandem with (and cannot be separated from) revelations from the field of artificial intelligence. Game engines built to engineer open worlds and graphics accelerators refined by fierce industrial competition led to significant breakthroughs that had no obvious connection to defense—in manufacturing, biotech, and training AIs.

By the start of the 2020s, the very same software platforms were being used to train autonomous vehicles, to plan cities and update climate prediction methodologies that hadn’t substantially changed since the 1970s. Software simulations that emerged from military applications became integral to understanding and predicting the weather, both of which produced models of agents and environments later abstracted and universalized as the Infinity Mirror grew. It is rare for a technology to find its ultimate application on the first go. Simulations are no exception.

4 WHOLE EARTH SIMULATION

4.1 APOLLO 13 AND DIGITAL TWINS

More than fifty years after Stewart Brand petitioned NASA to see a photograph of Earth from space, a handful of new projects were conceived to create planetary digital twins. Brand’s hope was that the photograph would raise planetary consciousness and direct it toward a threatened biosphere. While many claim he was successful, Brand himself expressed ambivalence. Half a century later, the fanfare around complex, dynamic simulations of the whole Earth suggested these could succeed in ways a static image could not.

The term *digital twin* was coined by NASA in 2010, but the organization has retrofitted an origin story dating back to the 1950s and 1960s, when replicas of early space capsules were used for training and during space flights, mirroring change as they were communicated—with a slight delay—from astronauts in orbit. When the oxygen tank on Apollo 13’s service module blew out in April 1970, engineers in Houston, Texas, worked across fifteen separate simulation devices to figure out a way to save the crew. Ultimately, they found a way to reconfigure the lunar lander so that its oxygen supply would last long enough to return three humans to Earth.

Digital twins are bespoke, dynamically evolving systems composed of three parts: a physical object or system, a computational model of that object or system, and an equally important communication channel to connect them. The physical and computational models are recursive: input to one alters the other. In some cases, digital twins capture the underlying physics of existing systems. In others, the twin might be based on a prototype, meaning it can provide feedback as the product is refined. Conversely, the twin itself can serve as a prototype before anything concrete is built.

Digital twins proved highly useful in manufacturing. Aircraft engines, trains, offshore oil platforms, cars, freight vessels and wind turbines could all be designed

29. PEO STRI, “One World Terrain.”

30. Bohemia Interactive, “VBS4.”

31. In the same interview, Morrison described some of the work partner militaries had been doing to simulate future battle spaces, including a “snake robot” for the Australian Defence Force, who started conducting trials using the VBS series since 2003: “It was a robot snake that laid explosive devices, and each device was a part of the snake” (for the full interview, see Stuart, “How Simulation Games Prepare,” 2019).

32. BAE Systems, “BAE Systems Completes Acquisition.”

and tested digitally before being put into production, and their ongoing performance could be monitored and understood. Not only the end product but also the assembly line on which it was produced was modeled. In this way, should an issue emerge after the product is released, it becomes much easier to use artificial intelligence to assess the many possible remedies—product recall, process alteration, use of new materials, and so forth—to minimize response times and improve cost-efficiency and safety.

As the worlds of augmented and virtual realities expanded, the interplay between non-digital objects and their virtual counterparts narrowed—a transition enabled by the ever-increasing number of sensors active in the world. A clear example is electric vehicles, which contain advanced telemetrics as well as highly optimized production lines, analyzed in detail in digital form by manufacturers. [33] The dynamic of recursive feedback in industrial production illustrates how the increased complexity and application of simulation does not mean the real world is ignored but rather transforms and is transformed by it.

4.2 UNREAL GROUND TRUTH

The game studio Blackshark was known for solving technical challenges in open world gaming. In 2016 they were approached by Microsoft to work on its famous Flight Simulator series. Microsoft explained that they had a high-resolution surface image of the entire planet and wanted to make it 3D. At the time, Google Earth's 3D coverage was around 10–20 percent of the total world map, painstakingly produced using roving cars and light detection and ranging (LiDAR).

Blackshark teamed up with Maxar, the satellite technology company who provided much of the satellite imagery used by Google Maps (and who became a household name after their images of a Russian military build-up at the Ukrainian border in February 2022). More recently, they also usurped BSim as the provider of the US Army's One World Terrain. Together, they took a planet-sized scroll of two-dimensional images and matched them to data parameters such as local population density, regional architectural styles, size of sidewalks, and the angle of shadows beside structures used to correct their angles so they would appear upright. They then applied geotypical skins—best guesses produced with machine learning—and kept running the model until they achieved more than 90 percent accuracy.

The outcome was known as Synth 3D: a model of 1.5 billion buildings and 30 million square kilometers of vegetation in 3D, available for use in building augmented/virtual reality applications, predictive AI deployed at a planetary scale. It allowed developers to port familiar game mechanics into ultra-real settings, allowing players to drive anywhere, to understand the impact of natural disasters, to take virtual vacations, or to scout locations for movies. The system was used by Walmart to experiment with drone delivery—though when the company tested its findings in reality, a dog showed up that hadn't been included in the simulation and took out the drone. Dogs were included in the follow-up version.

A 2019 paper from the Karlsruhe Institute of Technology in Germany launched a plugin “for synthetic test data generation utilizing the Unreal Engine” known as UnrealGT, used to create generic data sets for applications such as unmanned aerial vehicles and autonomous driving. [34] For the most part, autonomous vehicles are predominantly trained in synthetic environments created using 3D engines like Unreal or NVIDIA's Omniverse—the software Amazon uses to create real-time models of its warehouses. Synth 3D, in turn, pays special attention to synthetic airport reconstructions that allow airline companies to test and validate airplane sensors for autonomous landing.

4.3 EXTREME SILICON COMPUTING

Every year more sensors, cameras, and Internet of Things chips are integrated into the world in the form of satellites, ground station sensors, ocean buoys, domestic devices, or weather balloons. In 2023, the Federal Agency for Cartography and Geodesy announced it was working on a “digital twin for Germany.” [35] The system produces high-resolution geodata gathered using Geiger-mode LiDAR and single photon LiDAR enhanced by satellite and real-time sensor updates facilitated by AI. The stated aim was to offer “a realistic mirror image” of the nation for use in forest condition monitoring, precision agriculture, spatial planning, and adaptation to extreme weather. [36]

By this point, many predicted that within five to ten years weather forecasts would be continuous, hyperlocal, and 100 percent accurate. Their rationale was complementary advances in high-performance computing combined with AI training and inference: a symbiotic co-evolution of hardware and software developing just as new, exascale-class supercomputers became able to simulate precisely the sort of climate change-related weather effects pressuring biological, technological, and political life to adapt. [37]

Until the early 2020s, climate models were able to resolve atmospheric conditions within a ground resolution of 10 to 100 kilometers. Thomas Schulthess of ETH Zu-

33. The 2023 Hummer EV used Epic Games's Unreal Engine to visualize a digital twin of itself on its 13.4-inch dashboard display. The interface was designed by Perception, the creative studio responsible for inventing the technology in Marvel movies, and bears no small resemblance to the inside of Iron Man's helmet. As well as running real-time diagnostics on the vehicle, users are able to customize the skins of the vehicle on-screen and to reimagine the terrain as something quite different than the suburban roads they may be driving on—such as Mars, for example.

34. Pollok et al., “UnrealGT.”

35. Hopfstock et al., “Building a Digital Twin.”

36. Simulations are places where multiple competing interests overlap—whether that be challenger theories in science, wants and needs in social models, or the competitive and collaborative aspects of game worlds. Serious games are instances in which the interests of players are pitted against one another to arrive at useful outcomes, such as when volunteers were asked to play a farming simulator to develop protocols against African Swine Fever (UVM, “Video Games”), or to run operations in a shipping port as a way to develop greener practices (Deltares, “Port of the Future”). Sometimes the dynamics are unplanned. They may amount to case studies of governance, as in Kio-tv's “EvE Online,” which can host 20,000 participants across 8,000 solar systems engaged in war and commerce. Loot systems like Dragon Kill Points may stand in for emergent political economy to solve redistribution problems in massively multiplayer online games like *EverQuest* or *World of Warcraft* (see Citarella, “DKP”).

37. IMBUILD008—NVIDIA A100 AND SUNWAY SW2610: The months shortly after the public release of GPT-3.5 were characterized both approvingly and with great reservation as an “AI arms race.” Both LLMs and generative AI were not only being evaluated for possible application in warfare but they were also being considered more broadly in all fields where intelligence was at work—from script writing to cooking. OpenAI's GPT models were built in Microsoft servers running cabinets filled with NVIDIA A100 Tensor Core GPUs, sold on boards featuring eight individual units at around \$200,000 each. One day a new application that wasn't possible before discovers you,” said Jensen Huang, when interviewed by the CNBC network, highlighting the role of NVIDIA GPUs and its general-purpose GPU application programming interface CUDA played in AlexNet, the convolutional neural network that won the ImageNet 2012 image recognition contest. Often cited as the big bang moment for AI in the 2010s, the contest proved that the sort of parallel processing being used to generate realistic computer graphics could become the substrate on which deep learning would evolve. As AI advanced towards the end of the decade and with breakthroughs in image generation in 2020 and beyond, NVIDIA's generalization of its hardware with the \$8 billion CUDA project paid off even further. Its new range of chips provided relief for the company following the boom-and-bust cycles of 2020–23 brought about by COVID-19 factory shutdowns, an energy crisis exacerbated by wars in eastern Europe and the Middle East, a rapid increase in the number of people working from home, and a spike then crash in cryptocurrency prices that saw demand for NVIDIA GPUs skyrocket then fall. After almost a decade of flatlining stock prices, NVIDIA's share price went through the roof. When the United States announced export controls designed to hamper Chinese technological advancement on October 7, 2022, the company needed to rewire its supply chains to keep on serving a market that accounts for a full quarter of its revenue. The lower-spec H800 was designed specifically to get around US rules, though this too was included in the ban when the controls were updated to “close loopholes” on October 17, 2023. The sanctions caused enormous upset in China. Among the many areas of business and defense applications hampered by the controls, its impact was felt on another arms race of sorts: the Top500 project world ranking of supercomputers, a list of the world's most powerful centralized computer systems updated twice yearly since 1993. In 2022, the United States dominated the top of the league with the most powerful individual systems but had just 128 supercomputers in the rankings compared with China's 173 (China, it should be noted, had just one system in the top 500 in the year 2000). Where the Tianhe-2 supercomputer ran on 16,000 computer nodes, each comprising two Intel Ivy Bridge Xeon processors and three Xeon Phi coprocessor chips, the machine that succeeded it, Sunway

rich and Bjorn Stevens of the Max Planck Institute for Meteorology have argued that this represented “incremental” gains, enabled by Moore’s Law, making it possible to simulate features like cyclones and gyres. However, resolutions below 10 kilometers, and particularly below 1 kilometers, they argue, would be a different proposition entirely—a “great leap” only possible in the era of high-performance computing assisted by AI inference. Suddenly it would be possible to “move from crude parametric presentations to an explicit, physics based, description of essential processes.” [38]

One example was the Simple Cloud Resolving E3SM Atmosphere Model (or SCREAM) that ran on the Frontier supercomputing system at Oak Ridge National Laboratory, pushing the grid size of a full Earth climate model down to a resolution of 3.25 kilometers. During a ten-day window in 2023 using 9,000 of the Frontier system’s 9,472 nodes, SCREAM was able to simulate a year per wall-clock hour. Where current Earth system models approximate cloud formation and behavior, models like SCREAM drastically reduce major systematic errors in precipitation prediction. Although the prospect of including ocean, ice, or industrial processes in the same model presents an alarming computational burden, it didn’t stop others from making alternate plans.

4.4 EARTH-2 AND DESTIN-E

In 2021, NVIDIA co-founder Jensen Huang argued that the next frontier in gaming would be the inclusion of the “laws of particle physics, of gravity, of electromagnetism, of electromagnetic waves, [including] light and radio waves . . . of pressure and sound.” [39] While gaming was NVIDIA’s first major gambit, their sights were now focused elsewhere. That same year the company unveiled a supercomputing project known as Earth-2. During the announcement Huang said “we must know our future today—see it and feel it—so we can act with urgency. To make our future a reality today, simulation is the answer.” [40]

A series of demonstrations were published in 2023. One accelerated analysis 700,000 times to help engineers with the planning and operation of carbon capture and storage [41], while the other ran FourCastNet (a weather forecasting model that provides accurate short- to medium-range global predictions at 0.25 resolution) with huge speedups and accuracy improvements in predicting an extreme weather event. [42]

Another digital twin project, Destination Earth (or Destin-E), was funded by the European Union as part of a digital overhaul and Green Deal initiative “to monitor and predict environmental change and human impact in support of sustainable development.” Destin-E was to be constituted from “more than big data atlases,” combining new models of the Earth system enabled by high-performance computing “to close substantial and recalcitrant gaps in our ability to look into the future.” [43]

Outlining the desired final product, computer scientist Peter Bauer and colleagues explained that “a digital twin of Earth would fully integrate observations with an Earth system model and human subsystems for, for example, water, food and energy resource management, to assess the impacts on, and influences from, these subsystems on Earth system trajectories.” A crucial aspect of the project was to bridge the gap between climate models that monitor coupled components of the overall planetary system over decades with weather models that run across far smaller proximities and timescales: “The twin would allow us to assess possible changes and their causes consistently across local and global spatial scales and over timescales stretching from days to decades.” [44]

The overview effect—the “cognitive shift” reported by some astronauts after viewing Earth from space—is digitized to become a “single source of truth” in SYNTH3D, VBS4, Destin-E, and Earth-2. As a marketing strategy, it teases mastery over the planetary terrain, but also leads us toward the larger context in which anthropogenic and climate effects are felt. The planet is no mere globe but an evolving multiscalar causal web where genes, cells, organisms, social groups, buildings, cities, ecosystems, and states interact.

These digital twins harbor echoes of Buckminster Fuller’s *World Peace Game* from 1961, an educational simulation devised to be war gaming’s more noble spirited cousin. They present us, in software form, with the conditions Frank et al. set out as indicators of an emerging planetary intelligence. [45] Only, unlike past models, digital twins are meant to establish an unbreakable causal connection between simulator and simulated—be they reinsurance calculations that change the course of real estate development, or testing preferable crops for a shifting terroir. Rather than a simulation scrabbling to process disturbances after the fact, the claim is that we can foresee them and automate the necessary response.

4.5 WHAT IF WE COULD SIMULATE EVERYTHING?

Before the 2010s it was assumed that the smallest, softest, and smartest parts of reality would forever remain unsimulated. Among the sciences it was biology, with its reputation for operating “close to the ground,” that was expected to be the firm-

TaihuLight ran on an architecture built from 40,960 Chinese-designed SW26010 Manycore 64-bit RISC processors, based on the Sunway architecture developed at the National Supercomputer Center in Wuxi, Jiangsu province. Likewise, Tianhe-3, which many believed to be China’s first exascale computer (meaning it was capable of performing a quintillion operations per second), stacked a greater number of Phytium 2000+ FTP chips, designed by the majority Japanese-owned firm Arm, with Matrix 2000+ MTP accelerators produced by China’s National University of Defense Technology, requiring an undisclosed but presumably gargantuan power and volume to achieve comparable results.

38. Timothy Prickett Morgan, “Climate Simulation.”
39. Dean Takahashi, “Nvidia CEO.”
40. Jensen Huang, “NVIDIA to Build Earth-2.”
41. NVIDIA, “Accelerating Carbon Capture.”
42. NVIDIA, “Predicting Extreme Weather.”
43. Bauer et al., “Digital Twin,” 80–83.
44. Bauer et al., “Digital Twin,” 81. IMBUILD009—EXTREME SILICON COMPUTING: In “The Digital Revolution of Earth-System Science,” Bauer et al. note serious concern within the community about the delivery of reliable weather and climate predictions “in the post-Moore/Dennard era,” and propose a novel infrastructure “that is scalable and more adaptable to future, yet unknown computing architectures.” Dennard scaling refers to the loose notion that as transistors shrink their energy requirements stay consistent, creating a heat threshold that led to the “multicore crisis” and partly to the need for parallel computation on distinct cores. “Increasingly, though, the recognition that small scales matter for climate predictions and that Earth-system complexity matters for weather predictions dawns on our community” (“Digital Revolution,” 105). This is both an “extreme-scale computing and data-handling challenge,” and even though porting computationally intensive code parts to novel architectures such as GPU-accelerated systems showed promising results, much of the code was written generations earlier and requires pain-staking rewrites. This was proved to be the case when the US National Center for Atmospheric Research’s high-resolution version of the Community Earth System model was adapted and optimized for the Sunway TaihuLight supercomputer. Instead, the team looks to algorithms and computer architectures designed in common as demonstrated by NVIDIA’s Earth-2 supercomputer and its physics-machine learning framework Modulus (see NVIDIA, “PhysicsNeMo”)—a move for which “the weather and climate community is largely unprepared” (“Digital Revolution,” 108). The publication of results produced by GraphCast, a machine learning reanalysis model by researchers at Google DeepMind in late 2023, further emphasized the insurgency (see Lam et al., “Learning,” 1416–21).
45. Frank et al., “Intelligence,” 47–61. They are not only a clear example of “an emergent complex adaptive system composed of multi-layered networks of semantic information flows,” 55, but also the way that self-representation is a fundamental first step toward prolonged “going-on,” 53. Much as groups of neurons within cortical columns create thousands of competing models (brains being one demonstration of intelligence among many), Earth is creating ever-more sophisticated models of itself which, like all models, are tools for action and greater understanding.

est hold-out: too complex for the mathematics that powered physics (whose revelations nobody expects to *touch*) or the synthetic interventions that characterized the discovery process in chemistry. Living matter, by contrast, could only be known through arduous and expensive *in vitro* experimentation.

In *Reconstructing Reality*, Morrison observes the mathematization of biology quite literally at the bleeding edge. She gives examples that include anticipating wound closures based on partial differential equations, free boundary problems used to predict cancer tumor growth, and models of lung responses to infection from which pharmacological treatments are derived. These practices were already taking place before the advent of new techniques either accelerated by or enabled by the computational architecture of GPUs.

Still thornier debates over the ethics and efficacy of modeling in economics and the social sciences spring from the mistaken assumption that models ought to be lifelike in order to provide meaningful information. Yet even small, finite, or idealized models can yield valuable insights about how populations react to new legal or fiscal arrangements. This is not *merely* simulation as a shadow of reality but a structure for prediction and intervention, especially with dynamic and unstable groups—from cells to societies.

“We try to simulate tissues and organs, how they grow, how their development works,” says James Sharpe of the Barcelona-based European Molecular Biology Laboratory, to explain how the availability of affordable GPUs transformed the organization’s practices. [46] By dividing the cell populations in a given tissue into smaller groups of cells and sending those computations to GPUs, tasks like microscopy image analysis can be completed in a fraction of the time they once took.

The boundaries of what can and cannot be simulated with existing technology and expertise is always changing. Finalists in the 2023 Gordon Bell Prize, hosted by the Association of Computer Machinery, included a simulation of a jet engine based on a decade-old NASA challenge, a simulation of quantum particles based on density function theory and the quantum many-body problem, as well as a simulation of a nuclear reactor complete with radiation transport plus heat and fluid dynamics inside the core. Along with simulations of existing phenomena we hope to better understand, simulations are absolutely integral to the technologies we aspire to build. They take center stage in Pasteur’s quadrant, where fundamental discoveries are sought in areas of immediate use.

In early 2022, researchers from Google DeepMind ran a trained neural network to stabilize the plasma in an experimental tokamak fusion reactor in Lausanne, Switzerland. The AI was broken into two parts: one which ran on a simulation of the reactor and learned to control it, and a smaller, faster-running network that ran the reactor itself. The AI processed ninety different measurements 10,000 times per second, adjusting the voltage in nineteen large magnets to hold the plasma in place. Although the system ran for just two seconds, which is all that the experimental mechanism is capable of so far, the AI adjusted magnets in ways that humans had not tried before.

Evan Schneider of the University of Pittsburgh has used the Frontier system to run simulations of how our galaxy has evolved over time—how gasses flow in and out of the Milky Way, coalescing into stars and ultimately dissipating as those stars explode. The resolution of these galactic simulations, which included not only large-scale properties of the galaxy at 100,000 light-years across but also properties of the supernovas at about ten light-years across, was high enough to zoom in on individual exploding stars. “It would be analogous to creating a physically accurate model of a can of beer along with the individual yeast cells within it, and the interactions at each scale in between,” Schneider told journalists. [47]

The ability to model multi-scale phenomena and their cause–effect mechanisms had once been a major hurdle. But a new generation of researchers pioneering “simulation intelligence” brought about a new paradigm of guided technological development, the fundamentals of which would be carried forward to the next generation of hardware design and ultimately to the Infinity Mirror. [48]

The researchers at Pasteur-ISI, for example, led by rocket scientist-turned AI engineer Alexander Lavin, developed simulation test beds as *in-silico* playgrounds for human experts and AI agents to design and experiment. The team also has its own digital twin Earth project in collaboration with NASA’s Frontier Development Lab: “Existing scientific methods are deductive and objective-based. The next generation of science, brought about by innovations in simulation, AI/ML, and accelerated computing, can be inductive and open-ended; human-machine teams will efficiently explore an exponentially larger space of hypotheses and solutions, in all domains at all scales.” [49]

5 INFINITY MIRROR

To understand how the Infinity Mirror came to be, it is necessary to unpack the interplay between hardware, simulations, and intelligence. So far we have witnessed the co-evolution of simulations and the hardware on which they run. Better

46. Berta Carreño and Laura Howes, “The Rise of GPU Computing.”

47. Sophia Chen, “The World’s Fastest Supercomputers.”

48. The “simulation intelligence” stack is outlined in a paper with a conspicuously high-profile line-up co-authored by figures from across industry (Intel, Qualcomm AI) and research (Oxford University, Alan Turing Institute, and the Santa Fe Institute). It includes multi-physics and multi-scale modeling, surrogate modeling and emulation, simulation-based inference, causal modeling and inference, agent-based modeling, probabilistic programming, differentiable programming, open-ended optimization and machine programming. See Lavin et al., “Simulation Intelligence”, arXiv.

49. Pasteur-ISI, “Technology: What If Simulators . . .”

hardware enables better simulations, which in turn demand and help build better hardware. They may do this through market pressures that beg for faster, more complex, and time-efficient models requiring semiconductor innovation beyond the status quo. They may shed light on new possibilities that would be otherwise inconceivable, as with quantum computers whose activities may *only* be understood through simulated results.

As philosopher of cognition Andy Clark, and others, have argued, knowledge is acquired and sorted *spatially*. “Thought is movement,” writes Jeff Hawkins in *A Thousand Brains*. If human thought can be understood as patterns of interaction between cells, constantly shifting inside a plastic frame of galaxy-like complexity, it stands to reason that the computing devices best able to calculate the relationships between moving objects and the physics that governs these objects both play a crucial role in the artificial expansion of intelligence.

To provide an overview, we can lay out a chronology beginning with Kriegsspiel in 1811—acknowledging that the use of physical and numerical modeling likely far preceded it—leading to the “simulation crisis” of the early 2020s: an inflection point defined by the COVID-19 pandemic, the 2021 cryptocurrency bull market, factory bottlenecks in China and elsewhere, and the early flourishing of artificial general intelligence. During this period we see the evolution of modeling, prediction, and intervention based on computer simulations. Seemingly distinct fields overlap and open adjacent pathways for one another. A new all-encompassing interdisciplinary practice is embedded globally.

The application of GPU computing across the full breadth of scientific disciplines—as opposed to in studies of the brain, AI, or computation itself—was relatively slow on the uptake. One reason for this was decades of legacy code that required laborious ports and rewrites, making it harder to introduce new hardware. Another was the shortage of GPUs themselves, though as supply normalized the co-design of algorithms and computation (with increased integration of machine learning) began to reshape research. While the atomic limit of transistors was demonstrated [50] by introducing a single phosphorus atom across a silicon crystal at liquid helium temperatures, engineers predicted it would be crises in the machinery of chip production itself that would eventually bring about the end of Moore’s Law and the physical limits of silicon computing.

From 2025 onward, high-numerical-aperture extreme ultraviolet (EUV) photolithography became the means by which chip engineers were able to continue shrinking the geometry of transistor gates to the critical lower limit of 0.25 nanometers. Over three decades prior, chip designers and engineers had reduced resolution by two orders of magnitude [51]: first from 365 nanometers, generated using a mercury lamp, to 248 nanometers, via a krypton–fluoride laser in the late 1990s, and then to 193 nanometers, from an argon–fluoride laser, in early 2001. Immersion lithography, which uses water to significantly enlarge the numerical aperture, reduced the wavelength to 193 nanometers, but it was the 20-year development of EUV that brought an unparalleled reduction to just 13.5 nanometers by leveraging an entirely new way of generating light. [52]

The issue is not the theoretical lower limit of electron gates—an on-off gate built from a single silver atom could do the trick—but rather the complex interplay between specialized elements as well as factors such as heat, quantum tunneling, and interference from background radiation that constantly bombards Earth. Moore’s Law is not a law of nature but an aspiration. It requires an elevated level of research and development investment and relies on some of the most sophisticated experimental technologies ever devised, and creative minds to devise them. Yet it has limits.

Along with continued improvements in silicon computers, a speciation across alternate substrates took forward the capacity to compute. Each of these in turn enabled new types of simulation. This “Cambrian explosion of hardware” advanced most immediately in the service of brain emulation and biological digital twins, which used neuromorphic chip architectures and evolutionary algorithms to more accurately mirror biological phenomena. Other areas in which breakthroughs occurred included inverse design and agent-based modeling, which proved to be well suited to spectral photonics: the parallelizing of computations on different wavelengths of light.

Each breakthrough—in quantum computation, analog inference, or cortical processing using biological neurons—involved some degree of simulation across research, development, or manufacturing. The best-suited hardware, once released into the world, found applications nobody could have predicted: deep-mantle geothermal energy, advanced gene therapies, ecosystem monitoring and planning. By 2030, the need for simulation technology was so widespread that its pre-twentieth century associations with falsehood and misrepresentation were all but forgotten.

The integration of simulations capable of describing, predicting, and responding to causal, collective, emergent, and open-ended phenomena is fundamental to planetary intelligence. It was not long, however, before the cost of running so many codependent simulations on Earth made themselves apparent in the data.

50. Fueschle et al., “Single-Atom Transistor,” 242–6.

51. This was achieved by working on a combination of three factors: the wavelength of the light; the k_1 coefficient, which stands in for a range of process-related factors; and the numerical aperture, a measure of the range of angles over which the system can emit light. The critical dimension—that is, the smallest possible feature size you can print with a certain photolithography-exposure tool—is proportional to the wavelength of light divided by the numerical aperture of the optics. To achieve smaller critical dimensions, engineers must use shorter light wavelengths, or larger numerical apertures, or a combination of the two.

52. As Jan van Schoot explained, EUV involves “hitting molten tin droplets in mid flight with a powerful CO₂ laser. The laser vaporizes the tin into a plasma, emitting a spectrum of photonic energy. From this spectrum, the EUV optics harvest the required 13.5-nm wavelength and direct it through a series of mirrors before it is reflected off a patterned mask to project that pattern onto the wafer. And all of this must be done in an ultraclean vacuum, because the 13.5-nm wavelength is absorbed by air.” “This Machine,” 2023.

Autopoiesis refers to self-creation or organisation, a network of processes that recursively depend on one another for their generation and realization. An autopoietic system, then, develops the “capacity to maintain [its] identity in spite of fluctuations and perturbations coming from without,” but also from within. This system is never static. For as long as it persists it must be constantly remade, “maintaining the physiochemical and information processing capacities that constitute its own ‘going-on.’” [53]

In 2034, a number of Earth’s most advanced simulations began to show a similar anomaly. As the world’s supercomputers ran scenarios of future coastline erosion, galactic mining schemes, and rapid urban redevelopment, an uncategorizable event increased noise in the system leading to an increased number of errors that cast their usefulness in doubt.

In time researchers determined that the error was not in fact a black swan event—not a solar flare or unsurpassable technical threshold—but something they had been expecting since the 2020s: the moment when the representational complexity of the system doing the modeling surpassed all the available data it was expected to model. Like Y2K or artificial general intelligence before it, this simulation point omega had been a focal point for speculation for decades. Would overfitting reality lead to epistemic back holes, a total disintegration of a ground truth with which to act?

Despite the efficiency gains of unconventional computation, the energy use of information processing alone had reached a hundred quintillion (10²⁰) joules of energy per year by 2040, compared with a hundred trillion (10¹⁴) joules just twenty years prior. Expecting that energy demand will continue to increase where it can, solar-powered satellite computers were launched into orbit around Earth in huge quantities. Once stable, they combined to form a federated entity known as the Infinity Mirror: a fleet of supercomputers that encircled Earth, a distant descendant of vacuum tubes, microprocessors, GPUs, and photonic cores.

Of the 90,000 terawatts of solar energy absorbed by Earth’s surface every year, a small quantity was caught in order to power the machine, a glassy overseer suspended at all times above the Arctic running the simulations integral to planetary intelligence, bouncing the rest into space. Computation had joined many other industrial activities—mining, material processing, toxic synthesis—off-planet, leaving the biosphere to bloom once more beneath its technological shell.

With the functionally limitless boost in computational capacity operating beyond the scope of anything possible on Earth, models of the galaxy began to predict fluctuations in the output of distant stars comparable to our own: technosignatures considered statistically incontrovertible, a suggestion of life at work. Though the distance between star systems remained, the predictions were considered contact of a sort. The discovery of life not as physical presence but mathematical certainty.

It remained unlikely that frail humans would ever reach those distant places to find out for sure. But the number of twinkling suns continued to increase the longer the simulation ran. Perhaps this was what it meant to be the first intelligence in a youthful universe, they thought, pained by their ongoing solitude but confident of things to come.

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