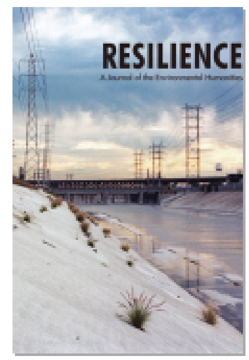
Toward a Speculative Nanoecology: Transscalar Knowledge, Disciplinary Boundaries, and Ecology's Posthuman Horizon



Zach Horton

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Introduction: Probing the Nanocosmos

In the iconic 1951 film *The Day the Earth Stood Still*, an alien messenger, Klaatu, arrives in Washington DC via flying saucer to deliver a warning to the nations of Earth: Earthlings have, through their development of atomic technology, created weapons powerful enough to eventually threaten their galactic neighbors. Therefore, Earth must fully disarm or face immediate annihilation by an autonomous, robotic peacekeeping force, locally represented by Gort, a metallic, humanoid robot capable of vaporizing objects via a ray emitted from its "head." From its opening shot of a galactic cluster, the film signals a shift in scale. Earth no longer circumscribes the world. Humanity poses a threat to the larger interplanetary ecosystem, represented as a hybrid organic-technological milieu. In the 2008 remake of this science-fiction classic, GORT (Genetically Organized Robotic Technology) looks and acts much the same but has grown in size by at least a factor of ten. Human military forces lock it away in a secure observation chamber in an underground facility. At the climax of the film, however, the appearance of minute, spiderweb-like etchings on the observation pane separating the humans from their robotic "captive" signals a scalar jump from the gargantuan to the diminutive, as GORT shifts into its offense mode. Its size and armament are revealed as red herrings in this remarkable sequence, which features the robot's disintegration into a swarm of insect-like nanobots. At the human scale, they appear to be a black cloud that consumes everything human tainted, including flesh, military tanks, a civilian eighteen-wheeler, and Giants Stadium. This is an example of what Colin Milburn calls “nano/splatter,” a subgenre of horror as well as laboratory science, marked by a “staging and restaging [of] disintegration” that “works performatively to relocate life elsewhere, beyond biology.”[1] While the original film evoked an intergalactic ecology of humanlike aliens and autonomous robots, the remake extends its scalar cinematic gaze downward and inward, maintaining the uneasy ecological entanglement of the biological and nonbiological but revealing it to exist at the smallest as well as largest levels. The human and robot body are no longer molar units in the confrontation and negotiation staged by the film: both molecularize and interpenetrate in the generation of new forms of (post)biological life. At the same time that the human race is evaluated as a species body for suitability of entrance into a larger galactic ecosystem, it is revealed to be already galactic at other scales, a nanocosmos vulnerable to decomposition, threatened by nanosystems that are every bit as vital as the celebrated human individual.

What happens if we pursue this logic further, taking seriously the dual proposition that ecology is scale unstable and that it is extensible beyond organic phenomena? On one hand, the instability of scale as both observational and experimental frame, as well as the emergence of scale-sensitive properties, has been actively confronted by many ecologists. Simon Levin influentially argued in 1992 that scale should be regarded as “the fundamental conceptual problem in ecology, if not in all of science.”[2] A number of ecologists have recommended attentiveness not only to different scales but also to the scalar dependency of ecological properties and measurements in general. John Bissonette has forcefully argued that “the challenge for landscape ecology is to build conceptual frameworks that explicitly and simultaneously incorporate multiple scales.”[3] Despite these—and many other—promising developments in multiscalar ecology, the scientific discipline remains, within the hierarchy of the natural sciences, firmly ensconced as a subfield of biology. The biological boundaries of ecology are strictly policed by ecologists. A standard textbook in the field insists that “Ecology is a branch of biology, while [by contrast] environmental science is an interdisciplinary field that incorporates concepts from the natural sciences (including ecology) and the social sciences (e.g., politics, economics, ethics)."[4] For ecologists, then, the systems that comprise their object of study are taken to have the *organism* as their basic constitutive unit, their smallest scale entity. At the deepest level, then, ecology contains powerful transscalar potentials that are waiting to be liberated, yet it remains disciplinarily shackled to a quantifiable organic framework. I suggest that this bias is more than disciplinary inertia or a pragmatic response to limited experimental or conceptual resources. It is overdetermined by the larger paradox of anthropocentrism: when we use human thought in an attempt to access the world as it "really is," we get back only what Eugene Thacker calls the "world-for-us."[5]

Ecology's world-for-us problem manifests itself at two levels simultaneously. Perhaps more than any other scientific discipline, ecology is structured by and for instrumental management. An ecosystem is defined by its particular scale, region, and baseline set of relationships. Just as they come into view, they are rendered geographically, energetically, and conceptually closed, entities to be exploited, managed, or conserved. Let us call this the "instrumental problem." At another level, however, even the most seemingly objective and noninstrumental practices of ecology tend to rely on and reify humanist scalar biases. Why should the agential buck stop at the organism when we consider active participants in the production of the environment? For that matter, what authorizes such a confident separation between agents and the environment to which they adapt themselves and (in the reserved cases of ecosystem engineers) alter in turn? Most ecologists tend to carefully avoid assigning the human any privileged position and have thus partially avoided the epistemic problem of placing the human observer outside and apart from the system observed. The resulting posthuman disciplinary potentiality of ecology is nevertheless ultimately undermined by the (unacknowledged) twin humanistic biases of *organicism* and *scale*. As we shall see, putting ecology into discursive contact with nanotechnology will make visible a path forward, beyond these engineered humanistic barriers, at the same time that it will give us the analytic tools to reveal the entanglement between them: organicism and scale are two modes of the same humanistic substance that circumscribes our practices of ecology.

Nanotechnology, which slowly emerged as a discipline through the writings of futurists and science-fiction authors beginning in the 1940s, finally entered the laboratory in the late 1980s when Scanning Tunneling Microscopes were modified from atomic-scale imaging devices to atom-moving manipulators, promising a lucrative new field of bottom-up, nanoscale technology development that, to date, has largely failed to materialize. Nonetheless, as scientific practice and cultural imaginary, nanotechnology provides a generative test case for a posthuman ecological thought, as it has already given birth—though not without great struggle and pain—to the material-conceptual tools necessary to dismantle the sacred framework of scale-fixed, organic-centered humanism.[6] In what follows, I explore the (science-fictional) origins of laboratory nanotechnology, the practices of probe microscopy, and a famous dispute within the nanotech community as elements within a larger discourse and practice of transscalar ecology. In each case, I suggest that the actors in these dramas, whether fictional or actual, are exploring or arguing about the nature of ecology as much as the nature of nanotechnology. I will argue not only that the concept of ecology is applicable to the nanoworld but that ecology is what has ultimately been at stake during the development of the nanotech imaginary throughout the latter part of the twentieth century. The generative potential of nanotech, which I liken to magic, derives from its promise and threat of scalar instability. While this magic has been captured and harnessed by a form of speculative industrialism, my hope is that it can be liberated as a new form of ecological engagement across scales. This means not only that we should broaden the range of scales to which we apply the notion of ecology but that ecology, in order to shed its anthropocentrism, must become *trans*scalar: it must actively and dynamically grapple with the connections between beings across scales.

Feeling Our Way to the Bottom

Physicist Richard Feynman first catalyzed the field of nanotechnology when he gave his now-famous lecture, "There's Plenty of Room at the Bottom," to an audience at Caltech in 1959. "What I want to talk about is the problem of manipulating and controlling things on a small scale," he declared, and he proceeded to outline an ambitious vision of science-driven miniaturization of computers, robots, and information-storage technologies.[7] Ultimately, he suggested, we should be able to "arrange the atoms the way we want; the very *atoms*, all the way down!"[8] This phrase, "all the way down," along with the "bottom" at which there is so much room, suggests both a ground, a stable platform on which both science and engineering can find a common foundation, and an *underneath*, something outside the macroscale environment, other than and outside the familiar structures of matter. I read this basic conceptual aporia of the nanotech imaginary, this mythical slide "all the way down" that is both an escape from material constraints on production and the stabilization of a privileged scale, as an *ecological* aporia. Feynman's speculative formulation of future nanotechnology as well as K. Eric Drexler's more immediately influential revival and expansion of that vision in the 1980s produce a fictional utopia whose miraculous productivity and abundance violate the principles of ecology by appealing to the affordances of another world that contains radically different potentials of energy exchange and material interdependency.

As Colin Milburn and others have pointed out, Feynman's formulation of a technology that would bridge the macroscale and nanoscale makes direct use of a technique outlined by Robert Heinlein in his 1940 novella, "Waldo."[9] What scholars have overlooked, however, are the mythical and ecological dimensions of "Waldo" that the nanotech imaginary has inherited (as is so often the case in these cross-disciplinary gene transfers) along with its technical blueprints. In Heinlein's futuristic story, a misanthropic inventor with atrophied muscles, Waldo, is hired to solve a scientific mystery: "deKalb receptors," meant to harness wirelessly transmitted "radiant power" for purposes of vehicular transportation, are failing at an alarming rate, even though no one can find anything wrong with them. During Waldo's investigation, he encounters a very old man, Grandpa Schneider, who shuns all electronic technology and yet can repair deKalb receptors through telepathy. When Waldo learns that Grandpa Schneider has supposedly tapped into the abundant energy of an "Other World" simply by harnessing it through thought, he hypothesizes that the nervous system acts as the interface between these dimensions—that is, that it inhabits both worlds. The nervous system thus forms a link not only between the organic body and the transscalar robot slave hands but also between the human environment with its attendant infrastructure and the mysterious Other World that acts as a storehouse of energy outside but connectible to our environment: "Maybe we've repealed the law of conservation of energy. Those deKalbs are drawing energy that was never before in this world!"[10] K. Eric Drexler, nanotech's most fervent promoter, is clearly employing the same conceptual maneuver when he writes in 1986 that nanotech "assemblers will be able to make virtually anything from common materials without labor . . . opening a new world of possibilities. They will indeed be engines of abundance."[11] For Drexler, these mechanisms of abundance are literally engines—tiny molecular machines modeled on industrial robotic technology—but now constructed at the nanoscale out of individual atoms and molecules. He dubs the production of these future nano–industrial machines "mechanosynthesis."[12] Because Drexler's nanomachines and nanofactories exist only virtually, as computer models that transpose macroscale industrial mechanics into the nanoworld, we can think of Drexler's conceptual ecology as a form of *speculative industrialism*. Crucially, this practice employs the rhetoric of industrial production yet relies on an imprinting of macroscale structures onto the nanoscale from above in an example of hylomorphism, or the imposition of form from outside the matter in question.

While virtual, Drexler's speculative industrialism has conceptually, affectively, and economically driven the development of lab-based nanotechnology.[13] Institutionalized nanotech began to make particularly rapid progress in probe microscopy and the discovery and synthesis of new materials in the 1980s and '90s. The Scanning Tunneling Microscope (STM) and then the Atomic Force Microscope (AFM) fulfilled Heinlein's dream of a device that would bridge scales and allow a human operator to "touch" objects at the nanoscale. Probe microscopy involves a miniature tip attached to a cantilever, off of which a laser is reflected. The end of the probe's tip is only one atom in diameter and thus interacts with the electron fields of other atoms on the sample's surface; the resulting nanomovements are amplified through the cantilever and laser and then recorded and digitized. A computer employs interfacial software to render this raw data in whatever form the operator chooses. The result is "a topographic map of the sample surface."[14] Because probe microscopy is nonoptical, it eliminates the possibility of observational distance (the microscope touches rather than sees) at the same time that it renders visualization the product of computational mediation. Thus the topographic rendering produced by the AFM is something like Borges's map that is the size of the territory it represents: the probe tip directly encounters every feature that it records, actually traversing the terrain of the nanoscale.[15] Here we have the map not as representation but as the territory—the haptic potentials of a surface—itself.

As Gimzewski and Vesna have noted, this represents a "major paradigm shift—rather than using lenses and waves, they were recording by feeling."[16] This implies not just a new way of imaging but a new way of encountering landscapes at smaller scales: "This opened up a new world, a world never really seen before on those terms—the nanoworld. . . . Our windows on the nanoworld looked not at parts of systems, but really at operating fully functional systems."[17] According to Gimzewski and Vesna, this tactile mode of encountering and mapping the nanoworld makes possible a shift from a conceptual and experimental model based on machines to a future scientific culture based on organic forms, "embracing biologically inspired shifts, new aesthetics and definitions."[18] Fully encountering and experiencing the nanoworld, on this account, requires that we recognize it not as a collection of machine parts but rather as an assemblage of organic systems, an ecosystem. Further, this realization has the potential to transform how we conceptualize and interact with not only the nanoworld but the macroworld as well. Colin Milburn has called this new way of "seeing" engendered by nanotech "nanovision," a form of perception that "discovers a scission—between present and future, between human and posthuman, between science and science fiction."[19] Because nanovision sustains a feedback loop between the macroscale and the nanoscale, imprinting macrodesigns on the nanoworld and importing nanopotentials into the macroworld, we might call this a form of scalar feedback.

In a classic article, Jay McDaniel argued in 1983 that scientific forays into the minutest scales of matter were causing cracks to form in the Western tradition of conceptualizing matter as inert, or lacking "any capacity for creativity" and "any capacity for sentience" or "a subjective appropriation of external influences."[20] Quantum mechanics had suggested that matter itself is indeterminate. It is inherently unpredictable and thus not inert as in Newton's physics. At the same time, the states of quantum phenomena are not discoverable in the classical sense of existing apart from an observer; rather, they are determined by apparatuses of observation, suggesting that for matter to form stable states at all, it must be able to enter into observational encounters by itself. Physicist and cultural theorist Karen Barad has pushed this logic further, arguing that the realization that "objects" don't come to be separated from observational apparatuses, or to acquire definite properties of any kind, until an "agential cut" is made that differentiates one part of matter from another and stabilizes those relationships—this calls us to engage in "a rethinking of the very nature of knowledge and being."[21] The transscalar nature of quantum indeterminacy authorizes a new engagement between humans and matter, or rather the active process of "mattering," even as it entails a Copernican shift away from the human as the center of the universe. "There are no preexisting, separately determinate entities called 'humans' that are either detached spectators or necessary components of all intra-actions. . . . 'Humans' are emergent phenomena like all other physical systems."[22]

While this may deflate the pretensions of the human(ist) ego, it also constitutes the latest joyous dispatch from Nietzsche's "gay science" of posthuman realism (Barad calls her version "agential realism"): matter is creative, not just because it can assemble itself in unique ways, but because it creates itself *as* matter. Its agency arises from within. This aliveness of matter is ontologically prior to any knowing subject and even to any emergent organism. Thus Barad's agential realism supports and implies the figuring of matter as an ecosystem of differentiated and differentiating agents engaged in continual acts of intra-active production at all scales.

Nathan Brown further expands this argument for what we might call an ecosystemic recognition of an organic nanoworld into the territory of Western metaphysics by targeting Heidegger with a well-aimed nanoprojectile. Where Heidegger had argued that nonliving objects such as stones are "worldless" because they lack relational access to other objects in their environment—as opposed to humans and animals, which have a world in the sense of perceiving other beings that are "accessible in such a way that dealing with such being is possible or necessary"[23]—Brown suggests that "nanotechnology forces us to confront a threshold at which non-living being is not-without-access, nor without world."[24] Probe microscopy purportedly gives "us" access to the nanoscale world, but Brown argues that such access is dependent on a more fundamental opening of nanoscale objects to the being of each other: "In the case of the STM, our 'access' to any information whatsoever about this particular environment is conditional upon the being-toward of two atoms and upon the being-between of the electrons exchanged though a network of surfaces."[25] It is, after all, the atomic tip of the STM needle that "feels" the topmost atom of the sample's surface. The human's access to this environment is predicated on a set of interrelationships among entities within that environment. It seems, then, that nanoscale entities do in fact have a world according to Heidegger's schema, in the sense of having access: they sense and react to other entities around them, unlike the stone that simply "lies on the path."[26]

Instead of thinking of nanoscale entities as subjects, Brown suggests that we acknowledge the noninert worlding of all beings as a "chiasmic threshold—at which an object is opened to world through its openness to other entities and at which world is opened to any living entity in so far as it approaches the condition of the object."[27] He deems this threshold "nothing-other-than-object."[28] Leaving aside the ontological problem that this poses for Heidegger, I wish to accept that nanoparticles are far from inert and, in fact, arrange themselves in complex, dynamic networks within which energy and matter are exchanged in intensive processes that are often far from equilibrium. The fact that humans are capable of tapping into the fundamental productive dynamics of the nanoworld indicates not that atomic scale matter is passive, awaiting form imposed from above, but that humans can at least potentially serve as coinhabitants and cocreators of nanospace—one of the reasons Barad gives for the entanglement of "mattering" and ethics.[29]

Sacha Loeve has generatively suggested that we conceive of probe microscopy not as *representing* objects at the nanoscale but as *producing* its own object of study—the encounter itself: "It is a dialogue that takes place down at the level of the object and its immediate surroundings—including the atomic-level part of the instrument (the apex of the tip)."[30] Here we return to the paradoxical duality of the nanoencounter: the probe microscope takes us "all the way down" to an environment in which we can resolve and experience the basic building blocks of matter in interaction with each other, but only by producing a new space, a theater of transscalar interaction that Loeve calls "imaginaction."[31] The raw data produced by this encounter, unlike that of traditional microscopy, "is not the picture itself: it is the curve below, expressing how the AFM 'feels' the mica in terms of variations of amplitude of its cantilever's vibrations during lateral scans. The picture is just a visual display obtained by a digital 'collage' of all the lateral curves of scanning."[32] The image—and by extension the pretense of objective knowledge—only emerges *after* the interaction and cannot be disentangled from that interaction. Nanoresearchers finds themselves plunged into a new world with new rules, where atoms sense and affect each other in complex networks of energetic and material flow, fully articulated to and inextricable from a robust environment that can only be viewed by being inhabited and can only be inhabited by being continually altered, remade, produced. I suggest that we may generatively think of this as a transscalar ecosystem and of nanotechnology as, at least potentially, a kind of radical ecology.

Plunging "all the way down" into a nanoecology presents us with some immediate difficulties. We cannot stand outside the transscalar, interfacial act of accessing the nanoenvironment; and thereby we become embedded within a space that is small enough to be embedded within ourselves. Scalar feedback. Like a video camera filming its own output, might viewing the ecosystem of entities at the "bottom" of our own bodies cause a kind of infinite scalar regress? In the mode of nanovision, we become coproducers of the nanoscale, an environment that operates according to completely different principles than those that govern the macroscale. Gravity has no effect in relation to the molecular and Van der Waal forces.[33] The ratio between mass and surface area for all entities is so radically altered that nanoscale economies of exchange are wholly incommensurate with that of the macroscale. It is no wonder, then, that Astrid Schwarz and Alfred Nordmann note a tension in nanodiscourse between "on the one hand many verbal descriptions of the nanoscale as the place of discontinuity, surprise, strangeness, and difference, and on the other hand most visual images that evoke a familiar world that readily submits to technical control."[34] The nanoworld is, on one hand, "just us" at the bottom and, on the other hand, a wholly alien ecology. As Mike McGehee, the director of the Center for Advanced Molecular Photovoltaics at Stanford University, has explained, "In our world, a soccer ball is going to fall to the ground because of gravity. In the nanoworld gravity doesn't matter, and it's all about intermolecular forces, so it's a whole different world. I think some scientists immerse themselves so much in that that they can almost experience that world."[35] McGehee himself, however, finds it alienating and experiences relief in "going home and cooking and fixing bicycles and cars and doing stuff with our hands where we can see what it is that we've built." This duality of macroaccessibility and absolute alterity is the key to the fecundity of nanotechnology as an engine for increased laboratory funding, the circulation of nanoimagery and nanofuturist texts, the generation of science-fictional scenarios, and the production of nano-materials in everything from suntan lotion to self-healing composites for spacecraft.[36]

The virtual potentials of nanotech, its fundamental production of possible futures, rest on two simultaneous extensions: an extension of reproduction from the organism to the atomic level, where it becomes a dual expression of matter and information (genetic and other codes), and an extension from material processes to financial speculation. The result is identical to what Melinda Cooper analyzes in the field of biotechnology as the neoliberal harnessing of life itself, at all its scales, for economic accumulation that aims to surpass life's own limits, resulting in a form of speculative reproduction that she deems "life beyond the limits."[37] Nanotech pushes even beyond the life-delimited boundaries of biotech. Its virtual dynamics—hitherto reserved for living organisms and their interrelationships with their environments—produce a similar surplus that can certainly be harnessed for human production, but it can also help us to recover the autonomous and creative dynamics of matter itself, beyond the human and beyond the organism. Extending the concept of ecology to the atomic realm enables and indeed forces us to encounter the heart of this primary productivity. I suggest that such a maneuver necessitates a conceptual reorientation of not only the relationship between the human and its environment but also between production and resources, or the limits to growth.

The Scalar Constraints of Nanoecology: Drexler versus Smalley

In 1972 K. Eric Drexler read the Club of Rome's first report, *The Limits to Growth*, which "raised questions that led me to explore what might be found outside the world it had framed—to look outward, at first, toward deep space, but later inward, to explore the potential of technologies in the nanoscale world."[38] Many future nanoscientists were influenced by Drexler's vision of a world of abundance that bypassed Earth's limits to growth; but as nanotechnology grew into a recognizable interdisciplinary field, scientists began to distance themselves from Drexler's blue-sky speculation. This culminated in a highly publicized debate between Drexler and Nobel Prize–winning nanoscientist Richard Smalley between 2001 and 2003. This exchange is of direct interest to us here because it reveals the scalar dynamics and political stakes of transscalar ecology. While scholars have generally read this debate as a political struggle over funding streams,[39] in what follows I read it as a struggle over the possibility and potentials of nanoecology.

In 1985 Smalley's team had discovered a new allotrope of carbon, C_{60}, or "Buckminsterfullerene," a soccer-ball-shaped structure composed entirely of carbon atoms.[40] Resembling Buckminster Fuller's iconic geodesic domes (a staple of 1950s futurism), these nanostructures can be fabricated in the lab and represent the strongest known molecular structures. In 2001 Smalley directly challenged Drexler's mechanosynthesis model of nanotechnology, in an article in *Scientific American* titled "Of Chemistry, Love and Nanobots." The article's subhead reads, "How soon will we see the nanometer-scale robots envisaged by K. Eric Drexler and other molecular nanotechologists? The simple answer is never."[41] Smalley goes on to consider how one might go about building a nanoassembler and concludes that it is impossible according to the laws of chemistry. Curiously, though, he frames his nanoscale narrative as a teenage love story. His opening paragraph sets the scene for a nostalgic, 1950s-era Hollywood romance:

> When a boy and a girl fall in love, it is often said that the chemistry between them is good. This common use of the word "chemistry" in human relations comes close to the subtlety of what actually happens in the more mundane coupling of molecules. In a chemical reaction between two "consenting" molecules, bonds form between some of the atoms in what is usually a complex dance involving motion in multiple dimensions. Not just any two molecules will react. They have to be right for each other. And if the chemistry is really, really good, the molecules that do react will all produce the exact product desired.[42]

Smalley's remarkable text maps the process of nanoscale chemical bonding onto an archetypal narrative of innocent teenagers slowly falling in love, performing various rituals of attraction to test their chemistry, gradually discovering their fated pairing, entering into a legally binding monogamous relationship, and then producing offspring within the boundaries of the consumptive unit of the nuclear family. The conservative, mythical quality of this hypothetical relationship is not accidental. Smalley's point is that there are implicit rules by which things are done: as any loyal consumer of Hollywood romcoms knows, "they have to be right for each other," and this rightness can only come from within the deepest recesses of their uniquely individual natures. Drexler fails to understand this, charges Smalley: Drexler's entire nanovision assumes that we can put individual atoms precisely where we want them to go and that they will *stay* there, when in fact we must defer to the inner lives of the atoms themselves. Drexler and his followers unwittingly place themselves in the unfortunate role of the matchmaker attempting to force the wrong pairing in act 1: "Wishing that a waltz were a merengue—or that we could set down each atom in just the right place—doesn't make it so."[43]

Smalley goes on to explain that Drexlerian nanoassemblers would suffer from two fundamental problems: The fat-fingers problem is that the articulated manipulators on any assembler designed to move atoms must themselves be made out of atoms and thus take up too much space relative to their raw material, rendering precise placement of atoms impossible. The sticky-fingers problem is that the atoms being moved will adhere to the atoms manipulating them—there's no way to turn atomic bonds on and off in order to keep the manipulator separate from the manipulated. These constraints represent the two prongs of an ecological pincher argument. Smalley here attempts to stabilize ground rules for the interaction between a nanomachine and its environment, figuring this interaction as a set of interconnections and dependencies and demonstrating that Drexler's conception of this interaction violates basic principles of life in the nanoworld, or what I am calling nanoecology.

Drexler responded directly to Smalley's article with an open letter published on the web accusing Smalley of deliberately misrepresenting his work. In it, he claims that his nanoassemblers will be built without "Smalley fingers" and notes that enzymes and ribosomes already assemble molecular structures in this way.[44] In an acrimonious exchange hosted by *Chemical and Engineering News* in 2003, Smalley and Drexler continue this point-counterpoint. Smalley notes that enzymes and ribosomes work under severe limitations and cannot possibly produce the intricate, computer-controlled, mechanical devices that Drexler has described. For one thing, they only work within an aqueous solution. For another, they can only work with organic materials: "Biology is wondrous in the vast diversity of what it can build, but it can't make a crystal of silicon, or steel, or copper, or aluminum, or titanium, or virtually any of the key materials on which modern technology is built."[45] He then exhorts Drexler to describe this "nonaqueous enzyme-like chemistry" that he sarcastically notes "has eluded us for centuries." Drexler declares in response that "Feynman's vision of nanotechnology is fundamentally mechanical, not biological," and that "the technical questions you raise reach beyond chemistry to systems engineering. Problems of control, transport, error rates, and component failure have answers involving computers, conveyors, noise margins, and failure-tolerant redundancy."[46] He explains that there is a difference between "solution-phase chemistry" and "machine-phase chemistry." It is the latter that his concept of mechanosynthesis is based on. It utilizes mechanical means to bring molecules together and thus doesn't rely on a liquid solution. He then closes by warning that such assemblers will be so productive and powerful that "failure to develop molecular manufacturing would be equivalent to unilateral disarmament."[47] Smalley angrily concludes the exchange by returning to the points he made in his *Scientific American* article, including its basic true-love narrative:

> There are too many atoms involved to handle in such a clumsy way. To control these atoms you need some sort of molecular chaperon that can also serve as a catalyst. You need a fairly large group of other atoms arranged in a complex, articulated, three-dimensional way to activate the substrate and bring in the reactant, and massage the two until they react in just the desired way. You need something very much like an enzyme.[48]

Smalley's tone then turns personal: "I see you have now walked out of the room where I had led you to talk about real chemistry, and you are now back in your mechanical world." He links Drexler's mechanical dreamscape with a computer program: "But, no, you don't get it. You are still in a pretend world where atoms go where you want because your computer program directs them to go there." Finally, he appeals to common decency and suggests to Drexler, "You and people around you have scared our children."[49]

Smalley emphasizes throughout this exchange that there are limitations to what chemistry can do. Atoms and molecules have their own rules, their own desires. Chemists (perhaps more than a little perversely) are like massaging chaperons: they can help catalyze certain events but can't force two reluctant parties together and expect that they will bond. All chemistry is done in solution, because it is a macroscale practice: chemists isolate certain substances and mix them together in different ratios and under different conditions to produce the results they want, articulable only at the scale of visible reactions. That is, chemists work with statistical aggregations of molecules, and what they can *do* is fundamentally constrained by *the statistical rules that their solutions follow*. Smalley repeatedly exhorts Drexler to follow these rules and limit his imagined structures accordingly. The implicit charge is that Drexler is thinking at the wrong scale and thus cheating his way out of the limitations by which all chemists must abide. Smalley repeatedly asserts what chemistry can and can't do and notes that "biology is wondrous . . . but . . ." He is thus invoking disciplinary boundaries as scalar boundaries: If you want to make things happen at the nanoscale, you must do it in aqueous solutions following empirically determined statistical rules, within the discipline of chemistry. If you want to work with enzymes and ribosomes to build organic structures at the scale of organelles, you need to accept the limitations of life-forms, within the discipline of biology. Chemistry and biology in these cases signify not only disciplinary communities and characteristic techniques and skills but also particular sets of material limitations.

Drexler's defense takes the form of denying that his version of nanotechnology is scale constrained as either biology (it is "fundamentally mechanical, not biological") or chemistry ("the technical questions you raise reach beyond chemistry to systems engineering"). Drexler's defenses continually invoke processes normally encountered in the discipline of engineering, at the macroscale. Mechanosynthesis, as speculative practice, imports macroscale structures and relationships to the nanoscale by bypassing all intermediate scales. Thus when defending himself against Smalley's attack on his scalar constraints, Drexler produces responses that Smalley finds incomprehensible: "I'm not working with solutions" (chemistry) "or organelles" (biology); "I'm manipulating atoms from the bottom-up" (physics), "using industrial technology methods" (engineering). Smalley doesn't have available institutional language with which to respond to this scalar proliferation and thus simply accuses Drexler of retreating "back in your mechanical world." By this, Smalley means that Drexler has abandoned chemistry and scaled up to engineering, where structural constraints are much looser but where blueprints are scale dependent and only describe possible structures embedded within a macroscale environment. Smalley's worry, then, is not only that Drexler, like an impetuous undergrad who enters his or her senior year still wanting to major in "everything," has failed to declare a discipline.[50] More fundamentally, Smalley is made profoundly uneasy by the scalar instability of Drexler's discourse. He accuses Drexler (a computer scientist) of working from computer models, where the behavior of atoms is programmed by humans and thus obeys arbitrary constraints rather than the constraints encountered through actual interaction, where observable limitations are keyed to the scale of the milieu being explored. Significantly, though, Smalley suggests that "you are still in a pretend world," conflating Drexler himself with the virtual environment of his molecular simulation software. Drexler is here figured as occupying two different environments simultaneously, an analog of his conflation of macroscale properties with nanoscale structures. Smalley implies that Drexler is in some sense living in an artificial ecology that operates according to principles he has programmed in. Drexler can interact with and manipulate these virtual molecules only because they behave like the macroworld in which his actual self simultaneously dwells. Smalley has here identified the antiecological logic of Drexler's version of nanotechnology and further has transposed it into a real-virtual binary designed to provoke horror in the empirical researchers who make up the readership of *Chemical and Engineering News*. Attending to the ecological dynamics of a particular scale means limiting oneself to actual interaction; conversely, virtual exploration—which opens up untold potentials for new material and conceptual configurations—is antiecological.

While most commentators see Smalley's final appeal for Drexler to stop "scaring our children" as a non sequitur and entirely unscientific, we can discern the significance of this accusation if we see that this debate is not really about the possibility of nanoassemblers at all. The "deeply troubling bedtime story" that American children have been told by the raconteur Drexler is not about destructive technology—hardly a new trope. Nor is it about self-replicating, gray-goo-producing technology in general. Smalley is quite precise when he describes the counternarrative that he has recently deployed to soothe the fears of "about 700 middle and high school students": "While our future in the real world will be challenging and there are real risks, there will be no such monster as the self-replicating mechanical nanobot of your dreams."[51] The nanobot that Smalley wants to refute is specifically mechanical. In other words, this dreamed-up beast is monstrous precisely because it is scale unstable—it is mechanical and nanoscale at the same time, obeying two sets of physical laws simultaneously. It isn't real, but that won't stop the kids from checking under the bed. Just thinking (or dreaming) about mechanical nanobots threatens the very boundaries of scientific knowledge and methodology with instability. Everything will come unstuck in our ecology of knowledge production (who will you mind then?) if we open the door to free-scaling knowledge production. Once again, ecology and disciplinary boundaries are linked in institutional knowledge production by precisely articulated scalar boundaries.

Smalley ridicules the idea that atoms could be placed one at a time without any regard for the complex field of proximate structures and competing attractive and repellent forces that make up nanoecology. An atom simply isn't an individual in a vacuum, analogous to a machine part that can be assembled at will. This argument strikes a blow right at the heart of Drexler's speculative industrialism, a biscalar process that, like a perpetual-motion machine, maintains output yield without further inputs (labor, raw materials). Dexler's transscalar ideology, so attentive to the large-scale needs of capital, has ignored the needs of the nanocosmos itself.

Ultimately, these are the stakes and the discursive lines traced by the Smalley-Drexler debate. Smalley argues that the nanocosmos is a robust ecology with its own principles of action and reaction, of exchange and production, and thus that we cannot simply engineer a scalar collapse and impose our macroscale, industrial blueprints on the nanoenvironment in a bid to escape our own limits to growth. Drexler's defense, however, exposes Smalley's reliance on a particularly rigid hierarchy of disciplinary boundaries defined by scale. Drexler's nanovision denies the naturalization of the political ecology of scientific knowledge production at the same time that it denies the naturalization of nanoecology. The danger Smalley recognizes in Drexler's radical proposals is that they could produce a scalar leakage that might propagate through all orders and scales of production in the technoscientific world. Thus Drexler argues for a transscalar ecology of knowledge production that Smalley disallows, while Smalley argues for a transscalar natural ecology that Drexler denies.

My argument for a nanoecology that breaks through ecology's biological limits while challenging nanotech's anthropocentric and hylomorphic approach to the nanoscale suggests a third possibility: we may adopt Drexler's transscalar disciplinarity while at the same time renouncing his speculative industrialism and its dream of scaling down the dynamics and mechanics of our macrocivilization in a colonization of the nanoscale. Smalley's attentiveness to the alterity and autonomy of the nanoworld must be combined with Drexler's irruption of scalar disciplinary boundaries if we are to arrive at a full-blown nanoecology.

Magical Ecologies

It should be clear by now that we cannot separate the material dimensions of nanotech from its discursive dimensions and that nanoecology represents a nonreducible locus of both. Just as nanotech's outputs are nature-culture hybrids, so is the assemblage of practices, philosophies, teleologies, narratives, substances, instruments, funding categories, and institutional hierarchies that constitute it. Nanotech, then, epitomizes the paradox that Bruno Latour identifies at the heart of the project of modernity: culture and nature are relegated to different domains of knowledge, but this division ends up producing and proliferating the very hybrid forms whose existence it denies. In Latour's words, "the more we forbid ourselves to conceive of hybrids, the more possible their interbreeding becomes."[52] This hybrid nature of nanotech is the key to understanding it as a form of production, for the most potent forms of production at the contemporary moment are all hybrids in this sense: they articulate discursive and material structures together in patterns that generate internal asymmetries—or intensities—that can be harnessed to drive the production of further hybrid forms. The resulting products are always part material (actual), part discursive (virtual or potential), and always equally real, in accordance with Henri Bergson's formula: "Everything will happen as if we allowed to filter through us that action of external things which is real, in order to arrest and retain that which is virtual: this virtual action of things upon our body and of our body upon things is our perception itself."[53] As we have seen, nanoperception is embodied and transscalar, and thus it is a transduction of the virtual into the actual, a feedback between scales that is capable of producing new forms.

This productive entanglement between the actual and the virtual is expressed in different mixtures in the nanovisions I have explored thus far, each of which has featured a macroscale (human) reach across scales (collapsing any intermediate scales) into a nanoworld that obeys different laws (of energetic potential for Heinlein, of speed and reproduction for Drexler, of bonding for Smalley) and makes possible radically new gradients for production, which proliferate into macroscale products. This scalar collapse, this production of macroscale outputs without macroscale inputs, mirrors the logic of magic: human-scale conjurers (witches, wizards, shamans, etc.) make contact with a spiritual world that exists outside the human scale and obeys radically different laws.[54] It is there that they perform their manipulations and then allow them to propagate back into the human-scale world as new forms *seemingly without macroscale cause*. Objects materialize, seemingly violating the laws of conservation of mass and energy. Transformations that would ordinarily require an extended period of time and multiple interventions in their processes of actualization instead take place nearly instantaneously, without intermediate steps. Water into wine. As the royal patrons of medieval alchemists knew well, the promise of magic is the short-circuiting of the scalar relationship between inputs and outputs, or base metal and the philosopher's stone.[55]

Appropriately, then, magic is an explicit concern in Robert Heinlein's "Waldo," the urtext of nanotechnology, to which we shall return for a moment. Waldo's empirical investigation into the failure of deKalb receptors to harness invisibly transmitted energy slowly leads to an unraveling of several characters' faith in the boundary between natural phenomena and mental fabulation—the latter limited only by the imagination. Ultrarational scientist Rambeau loses his grip on the actual (though not, in the narrative's economy, on the real) and shouts, "Chaos is King, and Magic is loose in the world!"[56] The turning point of the novella comes when its eponymous misanthrope comes to accept that Rambeau and Grandpa Schneider may have hit upon the truth—the source of the deKalb's energy may actually lie in a world outside the empirically observable one. It is worth quoting this passage at length:

> Magic loose in the world. It was as good an explanation as any, Waldo mused. Causation gone haywire; sacrosanct physical laws no longer operative. Magic. As Gramps Schneider had put it, it seemed to depend on the way one looked at it. . . .
>
> In the first place Schneider had used the phrase "the Other

World" time and again. What did it mean, literally? A "world" was a space-time-energy continuum; an "Other World" was, therefore, such a continuum, but a different one from the one in which he found himself. . . .

The Other Space was not entirely unreachable; Schneider had spoken of reaching into it. The idea was fantastic, yet he must accept it for the purposes of this investigation. Schneider had implied—no—*stated* that it was a matter of mental outlook.

Was that really so fantastic? If a continuum were an unmeasurably short distance away, yet completely beyond one's physical grasp, would it be strange to find that it was most easily reached through some subtle and probably subconscious operation of the brain?[57]

Heinlein's novella provides much more than a conceptual blueprint for cascading manipulator arms; its formulation of the relationship between the macroscale world and the "Other World" provides one of the essential dynamics of the nanotechnological imaginary. While Feynman may have borrowed the former in his historical talk, it is the latter that provides the basic narrative thread in nanotech discourse as it develops from Drexler's *Engines of Creation* onward. In "Waldo," the key to harnessing the nearly unlimited energy in the Other World is to first realize that it is coextensive with the macroworld yet othered from it and then to excavate or engineer a set of one-to-one homologous points between these two worlds to effect a transfer of energy between them. Waldo's transscalar manipulator arms effect this transfer, literally a reaching into the Other World, allowing him to make contact, to establish a gradient for flow.

According to Drexler, speculative nanotech's "unexpected prospects for averting the collision between civilization and the limits of the Earth offer reasons for hope where hope has been scarce."[58] By conceptually shrinking industrial machinery to the nanoscale and rendering plausible the production of abundant goods that no longer require commensurate inputs of matter and energy and no longer entail devastating ecological costs, Drexler draws on the Other World to rescue capitalism from the pessimism—driven by growing ecological awareness of "the limits of the Earth"—that threatens to engulf it. In his 2013 book, *Radical Abundance*, he revisits those rancorous years in the early 2000s that found his vision of magical industrial abundance fiercely contested by Smalley and other practicing nanoscientists. Here he suggests that the marginalization of his mechanosynthesis vision of nanotechnology was a matter of virtual political terror: "The clamor was all about nanorobotic bugs, funding, fear, and politics, far from anything reality based."[59]

In January 2000, *Wired* magazine had published an article by Sun Microsystems cofounder Bill Joy titled "Why the Future Doesn't Need Us." Joy argued that genetic engineering, robotics, and nanotechnology all posed existential risks to the human race, perhaps to all life on the planet. The prospect of self-replicating assemblers posed a particularly alarming problem: "An immediate consequence of the Faustian bargain in obtaining the great power of nanotechnology is that we run a grave risk—the risk that we might destroy the biosphere on which all life depends."[60] If Smalley is most concerned about Drexler's transscalar irruption of empirical knowledge practices, Joy has in mind another transscalar leap: from nanobot to biosphere. The excluded scalar middle here happens to circumscribe all life on Earth.

Science fiction has long rehearsed such minuscule threats to human existence; and in the age of nanotechnology, the genre is replete with visions of nanohorror, the flip side of magical abundance. These narratives turn on the terror of scalar instability: the smallest of things, assuming they can replicate and act in unison, pose the largest threats to the integrity of the human individual and species. I opened this essay by invoking one example: the nanotech remake of *The Day the Earth Stood Still*. I'll end our speculative sojourn with another, culled from the protean imaginary of 1990s nanofiction: Peter F. Hamilton's *The Nano Flower*. Here, too, the plot concerns an extraterrestrial encounter, in this case between the heads of future Earth's most powerful corporation, Event Horizon, and an alien microbe scooped up by one of its space probes near Jupiter. The head of the project, Royan, discovers that the microbe contains unique, circular genetic material arranged in concentric layers. Naturally, he begins to splice this genetic material into terrestrial plants, searching for a way to exploit the microbe's unique rock-digesting properties to construct an "asteroid disseminator plant" that will consume asteroids and separate out various mineral ores. Royan imagines it functioning as "a single space-adapted bioware organism . . . there really would be rivers of metal pouring into the global economy. Enough to support Western-level consumerism right across the globe."[61] The alien organism acts as the basic building block of this dream of limitless production and consumption of commodities, catalyzing the magical production of flows of metal and money disarticulated from terrestrial ecology. As Royan explains to his partner Julia, the head of Event Horizon, "I'm on the verge of creating nanoware here, Snowy, the most powerful technology there is. . . . It's pure von Neumannism, self-replicating, and capable of producing anything you can supply a blueprint of."[62]

But there is a problem: when Royan replicates a large number of alien microbes, they self-organize into an intelligent entity, activating latent potentials in their active genetic systems, which contain both code and processing functions. The result is what Royan dubs the "Hexaëmeron," "a protean entity capable of fashioning itself to operate in any environment."[63] The Hexaëmeron is capable of editing its own genetic sequences on the fly, reprogramming itself to function within any environment in a form of real-time evolution. More than a mere *organism*, however, it contains within itself an entire planetary *ecosystem*:

> The reason the alien gene sphere is so large in comparison to terrestrial DNA is because the shells contain the genetic codes for over six thousand different species—plants, insects, animals, sentient creatures. Survivors of life's endgame. . . . Left alone, it can engender an entire planet's ecology. That's its sole purpose; what it was *designed* for.[64]

Like Walt Whitman, the Hexaëmeron is a "kosmos," existing at multiple scales as microbe and planetary ecosystem, embodied in an actual environment and containing the multitudes of potential environments, a virtual horizon that is, in its own words, "my planet's evolutionary terminus, and progenitor."[65] Royan and Julia come to understand that the alien being represents an existential risk for current Earth ecology. Perhaps ironically, they treat the alien as a corporate entity, negotiate a deal between it and Event Horizon, and end up supplying it with the means of venturing far out to other star systems in search of a planet where its colonization efforts will prove less disruptive to Earth's natural and industrial ecologies. Part Drexlerian nanoindustrial drama, part affirmation of Smallean nanoecological integrity, and part horror at radically alien life that is both machinic and organic, planetary and microscopic, *The Nano Flower* rehearses the basic aporias of the nanotech imaginary. Ultimately, the alien cannot be assimilated into Earth's ecology or industry—and thus ruptures the categories of technology, life, and ecology—because it is fundamentally transscalar. This scalar aporia, central to nanotech more generally, is thus an example of what Eugene Thacker describes as "a furtive, miasmatic unintelligibility that inhabits any ontology of life."[66] If our goal, as I have suggested along with Thacker, is to rethink life and ecology in nonanthropocentric ways, nanotechnology, in all its transscalar horror, both natural and supernatural, proves to be a generative starting point.

Conclusion

I have argued throughout this essay that nanotechnology, in both its actual and virtual dimensions, practically demands to be thought of as a form of ecology. Yet this extension of the concept of ecology produces a number of fractures within itself and within the nanotech imaginary, fractures that were perhaps already latent within them, like dormant or alien DNA. Most immediately, nanotech entities lyse the concept of life itself through their powers of self-assembly and organization into complex networks of material and energetic flow. They sense each other and thus "possess a world" in Heidegger's sense. Most strikingly, as I have argued, they possess a virtual dimension, a protean potential of becoming other. Yet they are also manipulable by entities at larger scales—potentially able to be captured by capital and organized into nanosized industrial machinery. We have even witnessed an incipient form of nano–deep ecology, an insistence by Richard Smalley that nanoecosystems are too resilient to be subjected to Drexlerian nanoindustrial development. Nanofuturists and speculative nanodevelopers are paradoxically hoping that they can exploit and feed nanoecology into the same capitalist production systems that are now exploiting macroecology, while simultaneously counting on the radical alterity of the nanoscale to produce a magical abundance, a nanoindustry that escapes the limits of the Earth's biosphere.

My argument is that an engagement with nanoecology requires that we question not only the magical thinking of nanocapitalists but also the often-anthropocentric deployment of ecology itself. While both nanotech and ecology contain their own humanist traps, they are complementary with regard to their posthuman potentials. Each contains what the other needs. As I argued at the beginning of this essay, ecology delimits its own boundaries with an implicitly humanist scalar and organic frame. The acquisition of a nonorganic horizon, coupled with a transscalar disciplinary opening or unfolding, would unbind ecology's fecund charting of interdependencies and engagement with the nonhuman from its scalar and organicist biases. Nanotechnology, as a speculative practice that is simultaneously discursive and material, already locates agency, vitality, and worlding beyond the organism. I have argued that it achieves this remarkable posthuman feat by engaging fundamental matter in creative forms of intra-action, taking seriously its agency as a generative, creative, and multidimensional assemblage of beings. At the same time, humanism and capitalism have conspired to rein in this radical potential, harnessing it as speculative industrialism, or the extension of business as usual to other scales. As my reading of the Drexler-Smalley debate makes clear, avoiding this pitfall requires an agile maneuver that simultaneously disavows the imposition of capital-industrial forms on the nanoscale (the negation of ecosystemic complexity) and ruptures the scalar disciplinary boundaries that pit the organic against the machinic (biology versus engineering). Ecology, as a knowledge system and praxis, provides precisely the tools required to pull off this feat. Nanoecology, then, marks the fluid ground where these two material-discursive structures may meet and become posthuman.

The nanocosmos is more than just another ecosystem to conserve or exploit; it ruptures the notion of ecology, opening it to its own latent transscalar potential. To take the challenge of nanoecology seriously, then, is to begin to think of ecologies across radically disparate scales, which may both entail and require an engagement with the protean magic of the nano: new horizons of conceptual and material becoming that cannot be contained at any single scale. Perhaps we can take the potentials of the nanocosmos as a call to allow scalar alterity its due and take inspiration from the radically other to explore new forms of production not modeled on industrial capitalism. What would the intermeshing of worlds implied by a transscalar ecology look like? Is it possible that this new landscape will turn out to be, to always have been, suffused with magic less concerned with the conjuring of human-scale commodities than with the production of new transscalar hybrids? Perhaps this is the price of contact with the Other World—the price of enchantment.

ABOUT THE AUTHOR

Zach Horton *produces research that reconsiders the intersections of media, technology, and ecology from the critical perspective of scale. He is preparing a book manuscript on the subject of scalar mediation, the cosmic zoom, and contemporary "particulate imaginaries." He currently teaches at the University of California, Santa Barbara. As a filmmaker, he recently completed a three-and-a-half-hour collaborative science-fiction film titled* Swerve, *about the entanglement between the virtual and the actual in a nanocontaminated dystopia (found online at http://www.swerveinterface.com).*

NOTES

1. Milburn, *Nanovision*, 167, 162.

2. Levin, "Problem of Pattern and Scale in Ecology," 1944.

3. Bissonette, preface, 23.

4. Cain, Bowman, and Hacker, *Ecology*, 8.

5. Thacker, *In the Dust of This Planet*, 5.

6. I use the term "posthuman" here in the sense of an explicit acknowledgment of the metaphysical assumptions that underlie historical humanism, along with an attempt to reconceive of our discursive and material practices without resorting to such shortcuts that place the human at the center of knowledge, agency, autonomy, and innovation. I am particularly indebted to Donna Haraway's cyborg theory (see Haraway, *Simians, Cyborgs, and Women*); to N. Katherine Hayles's insistence that information (and thus knowledge) is always embodied and distributed beyond the confines of the transcendental humanist subject (see Hayles, *How We Became Posthuman*); to Karen Barad's call to cleanse our understanding of physical matter of its humanist biases (see Barad, *Meeting the Universe Halfway*); and to Cary Wolfe's reminder of "the necessity for any discourse or critical procedure to take account of the constitutive (and constitutively paradoxical) nature of its own distinctions, forms, and procedures" (Wolfe, *What Is Posthumanism?*, 122).

7. Feynman, "There's Plenty of Room at the Bottom," 118.

8. Feynman, "There's Plenty of Room at the Bottom," 135.

9. The technique in question is the production of a set of robotic "slave hands" at a reduced scale, connected to a set of "master hands" that can control them remotely. Each pair of slave hands uses its reduced scale to fashion an even smaller set of hands, to an arbitrarily small size.

10. Heinlein, "Waldo," 81.

11. Drexler, *Engines of Creation*, 63.

12. Drexler, *Nanosystems*, sec. 8.1.

13. See, for example, Milburn, *Nanovision*, chap. 1; and McCray, *Visioneers*, chap. 7.

14. Hansma, "Surface Biology of DNA by Atomic Force Microscopy," 93.

15. See Borges, "On Exactitude in Science."

16. Gimzewski and Vesna, "Nanomeme Syndrome," 14.

17. Gimzewski and Vesna, "Nanomeme Syndrome," 14.

18. Gimzewski and Vesna, "Nanomeme Syndrome," 22.

19. Milburn, *Nanovision*, 13.

20. McDaniel, "Physical Matter as Creative and Sentient," 292.

21. Barad, *Meeting the Universe Halfway*, 23.

22. Barad, *Meeting the Universe Halfway*, 338.

23. Heidegger, *Fundamental Concepts of Metaphysics*, 196.

24. Brown, "Inorganic Open," 42.

25. Brown, "Inorganic Open," 39–40.

26. Heidegger, *Fundamental Concepts of Metaphysics*, 197.

27. Brown, "Inorganic Open," 41.

28. Brown, "Inorganic Open," 41.

29. See Barad, *Meeting the Universe Halfway*, 384.

30. Loeve, "Sensible Atoms," 210.

31. Loeve, "Sensible Atoms," 207.

32. Loeve, "Sensible Atoms," 212.

33. Goddard et al., *Handbook of Nanoscience, Engineering, and Technology, Second Edition*, sec. 10.8.

34. Schwarz and Nordmann, "'Hier Bin Ich Mensch, Hier Darf Ich's Sein!,'" 236.

35. McGehee, interview, March 20, 2013.

36. See "European Consortium Project to Explore Self-Healing Composites for Aerospace."

37. Cooper, *Life as Surplus*, 20.

38. Drexler, *Radical Abundance*, 13.

39. See, for example, McCray's excellent historiographical treatment of the subject in *The Visioneers*, chap. 7.

40. In 1996 Smalley and his team won the Nobel Prize in Chemistry for this work.

41. Smalley, "Of Chemistry, Love and Nanobots," 76.

42. Smalley, "Of Chemistry, Love and Nanobots," 76.

43. Smalley, "Of Chemistry, Love and Nanobots," 77.

44. Foresight Institute, "Drexler Writes Smalley Open Letter on Assemblers."

45. Drexler and Smalley, "Nanotechnology."

46. Drexler and Smalley, "Nanotechnology."

47. Drexler and Smalley, "Nanotechnology."

48. Drexler and Smalley, "Nanotechnology."

49. Drexler and Smalley, "Nanotechnology."

50. Drexler did in fact fail to declare a discipline as an undergraduate. He received his bachelor of science degree in "interdisciplinary sciences" from MIT, though his work was in computer science (McCray, *Visioneers*, 77).

51. McCray, *Visioneers*, 77.

52. Latour, *We Have Never Been Modern*, 12.

53. Bergson, *Matter and Memory*, 309.

54. I define scalar collapse as the conjoining of entities at two or more radically disparate scales within some form of speculative media that elides the difference between those scales. For an interdisciplinary discussion of scalar collapse, see Horton, "Collapsing Scale."

55. Holmyard, *Alchemy*, 15.

56. Heinlein, "Waldo," 109.

57. Heinlein, "Waldo," 72–73.

58. Drexler, *Radical Abundance*, 234.

59. Drexler, *Radical Abundance*, 208.

60. Joy, "Why the Future Doesn't Need Us."

61. Hamilton, *Nano Flower*, 416.

62. Hamilton, *Nano Flower*, 416.

63. Hamilton, *Nano Flower*, 511. In Jewish and Christian tradition, "Hexaëmeron" refers to the six days in which God created the world.

64. Hamilton, *Nano Flower*, 513–14.

65. Hamilton, *Nano Flower*, 509.

66. Thacker, *In the Dust of This Planet*, 268.

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