CONCLUSIONS

The agential realist elaboration of Bohr's philosophy-physics that I offer takes many of Bohr's insights seriously while making explicit the implicit ontological dimensions of his theory and moving these insights away from their humanist grounding. Despite important differences between them, Einstein and Bohr share a belief in humanism. However, humanism is based on ontological and epistemological presuppositions that are challenged by the quantum theory. Einstein wants the human observer removed from the system of interest while Bohr insists on the constitutive role of the human observer in measurement observations, but both presume that the notion of the "human" is a well-defined concept that refers to an individually determinate entity with inherent properties, like the ability to engage in cognitive functions that make the universe intelligible. This presupposition has been an obstacle to resolving some of the long-standing foundational problems in the quantum theory, such as the Schrödinger cat paradox, the EPR paradox, and the measurement problem. Agential realism resolves these issues in a way that is consistent with recent theoretical and experimental developments. Like other recent interpretations of the quantum theory, it is based on a relational ontology.[127]

The agential realist account does not position human concepts, human knowledge, or laboratory contrivances as foundational elements of the quantum theory. On the contrary, rather than giving humans privileged status in the theory, agential realism calls on the theory to account for the intra-active emergence of "humans" as a specifically differentiated phenomena, that is, as specific configurations of the differential becoming of the world, among other physical systems. Intra-actions are not the result of human interventions; rather, "humans" themselves emerge through specific intra-actions. And measurements are not mere laboratory manipulations but causal intra-actions of the world in its differential becoming. This means that quantum theory has something to say about the ontology of the world, of that world of which we are a part—not as spectator, not as pure cause, not as mere effect. Humanism takes the human to be exceptional. My posthumanist elaboration of Bohr's account understands the human not as a supplemental system around which the theory revolves but as a natural phenomenon that needs to be accounted for within the terms of this relational ontology. This conception honors Bohr's deeply naturalist insight that quantum physics requires us to take account of the fact that we are part of that nature which we seek to understand.

EIGHT

The Ontology of Knowing, the Intra-activity of Becoming, and the Ethics of Mattering

> Because believing a thing's true
> can bring about that truth,
> and you might be the shy one, lizard or electron,
> known only through advances
> presuming your existence, let my glance be passional
> toward the universe and you.
>
> —FROM ALICE FULTON, "Cascade Experiment"

Believing something is true doesn't make it true. But phenomena—whether lizards, electrons, or humans—exist only as a result of, and as part of, the world's ongoing intra-activity, its dynamic and contingent differentiation into specific relationalities. "We humans" don't make it so, not by dint of our own will, and not on our own. But through our advances, we participate in bringing forth the world in its specificity, including ourselves. We have to meet the universe halfway, to move toward what may come to be in ways that are accountable for our part in the world's differential becoming. All real living is meeting.[1] And each meeting matters.

CASCADE EXPERIMENT

> In the great future—we can arrange the atoms the way we want; the very *atoms*, all the way down!
>
> —FEYNMAN, "There's Plenty of Room at the Bottom"

Atoms aren't what they used to be. They aren't invisible, indivisible, immutable, impenetrable corpuscles running aimlessly in the void, constituting the sum total of existence; nor are they simply representative fictions, useful heuristics, or mere bookkeeping devices. Our evidence for the existence of atoms is multiple and robust, but it doesn't vindicate Democritus (nor any of the atomists up through the nineteenth century). Neither Democritus's atom nor his notion of realness, for that matter, survives today. Atoms have defied their inherited name—refusing the interpellative call of the mechanistic worldview. They simply aren't "uncuttable" little objects. And as for the famous void, well, it isn't all that is was supposed to be (or not be), either. According to quantum field theory, the vacuum is far from empty; indeed, it's teeming with the full set of possibilities of what may come to be. Matter is regularly created and destroyed. And the zoo of subatomic particles—including electrons, quarks, positrons, antiquarks, neutrinos, pions, gluons, and photons—isn't comprised of simple individual objects occupying specific positions in the vacuum we call space and time: not only is the very idea that they take up determinate positions in space not to be taken for granted, but part of their very nature seems to be wrapped up in the bubbling sea of possibilities that was to be but an inert backdrop for matter's passage. It's an ironic twist of history that the idea of an atom, proposed and adored throughout time for its simplicity (reducing diversity to order), is yielding such an intricate understanding of the nature of matter. It seems that the more fantastic our image of matter becomes, the more real it becomes (and vice versa).

As late as the end of the nineteenth century, many physicists were anti-realists in their stance toward atoms. Atoms were commonly held to be heuristic fictions, not bits of matter. Today scientists have no doubt that atoms are real. Not only do we have the means to "see" individual atoms, but we can pick them up, one at a time, and move them. Atomists as much as anti-atomists of yesteryear would no doubt be astonished by the technological feats we now regularly perform. Democritus's atom is not Newton's is not Dalton's is not Boltzmann's is not Einstein's is not Rutherford's is not Bohr's is not Feynman's. But this is not simply to say that the earlier images were wrong and we know better now, or that atoms are but social constructs that change as our ideas change. There's a much more interesting, and arguably more accurate, story to tell about this statement than either the naive realist account or the social constructivist account suggests. Not only has our image of the atom changed, but our practices of imaging and imagining and intra-acting with them have changed, and so have we.

During a *Morning Edition* program in the summer of 1996, the National Public Radio reporter Dan Charles pays a visit to the laboratory of the physicist Don Eigler at IBM's Almaden Research Center in the hills above San Jose, California. Charles sits down in front of a computer monitor and sets the stage for his audience as Eigler prepares to perform a maneuver at once of minute and gargantuan proportions:[2]

Dan Charles: The equipment Eigler has rigged up makes this seem simple, a lot less complicated, really, than your standard video game. All he has to do is sit down at his computer screen and go to work with the computer's mouse.

But this is no video game. Off in a different room, in a super-cooled vacuum chamber shielded from heat and vibration, Eigler is making a small change in the physical world, the most minute change possible.

Don Eigler: IBM scientist on a power trip here. I'm going to move an atom.

If you want to pick up a single atom, you need a very small pair of tweezers, one that's on the scale of the object you want to move. The tool that Eigler uses is a scanning tunneling microscope (STM) that has a special microscope tip that is so sharp there is only a single atom at the end of it, just the right scale for either "sensing" or "grabbing" hold of an individual atom.[3] With a few clicks of the computer mouse, Eigler maneuvers the STM tip so close to a gadolinium atom sitting on the surface of a piece of niobium that it begins to bond with the gadolinium atom. He moves the tip sideways, pulling the gadolinium atom across the niobium surface to a new location, and then pulls the tip back, releasing the atom.[4] The listening audience is treated to a sonic display of the single-atom manipulation, courtesy of Eigler's clever connection of the STM to a stereo that converts the strength of the "tunneling current" (used to sense the presence of an individual atom) to an audible tone:[5]

Don Eigler: OK, if you click on the left mouse button once, and we're out of the scanning mode. [sound of hum] See this little—an ounce of violet cursor here? That's where the tip is.

Oh, this is what's really cool. Watch this. We're going to move to this atom. [hum increases] Hear the frequency go up a little bit right there? Down. Up. That's a tip riding up on top of the atom, and when the tip goes up, the sound goes up, the frequency goes up. Now comes the fun.

[hum increases; sound of thumps] Ah, that was great. Every one of those thunks was the atom jumping from unit cell to unit cell across the surface, moving roughly one atomic diameter, and look, there it is—we moved it.

The proof is in the hearing. During the sideways tug of the gadolinium atom across the niobium surface, the audience hears distinct "thunks" as the atom is pulled across the unit cell structure formed by the spaces between the niobium atoms on the surface: that is, one can hear the atom being moved.

Then the NPR reporter Dan Charles is given a turn:

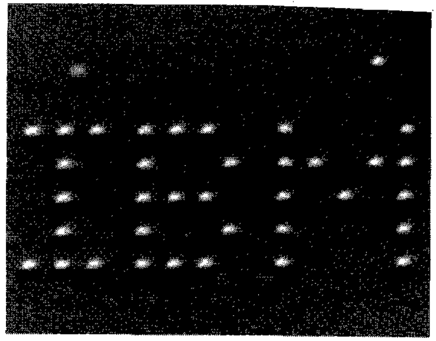
> *Don Eigler*: OK, now you're going to press and hold down the left mouse button. [sound of thump] You've got it. Try moving the mouse, holding the button down. [sound of thumps] OK. You've got the atom stuck over here on a step edge. That's OK. Let go. Oh, you still have it. Let go. See what happens.
> *Sound of thump*
> *Dan Charles*: There it is.
> *Don Eigler*: What you really need to see right now is the look on your face when you were moving an atom, and what you experienced while you were doing that is something that we experience also. It is the enormity of what you're actually doing, of just taking an atom and putting it where you want to go. You're controlling the structure of matter on the atomic level.

The interview with Eigler was the last installment in a three-part series on nanotechnology, and for those in the know, there was little surprise that Eigler was an honored guest.[6]

Don Eigler's fame as a nanotechnologist grows out of this remarkable discovery. Eigler and his colleague Erhard Schweizer reported their finding in an April 1990 issue of the journal *Nature*, where they dramatically displayed their achievement by using their STM to produce the world's smallest logo built from individual atoms (Eigler and Schweizer 1990). No one who has seen their image is likely to forget their institutional affiliation (see figure 30).[7]

In rearranging a few atoms on a surface, Eigler reconfigures our imaginations and the material possibilities for imaging, while undergoing his own set of transformations. A first-order phase change takes place as he is rapidly transformed into a new kind of expert—a nanotechnologist. Indeed, for some, he has become *the* emblematic nanotechnologist. And while nearly everyone in the nanotechnology business seems to have his or her own favorite promising candidate for how the future will be built, it is not at all surprising that Eigler's work sparked the immediate interest of nanotechnology enthusiasts who predict that humankind will be building machines and tools out of assemblages of individual atoms or molecules in the not-too-distant future. Eigler is a prime contributor to this stage of the new revolution, a fact that he explicitly acknowledges: "For decades, the electronics industry has been facing the challenge of how to build smaller and smaller structures. For those of us who will now be using individual atoms as building blocks, the challenge will be how to build up structures atom by atom."[8] The key to this future is not representing but intervening: not simply the imaging of atoms, but the ability to manipulate them.

The philosopher Ian Hacking's manipulability criterion for the reality of



30 The world's smallest logo, made out of thirty-five xenon atoms. A similar image, appropriately colored blue and titled "The Beginning," can be found in the IBM STM image gallery. This is now just one of many images of atom arrangements created with a scanning tunneling microscope (see, for example, the IBM STM image gallery on their website). *Reprinted with permission of IBM Research, Almaden Research Center.*

atoms seems at once on the mark and already dated by new technological advances. Recall that Hacking argues that while scientists need not take the objects of their investigations to be real, they have no choice but to believe in the reality of the tools that they use to manipulate objects: "Experimenting on an entity does not commit you to believing that it exists. Only *manipulating* an entity, in order to experiment on something else, need do that" (Hacking 1983, 263).[9] But the example of atom manipulation by an STM makes Hacking's claims for entity realism seem far too timid. What would be the justification, in this case, for any less confidence in the reality of the objects as opposed to the tools used to manipulate them? More to the point, what this example brings to the fore is the need to call into question the determinate category designations of "tools" and "objects" that Hacking's formulation assumes. Indeed, the lack of a fixed object-apparatus distinction is key to Eigler's group's ability to manipulate atoms.

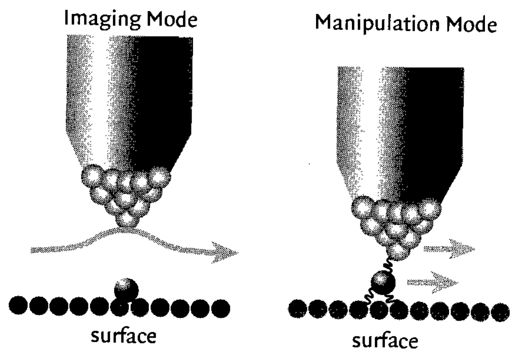
According to Eigler, "Atom manipulation came about almost by accident" (1999, 430). Encountering some "unusual streaks" across the STM images they were producing, Eigler and Schweizer decided to investigate. They found that the presence of the streaks was related to the operation of the microscope. If they brought the tip of the microscope sufficiently close to the sample, then streaks would appear. Eigler says that "this immediately suggested that we could use the tip to control the position" of the individual atoms (431), and so they set out to do just that:

> Trying out our ideas required modifications to the software we used to operate the microscope. Within a day the necessary modifications were made. These modifications allowed us to switch from an imaging mode where the

> tip executed a raster scan of the surface, to a mode in which we could move the tip of the microscope along any desired path across the surface, and with a tunnel current different from that used for imaging. With these modifications in place, I began by imaging an isolated xenon atom which was bound to a defect site on the platinum surface. I then stopped imaging, moved the tip directly over the xenon atom, increased the magnitude of the tunneling current in order to bring the tip a little closer to the xenon atom, and then I had the computer move the tip from the location where the xenon atom originally was to a new location not too far away. Once the tip reached the new location, I reduced the magnitude of the tunnel current in order to increase the separation between the tip and the xenon atom and thus return to the imaging mode. Next, I re-imaged the surface to find that the xenon atom had been successfully moved to the location of my choice. I then repeated the same experiment four times, and it worked each time. With this xenon atom, the milestone was achieved. (431–32)

Switching back and forth between imaging and manipulation modes, Eigler and Schweizer were able to both move individual atoms *and* demonstrate that that was in fact what they were doing (see figure 31). That is, in the hands of Eigler and Schweizer, the STM became a device for moving and for proving, for "intervening" and "representing" (to use Hacking's old terms).

Significantly, imaging and manipulating are complementary, that is, mutually exclusive modes of operation. In imaging mode, the "adatom" (in this case the xenon atom) is part of the surface being imaged (i.e., the object); whereas in manipulation mode, the "adatom" becomes part of the microscope tip (i.e., the agencies of observation). In fact, in the time-honored tradition of enlisting the sense of sight (and its limits) as a metaphor for knowing, Eigler invokes the well-worn example of the blind person with a cane to help convey the "haptic" sense of knowing that comes from operating an STM.[10] On Eigler's reckoning, STM imaging is akin to the practice of "cane traveling," the skillful practice a blind person uses to "see" or grasp the terrain. This is reminiscent of the example Bohr uses to help a general audience understand complementarity and Merleau-Ponty uses to describe the nature of embodiment (see discussion in chapter 4). Recall that Bohr's discussion focuses on two possible complementary practices: on the one hand, the man can hold the cane tightly so that it functions as an instrument of observation (an extension of the person trying to negotiate the room); on the other hand, he can hold it loosely so that it becomes an object of observation.[11] The cane is neither inherently part of the object nor the agencies of



31 Eigler and his colleagues reconfigured the STM so that they could switch back and forth between "imaging mode" (*left*) and "manipulation mode" (*right*) by changing the tunneling current. In imaging mode, the adatom sits on the surface and is imaged by the STM. In manipulation mode, the tunneling current between the adatom and the tip is increased, and the tip is used to move the adatom along the surface. *Illustration by Nicolle Rager Fuller for the author.*

observation. The line between subject and object is not fixed and it does not preexist particular practices of their engagement, but neither is it arbitrary. Rather, object and subject emerge through and as part of the specific nature of the material practices that are enacted.[12]

For Bohr, the relation between knower and known is much more intimate than either the notion of intervention or even the shift from sight to touch suggests: distance is not a prerequisite for objectivity, and even the notion of proximity takes separation too literally. Bohr argues that quantum physics teaches us that the belief in an inherent fixed Cartesian distinction between subject and object is an unfounded prejudice of the classical worldview, and that the acknowledgment of the inherent indeterminacy of object and apparatus, the material resolution of the indeterminacy, and the inseparability of their relation as it is materially enacted constitute the very possibility for understanding quantum phenomena objectively. Hacking's notion of intervening simply doesn't cut it. Against Hacking's "Don't just peer, interfere," an alternative motto might be "Not simply intervene, enact the between." Intra-acting, not merely intervening, is entailed in both experimental and theoretical practices.

What could be a more compelling emblem of the triumph of the scientific enterprise and its claims to scientific realism than the world's smallest corporate logo? Indeed, on the surface, the mini-IBM logo appears to be nothing less than the most literal incarnation imaginable of representationalism's claim of the one-to-one correspondence between words and things—the logos made flesh in its most base form, as if the result of some youthful naïveté that has mistaken the metaphoric for the literal. Arguably, however, this image marks the limits, rather than the confirmation, of this belief system. As one reporter commenting on one of Eigler's images aptly notes: "One almost could envision the cursive writing of René Magritte under the image: 'Ceci n'est pas un atom.' "[13] As with Magritte's famous painting *Ceci n'est pas une pipe*, the point is not that it really isn't a pipe but only a representation of a pipe, but rather that representations do not simply refer in ways that we have come to expect, that in fact the entire question of referentiality seems to have lost its self-evidentiary nature and givenness has lost its transparency, and we can no longer see our way through the game of smoke of mirrors that representationalism has become. Like a good magician, representationalism would have us focus on what seems to be evidently given, hiding the very practices that produce the illusion of givenness.

Although the STM images in the IBM gallery were created at temperatures near absolute zero so that the atoms placed in specific locations stick to the surface (and to our imaginations) "like little refrigerator magnets," they are not snapshots of preexisting things frozen in time—caught in the act as it were—but rather condensations of multiple material practices across space and time. Reading the phenomena—the difference patterns through which space, time, and matter come to be—including all the various apparatuses that help produce the illusion of the self-evidentiary nature of "the given" allows the frozen images to thaw out and the subject matter to come alive. The entangled sets of practices that go into making these images include: STM microscopes and practices of microscopy, the history of microscopy, scientific and technological advances made possible by scanning tunneling microscopes, the quantum theory of tunneling, material sciences, IBM's corporate resources and research and development practices, scientific curiosity and imagination, scientific and cultural hopes for the manipulability of individual atoms, Feynman's dream of nanotechnologies, cultural iconography, capitalist modes of producing desires, advertising, the production and public recognition of corporate logos, the history of the atom, the assumption of metaphysical individualism, complex sets of visualizing and reading practices that make such images intelligible as pictures of words and things, and the intertwined histories of representationalism and scientific practice. And this is merely an abbreviated list that doesn't even scratch the surface when it comes to the kinds of genealogies that are needed to give an objective accounting of the micrograph. This is not to say that each particular scientific practice includes everything under the sun, but rather "only everything relevantly interrelated" (Rouse 2002, 283). What is required is a joint effort that relies on multiple forms of literacy to make explicit the different apparatuses that are a part of the phenomenon being investigated (see Barad 2000).

In my agential realist account, scientific practices do not reveal what is already there; rather, what is "disclosed" is the effect of the intra-active engagements of our participation with/in and as part of the world's differential becoming. Which is *not* to say that humans are the condition of possibility for the existence of phenomena. Phenomena do not require cognizing minds for their existence; on the contrary, "minds" are themselves material phenomena that emerge through specific intra-actions. Phenomena are real material beings. What is made manifest through technoscientific practices is an expression of the objective existence of particular material phenomena. This is, after all, a realist conception of scientific practices. But unlike in traditional conceptions of realism, "objectivity" is not preexistence (in the ontological sense) or the preexistent made manifest to the cognitive mind (in the epistemological sense). Objectivity is a matter of accountability for what materializes, for what comes to be. It matters which cuts are enacted: different cuts enact different materialized becomings.[14]

Once it becomes feasible to manipulate individual atoms, the possibilities for making new configurations of atoms open out before us. In fall 2002, Don Eigler was back on National Public Radio talking about his lab's latest achievement. Ira Flatow, NPR science correspondent and host of *Talk of the Nation: Science Friday*, sets the stage:[15]

> *Ira Flatow:* How small can computers get? Just about every computer chip maker is trying to shrink their chips or to pack more power into the same size space, and last week in the online edition of the journal *Science*, researchers at IBM reported that they have built what they're calling the smallest computer chip circuit yet—one bil . . . one trillionth, that's one *trillionth* of a square inch—and to get it that small they had to make it out of individual molecules. Now the device is slow, it's impractical, but it can perform some of the basic operations for computing and it does it in a space about 260,000 times smaller than the most advanced silicon chips.[16]

Eigler explains that they are able to build operating logical circuits using a "molecule cascade," which they set up and initiate with their STM.[17] The analogy he draws is to the familiar cascading of dominoes:

> *Don Eigler*: "[It's] like playing with dominoes. You can imagine how you can set up a row of dominoes and then when you topple an initial domino it causes the whole chain of dominoes to fall over sequentially. We've done something just like that, but imagine instead of something as large as a domino, that the domino is made up out of, in our case, just two atoms forming a carbon monoxide molecule. And then by laying out the carbon monoxide molecules we can topple the first one sort of by hand, with the best hand we have that let's us interact with atoms, and then away it goes . . .

The "dominoes" are set up and the "topple" is initiated using the IBM researcher's "set of hands to the world of atoms and molecules"—a scanning tunneling microscope.

Taking in this latest development, one gets the distinct impression that this "cascade" experiment is not only a miniature mechanism for making computers on a scale that may soon leave silicon technologies in the dust, but also a metaphor for the increasingly rapid development of nanotechnologies that awaits us. But matter and meaning, the literal and the figurative, are never as separate as we like to pretend, and therefore no argument will be able to arrest the expanding public sentiment that the cascade experiment is much more than a metaphor, that the tiniest changes, rearrangements in the configurations of atoms, hold the literal potential to tunnel across different scales of space, economy, and imagination, that they may initiate a chain reaction in the not-too-distant future that will fan out and explode into a host of new technologies and reorganizations of power connecting the most minute to the most gargantuan. Nanotechnologies have been characterized by the refrain that anything that already exists on the horizon of our imaginations is already too limited a projection of the new sciences' potential. If Foucault is correct in his assessment that power operates through the specific constitution of bodies and subjectivities, then nanotechnologies have the potential to reconfigure the materiality of our being all the way down to the very atoms of existence, and beyond, to a point where individuality is itself undone by the specific entanglements of becoming that transcend the distinctions between bios and technics, organic and inorganic, artificial and natural, mind and body. Foucault's "microphysics of power" would not simply be operative at the scale of individual atoms; scale itself would be iteratively reconstituted as spacetimematter is reconfigured.

"NanoQuébec," a Canadian nonprofit organization committed to the development and commercial application of nanotechnologies, is but one of a growing number of appellations that visually perform a society's investment in re(con)figuring economies of scale, from the minute to the global. Not only are nation-states willing to consider reconstituting themselves in alignment with atomic reconfigurings, but no scale seems too large or small to conquer. Aerospace engineers, for one, are champing at the bit to learn from Mother Nature her secrets to molecular design that will enable machines to sense their environments, reproduce and disperse themselves, and carry out self-repair and regeneration, expanding the frontiers of exploration well beyond our solar system. Machines will generate new life; life will be reworked. The nanoscale is the scale of life processes, and the combination of computational nanotechnology and bio-nanotechnology foretells the possibilities of neuroelectronic interfaces that use nanodevices to join computers to the human nervous system. With one hand on a computer mouse and an eye to the future, not only do we make changes to configurations of individual atoms, but the very nature of who "we" are begins to shift. Our imaginations, bodies, desires, organizational structures of research and investment, and much more quake with the expectation of the impending "nano-tsunami" that portends immense changes to life on earth and beyond. "The economic potential [alone] of this new field of activity is dizzying. Studies estimate that the world nanotechnology annual market could reach more than a trillion dollars within twelve years."[18]

Already the potential of these new developments is generating new international and transnational configurations of university, industry, and government laboratories. Knowledge and product making are being reconfigured. The authors of a popular book on nanotechnology note that the "fusion of interdisciplinary knowledge coming together at the nanoscale will be one of the great benefits nanoscientists will introduce into our lives."[19] Those who would offer a requiem for physics while touting the new supremacy of the biological disciplines have failed to appreciate the transdisciplinary networks of knowledge and product making—transcending the divisions between physical, biological, and engineering disciplines—that are being (re)configured at a pace that humanities proponents of transdisciplinarity only dream about. The National Nanotechnology Initiative (NNI) website already boasts dozens of nanotechnology centers sponsored by the National Aeronautics and Space Administration (NASA), the National Science Foundation, the Department of Defense, and the Naval Research Laboratories.

It appears that the branching chain reaction has already been initiated and that ethical, legal, and social considerations seem destined to be forever behind the curve of cascading technological advances. But there is more to causality than the runaway scenario that unfolds in deterministic fashion.

Dominoes are surely not what Alice Fulton had in mind in her poem "Cascade Experiment," with its ethico-onto-epistemic attention to our responsibilities not only for what we know but for what may come to be. A cascade in Fulton's sense is not a serial chain of consequences, an inevitability set in motion by some initial act, but an iterative reconfiguring of possibilities entailed in our passional advances toward the universe.

BIOMIMICRY, MIRROR IMAGES, AND THE OPTICS AND POLITICS OF REFLECTION

> Silently and efficiently, the new team member toils away in a chemistry lab at the University of California at Santa Barbara. With perfect precision, she lays down an ultrathin layer of an organic substrate. Onto this, she deposits interlocking calcite crystals, atom by atom. The two layers bond into a delicate crystal lattice. Under a microscope, it calls to mind the flawless thin-film layers on a silicon chip.
>
> But there is no clean room, vacuum chamber, or chip gear in this lab, where professors Galen D. Stucky and Daniel E. Morse brainstorm new materials. For that matter, the "team member" is no ordinary staff researcher. She's a mollusk—an abalone. And like so many of nature's creations, she has acquired, through millions of years of evolution, an exquisite form of molecular machinery to create her shell—machinery that leaves today's best fabrication tools in the dust.
>
> —NEIL GROSS AND OTIS PORT, "The Next Wave for Technology"

"The only true nanotechnologist today is Mother Nature," explains Michael Roukes, a California Institute of Technology physics professor, "but slowly humans are learning to mimic her handiwork."[20]

In her 1997 book entitled *Biomimicry: Innovation Inspired by Nature*, the nature writer and conservationist Janine Benyus names "an emerging discipline that seeks sustainable solutions by emulating nature's designs and processes."[21] According to Benyus, biomimicry marks the beginning of a new postindustrial era: "Unlike the Industrial Revolution, the Biomimicry Revolution introduces an era based not on what we can extract from nature, but on what we can learn from her." Benyus has received several awards, including the Rachel Carson Environmental Ethics Award. She is the cofounder of the Biomimicry Guild, which brings biologists, industrialists, inventors, and designers to the drawing board, teaching clients that include Nike, Hewlett-Packard, and Novell to draw inspiration from nature to solve

human problems. Biomimicry is being hailed as nothing less than an answer to Rachel Carson's *Silent Spring*, but even biomimicry's strongest proponents, Benyus included, acknowledge that, like other technologies, it will not necessarily be spared the dangers of misuse and abuse:

> Biomimics develop a high degree of awe, bordering on reverence. Now that they see what nature is truly capable of, nature-inspired innovations seem like a hand up out of the abyss. As we reach up to them, however, I can't help but wonder how we will use these new designs and processes. What will make the Biomimicry Revolution any different from the Industrial Revolution? Who's to say we won't simply steal nature's thunder and use it in the ongoing campaign against life?
>
> This is not an idle worry. The last really famous biomimetic invention was the airplane (the Wright brothers watched vultures to learn the nuances of drag and lift). We flew like a bird for the first time in 1903, and by 1914, we were dropping bombs from the sky. (Benyus 1997)

Mimicry is the highest form of flattery, or so the saying goes. Perhaps this familiar adage provides a clue to why biotech companies might be interested in biomimesis, not only as a method but as camouflage against the prying eyes of would-be critics. Some biotech companies have already enlisted biomimesis in their attempts to hoist themselves above the murky pool of ethical, legal, and social concerns, posing as benign inventors, if not downright all-natural Mother Nature–loving sustainability advocates. Camouflage, of course, is nature's own biomimetic technology, imitated and popularized by the military during World War I. Imitating imitation is nothing new, but the forms mimesis is taking are.

A Canadian biotech company recently purchased a decommissioned U.S. Air Force base on the American side of the border just outside Plattsburgh, New York, to farm genetically engineered Spidergoats, thousands of them; but Jeffrey Turner, founder, president, and CEO of Nexia Biotechnologies, isn't interested in cloning goats per se.[22] Referring to Dolly as a "scientific stunt," Turner explains to one reporter that "Nexia's project is less about altering nature than harnessing it. The company's goal isn't to create weird goats; they're merely a means of producing useful quantities of spider silk, a simple substance created eons ago by natural evolution. . . . What Nexia is really up to isn't mere genetic engineering, it's 'biomimicry.' "[23] Spider silk is the holy grail of material sciences—it's five times stronger than steel and stretches 30 percent farther than most elastic nylon—with a host of medical, industrial, and military applications, including biodegradable sutures for surgery, replacement ligaments or tendons, industrial fibers, and bullet-proof vests. There are even recreational applications like fishing line and tennis racket strings. Even the haute-couture fashion world is already salivating over the possibilities of spinning new fabrics.

"It's way beyond anything we humans can make. Milled steel pales next to it." Turner is awed by the ingenious engineering talents of the spider, which, he explains, were honed by the competitive pressures of nature's own military exploits: "The spider's evolution comes out of a kind of arms race between spiders and bugs. The bugs start flying to get away from spiders, so the spiders have to come up with a new weapon." Well, then, what could be more natural than scientists at the Canadian biotech company Nexia teaming up with the Materials Science Team of the U.S. Army Soldier Biological Chemical Command to take some lessons from spiders? (Who's copying whom? Is copying ever not a form of self-replication? When it's all done with mirrors, it's difficult, if not impossible, to find out who's really spinning the sticky web.) Emulating not only nature's best ideas for peaceful coexistence but also its ingenuity in the face of military challenges, this is taking nature as inspiration to a new level. And much like the envious fecundity of Mother Nature's symbiotic relationships, the relationship between Canadian-based Nexia and the U.S. military is proving to be very productive indeed. In the January 2002 issue of the journal *Science*, this international interdisciplinary industrial-military hybrid team announced a major materials-science breakthrough: a way to spin silk from goat's milk (Lazaris et al. 2002). The implications and the payoff from this research are potentially enormous. Nexia now holds the patent on a recombinant spider silk, trade-named BioSteel®, and it is moving rapidly toward commercial development. BioSteel®, according to the company and its promoters, has the additional advantage of being eco-friendly in both its composition (it is biodegradable) and its production process (which is water based), as opposed to most other synthetic fibers.[24]

So while Nexia is busy making recombinant spider silk for a host of medical, military, and industrial applications by taking genes from golden orb-weaving spiders and putting them into fertilized goat eggs so that the goat will secrete spider silk into its milk, which can be profitably harvested by the company, Turner is spinning the yarn, flattering the spider's talents for manufacturing a materials-science wonder—"a self-assembling, biodegradable, high-performance, nanofiber structure one-tenth the width of a human hair that can stop a bee traveling at 20 miles per hour without breaking."[25] And so it shouldn't surprise us that when Jeffrey Turner is asked the "big-E" ethics question that many biotech company execs treat with great annoyance, as if such questions are pesky little black flies that keep swarming no matter what public relations repellent is applied, he responds with the confidence of a jujitsu master, smiles at the futility of fly swatting, and instead uses the fly's own energy, working in concert with the spider, to outwit the flies at their own game: with great aplomb, Turner calmly mimics the "biomimicry" biomimics. What could be more natural than taking nature as inspiration? Even nature does it. No wonder Jeffrey Turner claims to be a practitioner.

Benyus is well aware of the potential for the misuse of biomimicry. In fact, she points specifically to Nexia's transgenic "mimicking" (the quotation marks are Benyus's) of spider silk, which turns goats into "cheap factories" (this description is Turner's), as a case in point:[26] "Every fiber of my being cries when I hear that. That's the antithesis of the kind of respect, the maturity that we need. So I think in terms of what we shouldn't be doing, I think this transgenic engineering is the height of hubris. It's a biological transgression of the worst kind."[27]

Benyus has a principled complaint against transgenic engineering: nature doesn't do it—nature doesn't trade genes across classes of organisms—and so we shouldn't, either. That is, Benyus advocates adopting nature not only as model but also as mentor and measure: "If nature as model says, 'What would nature do here?' nature as measure says, 'What wouldn't nature do here?' " (ibid.). In other words, Benyus's ethical principle for biomimicry is biomimetic: "Biomimicry says: if it can't be found in nature, there is probably a good reason for its absence. It may have been tried, and long ago edited out of the population. Natural selection is wisdom in action."[28]

Now, the suggestion of an ethics based on the principle of following nature's lead will no doubt sound like an all-too-familiar drone for some, and for good reasons. Natural law arguments for social policy abound, and there are copious examples of misguided attempts to enlist nature as a justification for every possible social prejudice, including racism, sexism, and homophobia. Social Darwinism is a well-known example illustrating the dangers of biomimicry as a social or ethical principle. Going back to Friedrich Engels, critics of social Darwinism have argued that Darwin takes his inspiration from social and economic doctrines based on competition and survival of the fittest, reads them into nature, and then social theorists use Darwin's "nature" to justify social policy based on natural selection, saying that they are simply taking their inspiration from nature.[29] But the dangers of entering this house of mirrors have not escaped Benyus, who explicitly warns against taking our ethical principles from the natural world:

> For people as they did during the period of Social Darwinism to look to the natural world to figure out who should live and who should die or who should breed—that's really, really dangerous, I think. Because how other organisms are being judged by natural selection and the kinds of societies that they've knit together, we can't pick a species and say we should be more like that. I think looking to nature for our mores and our ethics and our morality is really dangerous. We are a unique species, an ethical moral animal, and there are some places that it just doesn't fit.[30]

This advice—to look to nature as an ethical measure but not as a basis for our ethical principles, "to judge the rightness of our innovations" based on nature's designs but not to judge the rightness of our actions based on nature's way of doing things—seems reasonable enough at first glance. However, this principle ultimately falters on the very issue that the example of social Darwinism brings to light: how are we to understand the notion of "nature" that is being invoked? Benyus's principle relies on a belief in human exceptionalism and a hard distinction between nature and humans: we humans are a species unique in all the animal kingdom by virtue of our ethical character; we are historical creatures; while nature, on the other hand, has a givenness that is outside of culture; nature is found in the rain forest and the swamp, environments threatened by (nonindigenous) human culture(s). Furthermore, Benyus's distinction seems to presume that designs are simply transparently there in a way that actions may not be, that we have an immediate access to nature's designs in a way that gets clouded when we turn to observing behaviors, that material designs can be separated from the agential practices that produce them. This presumption that there is a pure nature separate from culture operates throughout Benyus's work. As with all mirroring practices, biomimicry has a built-in optics based on a geometry of distance from that which is other. But is there a "pure nature" (both epistemologically and ontologically speaking) to which we can turn for inspiration? And how pure is this implied notion of purity when its invocation throughout history has helped to perpetuate some of the most heinous crimes known to humankind? (Isn't the very notion of "race" nothing save the notion of "purity" put into practice?) Furthermore, and with astonishing irony, the discourse of nature as separate from culture seems strikingly out of step with the very practices of biomimetics, which, not incidentally but rather by virtue of its own principles, actively reworks the boundaries between nature and culture. And isn't the undoing of the very idea of an inherent nature-culture boundary a useful tool, if not a prerequisite, for

destabilizing sexism, racism, and homophobia and other social ills that are propped up by this dualism and its derivatives? It is ironic that while environmental activists are busy reifying a notion of nature based on purity, with all its problematic implications, the enterprise of bioengineering is making it crystal clear that the nature-culture dualism is a construction, a point that feminists and other social critics have been trying to get across for some time. What is at issue and at stake is "what counts as nature, for whom, and at what costs" (Haraway 1997, 104).[31]

This is not an argument for or against biomimetics or other technoscientific practices writ large. On the contrary, the point is that these practices hold both incredible promise and unfathomable dangers. Which is not the end point but the beginning point for ethical considerations.

DIFFERENCES THAT MATTER: DIFFRACTIONS, DIFFERENTIAL EMBODIMENT, AND THE ONTOLOGY OF KNOWING

> The "eyes" made available in modern technological sciences shatter any idea of passive vision; these prosthetic devices show us that all eyes, including our own organic ones, are active perceptual systems, building in translations and specific ways of seeing, that is, ways of life. There is no unmediated photograph or passive camera obscura in scientific accounts of bodies and machines; there are only highly specific visual possibilities, each with a wonderfully detailed, active, partial way of organizing worlds. . . . Understanding how these visual systems work, technically, socially, and psychically ought to be a way of embodying feminist objectivity.
>
> —DONNA HARAWAY, *Simians, Cyborgs, and Women*

"Eyeless Creature Turns Out to Be All Eyes," announces the *New York Times*. The *Times* article summarizes the results of a study published in the August 23, 2001, issue of the scientific journal *Nature*, in which an international team of material scientists, theoretical physicists, chemists, and biologists report their amazing finding that the brainless and eyeless creature called the brittlestar, an invertebrate cousin of the starfish, sea urchin, and sea cucumber, has a skeletal system that also functions as a visual system.[32]

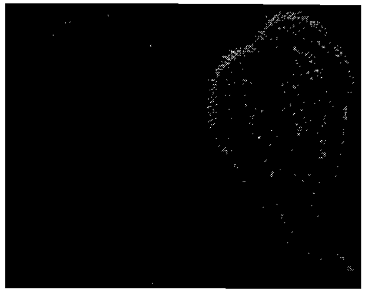
> The brittlestar, a relative of the starfish, seems to be able to flee from predators in the murky ocean depths without the aid of eyes. Now scientists have discovered its secret: its entire skeleton forms a big eye. A new study shows that a brittlestar species called *Ophiocoma wendtii* has a skeleton with crystals

> that function as a visual system, apparently furnishing the information that lets the animal see its surroundings and escape harm. The brittlestar architecture is giving ideas to scientists who want to build tiny lenses for things like optical computing.

The researchers found that the approximately ten thousand spherically domed calcite crystals covering the five limbs and central body of the brittlestar function as microlenses, and that the microlenses collect and focus light directly onto nerve bundles that are part of the brittlestar's diffuse nervous system. Remarkably, the brittlestars secrete this crystalline form of calcium carbonate (calcite) and organize it to make the optical arrays. According to Dr. Alexei Tkachenko of Bell Laboratories, one of the authors of the study, "The brittlestar lenses optimize light coming from one direction, and the many arrays of them seem to form a compound eye" (quoted in the *Times* article). "It's bizarre—there's nothing else that I know of that has lenses built into its general body surface," says Michael Land, who studies animal vision at the University of Sussex in Brighton, England.[33]

The fact that certain species of brittlestars respond to light was already well established, but the mechanism of their superior visual capacity was not known.[34] These photosensitive brittlestars are able to navigate around obstacles, flee from predators, and detect shadows. They also turn lighter in color at night and darker during the day (see figure 32). At first glance, this evolutionary strategy seems ill conceived, since it increases their visibility to predators. But if the brittlestar's goal is to increase its vision (the better to avoid predators), to collect as much light as possible during the night, and likewise to protect its visual system from oversensitivity, overexposure to light, during the day (the better to put on "sunglasses"), then nature's selective process seems justified.

To test their hypothesis that "these calcitic microstructures might have a function in directing and focusing the light on photosensitive tissues" (Aizenberg et al. 2001, 820), the researchers at Bell Labs used a technique called optical lithography, which is a process also used for inscribing circuits on microchips: "To detect and visualize the lensing effect, we designed a lithographic experiment. A DAP [dorsal arm plate] of *O. wendtii* [one of the species that exhibit photosensitivity] was cleansed of organic tissue, and a low-magnification scanning electron micrograph (SEM) of its dorsal surface was recorded as a reference image." Figure 33a shows the SEM of the dorsal arm plate cleansed of organic material; in figure 33b, the SEM (using greater magnification) of the peripheral layer of a dorsal arm plate clearly shows the lens structures of *O. wendtii.*



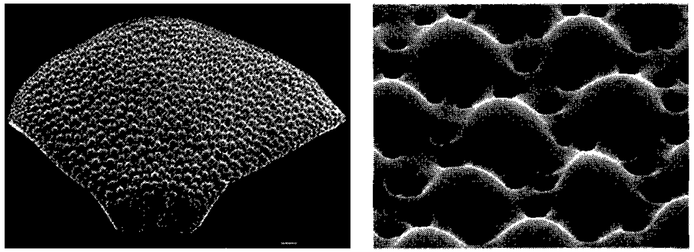
32 Photosensitive brittlestar. From J. Aizenberg et al., "Calcitic microlenses as part of the photoreceptor system in brittlestars," *Nature* 412 (2001): 819, figure 1b. *Reprinted with permission of Macmillan Publishers Ltd. Images courtesy of Nature Publishing Group, London.*

The lensing system was analyzed by placing the prepared sample on a silicon wafer. Mimicking the process used to optically engrave circuits on a silicon wafer in the making of microchips, the researchers shined light through the lenses, etching the photosensitive wafer. By analyzing the etchings, the researchers were able to deduce the focal length of the lenses. This was compared to a transmission electron microscopy study of thin sections of decalcified dorsal arm plates, which revealed *bundles of nerve fiber located precisely at the focal plane of the lens system.* On the basis of this finding, the researchers offered the following conclusion: "We suggest that the array of calcitic microlenses with their unique focusing effect and underlying neural receptors may form a specialized photoreceptor system with a conceivable compound-eye capability" (Aizenberg et al. 2001, 821).

In talking with the press, Joanna Aizenberg, a Bell Labs scientist and the lead author of the study, also makes use of the more high-tech comparison to a digital camera that builds up a picture pixel by pixel.[35] In this exchange, one quickly loses track of whether the digital camera is a metaphor for brittlestar vision or the reverse, especially as the metaphor begins to take on a strikingly material form:

> Instead of trying to come up with new ideas and technology, we can learn from this marine creature. . . . The [calcitic] lenses surround the whole body, looking in all different directions and providing peripheral vision to the organism. . . . This is the quality we all want to incorporate in optical devices, in cameras in particular. Instead of having one lens pointing in one direction, you could have thousands of lenses pointing in different directions. This will give you perhaps a 360-degree view of the whole space.[36]

In summary, the remarkable finding of this international multidisciplinary team of scientists is that the brittlestar's skeletal system is composed of



33 The image on the left (*a*) shows a scanning electron micrograph (SEM) of the dorsal arm plate of a brittlestar (*O. wendtii*); the image on the right (*b*) is an SEM (increased magnification) showing calcite lenses on the peripheral layer of a dorsal arm plate skeletal section. From J. Aizenberg et al., "Calcitic microlenses as part of the photoreceptor system in brittlestars," *Nature* 412 (2001): 819, figures 1c and 1f. *Reprinted with permission of Macmillan Publishers Ltd. Images courtesy of Nature Publishing Group, London.*

an array of microlenses, little spherical calcite crystal domes (on the order of tens of microns in diameter) arranged on its surface, which collect and focus light precisely on points that correspond to the brittlestar's nerve bundles, part of its diffuse nervous system, suggesting that the combined system seemingly functions as a compound eye (an optical system found in insects).

Roy Sambles, a physicist who works on optics and photonics at the University of Exeter in England, expressed his enthusiasm for this brainless creature's ingenuity:

> It's astonishing that this organic creature can manipulate inorganic matter with such precision—and yet it's got no brain. It's starting with a soup of chemicals and pulling out this wonderful microstructure.[37]

> Human ingenuity came up with microlens arrays only a few years ago, and they are used in directional displays and in micro-optics, for example as signal-routing connectors for signal processing. Once again we find that nature foreshadowed our technical developments. The same applies to photonic solids, structures that can selectively reflect light in all directions. Photonic materials have stimulated much research over the past ten years because of their potential in light manipulation, yet they are to be found in opals and in the wings of butterflies. But then, nature has been in the business of developing functioning optical structures for a very long time.[38]

The brittlestar may not get full credit for its superior ingenuity, which exceeds the current technological ingenuity of humans, but a larger, older, and

wiser configuration called "nature" does. As one National Public Radio reporter put it: "Even the most primitive creatures might have the edge over modern science."[39] (So what makes it "primitive" again?)

While this discovery is a fantastically interesting scientific result, it's probably fair to say that the excitement surrounding this finding and the wide reporting of this story have more to do with its potential applications than with pure amazement at the ingenuity of the brittlestar's bodily knowhow. Consider the appropriately measured tone of the acknowledgment in the technical article's closing sentence:

> The demonstrated use of calcite by brittlestars, both as an optical element and as a mechanical support, illustrates the remarkable ability of organisms, through the process of evolution, to optimize one material for several functions, and provides new ideas for the fabrication of "smart" materials. (Aizenberg et al. 2001, 821)

Understatement (or least reserve) is considered good professional etiquette in scientific publications, and while summaries such as the ones in the "News and Views" section of *Nature* allow quite a bit more leeway, statements to the popular press follow a different set of rules altogether. So it perhaps isn't surprising that a *Discover Magazine* reporter juxtaposes a statement by Aizenberg expressing her amazement at the brittlestar with a pull-no-punches opening line that makes the stakes crystal clear:

> Until now, engineers have only dreamed of such perfect microlenses, which could be invaluable in optical networking and microchip production. Aizenberg is inspired. "This is very clever engineering," she says. "We may be able to mimic it, borrowing from nature a design that has already been working for thousands of years."[40]

As might be expected, the press releases from Bell Labs (owned by Lucent Technologies) are very upbeat about the discovery. A press release dated August 22, 2001, entitled "Bell Labs scientists find remarkable optics in marine creatures that may lead to better microlenses for optical networks," explains that this multifunction biomaterial may lead to better-designed optical elements for telecommunications networks and faster computers through improved optical lithography techniques:

> Scientists hope to mimic nature's success and design microlenses based on the brittlestar model. Such biomimetic lenses may prove useful as components of optical networks, and in chip design, where they could potentially improve optical lithography techniques. "Biomimetics builds on nature's

expertise," said John Rogers, director of nanotechnology research at Bell Labs. "In this case, a relatively simple organism has a solution to a very complex problem in optics and materials design."

A year and a half later, on February 21, 2003, Bell Labs issued an enthusiastic report on Aizenberg's latest achievement, published in the journal *Science*: "the creation of the world's first micro-patterned crystals inspired by bioengineering found in nature" (Aizenberg et al. 2003). The summary phrase, written in bold under the title and designed to catch the reader's eye, is telling: "Study of how nature designs crystals in sea organisms may be important to nanotechnology." With a wink to the brittlestar, in a show of reverence that resembles the kind of respect for nature that Benyus exudes, Aizenberg explains the project thus:

> I have always been fascinated with nature's ability to perfect materials. . . . The more we study biological organisms, the more we realize how much we can learn from them. We recently discovered that nature makes excellent micro-patterned crystals, and we decided to see if we could copy the natural approach in the lab, since this technique may be useful in nanotechnology.

In contrast to the "top-down" approach currently used to make lenses, whereby glass is ground down to match the specifications of the lens, Aizenberg and her colleagues used a "bottom-up" technique, popular in nanotechnology development, in which successive layers of calcite are built up to make the lenses. The report makes effective use of the lead scientist's enthusiasm and engages it to ratchet up the excitement a notch, predicting nothing less than a revolution in manufacturing optical devices: "The new Bell Labs approach may revolutionize how crystals are made in the future for a wide variety of applications."

The themes of visualization, inscription devices, embodied sight, and biomimesis are no doubt sufficient stimuli to generate a Pavlovian response in a host of scholars who focus on questions of representation and related questions of epistemology, but the brittlestar's optical system is different in kind from the visualizing systems that many scholars in science studies and cultural studies are fond of reflecting on. What is at issue is not the geometrical optics model that positions language or representation as the lens that mediates between the object world and the mind of the knowing subject, a geometry of absolute exteriority between ontologically and epistemologically distinct kinds. The history of Western epistemology displays great diversity and ingenuity in generating different kinds of epistemological and

visualizing systems (Plato's is not Descartes's is not Kant's is not Merleau-Ponty's is not Foucault's), but as long as representation is the name of the game, the notion of mediation—whether through the lens of consciousness, language, culture, technology, or labor—holds nature at bay, beyond our grasp, generating and regenerating the philosophical problem of the possibility of human knowledge out of this metaphysical quarantining of the object world.[41]

The brittlestar is not a creature that thinks much of epistemological lenses or the geometrical optics of reflection: the brittlestar does not have a lens serving as the line of separation, the mediator between the mind of the knowing subject and the materiality of the outside world. Brittlestars don't *have* eyes; they *are* eyes. It is not merely the case that the brittlestar's visual system is embodied; its very being *is* a visualizing apparatus. The brittlestar is a living, breathing, metamorphosing optical system. For a brittlestar, being and knowing, materiality and intelligibility, substance and form, entail one another. Its morphology—its intertwined skeletal and diffuse nervous systems, its very structure and form—entails the visualizing system that it is. This is an animal without a brain. There is no *res cogitans* agonizing about the postulated gap (of its own making) between itself and *res extensa*. There is no optics of mediation, no noumena-phenomena distinction, no question of representation.

Brittlestars are not fixated on the illusion of the fixity of "their" bodily boundaries, and they wouldn't entertain the hypothesis of the immutability of matter for even a moment. Dynamics aren't merely matter in motion to a brittlestar when matter's dynamism is intrinsic to the brittlestar's bio-dynamic way of being. A brittlestar can change its coloration in response to the available light in its surroundings. When in danger of being captured by one predator or another, a brittlestar will break off the endangered body part (hence its name) and regrow it. The brittlestar is a visualizing system that is constantly changing its geometry and its topology—autonomizing and regenerating its optics in an ongoing reworking of its bodily boundaries.[42] *Its discursive practices*—the boundary-drawing practices by which it differentiates itself from the environment with which it intra-acts and by which it makes sense of its world, enabling it to discern a predator, for example—*are materiality enacted*.[43] The brittlestar's bodily structure is a material agent in what it sees and knows as part of the world's dynamic engagement in practices of knowing. Similarly, its bodily materiality is not a passive, blank surface awaiting the imprint of culture or history to give it meaning or open it to change; its very substance is morphologically active and generative and plays an agentive role in its differential production, its ongoing materialization. That is, *its differential materialization is discursive*—entailing causal practices reconfiguring boundaries and properties that matter to its very existence.[44] The ongoing reconfigurings of its bodily boundaries and connectivity are products of iterative causal intra-actions—material-discursive practices—through which the agential cut between "self" and "other" (e.g., "surrounding environment") is differentially enacted (e.g., in one agential cut, a given arm is part of the former; in another it is part of the latter). The ability to distinguish self from other, to track and dodge predators, for example, is requisite for the brittlestar's survival, but this does not imply that the categories need to be fixed; on the contrary, the brittlestar's survival depends on its capacity to discern the reality of its changing and relational nature. Intelligibility and materiality are not fixed aspects of the world but rather intertwined agential performances. This eye, this being, is a living optics topologically enfolding bits of the environment within itself and expelling parts of itself to the environment as part of its biodynamics. This apparatus serves both as the condition for the possibility of the intertwined practices of knowing and being and as a causally productive force in its further materializations. Talk about a multifunction biomaterial!

Brittlestars challenge not only disembodied epistemologies but also traditional, and indeed many nontraditional, notions of embodiment. Bodies are not situated *in* the world; they are part *of* the world.[45] Objectivity can't be a matter of seeing from somewhere, as opposed to the view from nowhere (objectivism) or everywhere (relativism), if being situated in the world means occupying particular coordinates in space and time, in culture and history. Just as the importance of the body as a performance rather than a thing can hardly be overemphasized, so should we resist the familiar conception of spacetime as a preexisting Euclidean container (or even a non-Euclidean manifold) that presents separately constituted bodies with a place to be or a space through which to travel. "Position" is neither an absolute nor an a priori determinate feature of space. The spacetime manifold does not sit still while bodies are made and remade. The relationship between space, time, and matter is much more intimate. Spacetime itself is iteratively reconfigured through the ongoing intra-activity of the world. The world is an ongoing intra-active engagement, and bodies are among the differential performances *of* the world's dynamic intra-activity, in an endless reconfiguring of boundaries and properties, including those of spacetime. Technoscientific and other practices entail space-time-matter-in-the-making. Nothing stands separately constituted and positioned inside a spacetime frame of reference, nor does there exist a divine position for our viewing pleasure located outside the world.[46] There is no absolute inside or absolute outside. There is only exteriority within, that is, agential separability. *Embodiment is a matter not of being specifically situated in the world, but rather of being of the world in its dynamic specificity.*

Interestingly, some ophiuroids have bioluminescent arms that continue to wiggle and emit light after breaking off. Marine biologists understand this as an effective survival tactic that a brittlestar performs to distract predators while it escapes. Is this jettisoned limb simply a piece of an organic-inorganic structure shuttering with remnant reflex energy or a companion species helping out? If the detached limb's continuing movements are judged to be mere reflex on the basis that the fragment has no brain, what of the original organism that is a smart material without a brain, and a living contestation of the organic-inorganic binary? Brittlestar species exhibit great diversity in sexual behavior and reproduction: some species use broadcast spawning, others exhibit sexual dimorphism, some are hermaphroditic and self-fertilize, and some reproduce asexually by regenerating or cloning themselves out of the fragmented body parts. When is a broken-off limb only a piece of the environment, and when is it an offspring? At what point does the "disconnected" limb belong to the "environment" rather than the "brittlestar"? Is contiguity of body parts required in the specification of a single organism? Can we trust visual delineations to define bodily boundaries? Can we trust our eyes? Connectivity does not require physical contiguity. (Spatially separate particles in an *entangled state* do not have separate identities but rather are part of the same phenomena.)[47] Is the connection between an "offspring" regenerated from a fragmented body part and the parent brittlestar the same as its connection to a dead limb or the rest of the environment? Imagine the possibilities for lost limb memory trauma when it comes to brittlestars! Rethinking embodiment in this way will surely require rethinking psychoanalysis as well.

Brittlestars are living, breathing, mutating liminal diffraction gratings—they live at the edge of *being* diffraction gratings. Negotiating complex sets of changing relations concerning bodily boundaries, brittlestars are evolutionarily attuned to processes of differentiation. They simply cannot afford to ignore potential diffraction effects. Diffraction effects limit the ability of a lens (or system of lenses) to resolve an image. The greater the diffraction effects, the less determinate the boundaries of an image are, that is, the more the resolution is compromised. This is a fundamental physical limit (not merely a practical one).[48] Brittlestars have evolved in intra-action with their environment in just such a way that their microlenses are optimized to maximize visual acuity (for the discernment of predators, hiding places, and other important phenomena) in a creative tension, a trade-off, between the resolution of detail and diffraction effects.[49] How that tension is negotiated clearly matters: the possibilities for survival are at stake in the brittlestar's ability to differentiate bodily boundaries. *Diffraction is not about any difference but about which differences matter.* The brittlestar lives agential separability, the possibilities for differentiation without individuation.

Brittlestars know better than to get caught up in a geometrical optics of knowing. Clearly they are in a different genus from the mediating machines, inscription devices, lenses, panopticons, and various other epistemological tools that many scholars in science studies and cultural studies fancy. These approaches too often figure visualization as a matter of geometrical optics, leaving important factors of physical optics aside. But this will produce a fuzzy image at best. Limiting an analysis to the domain of geometrical optics, in the neglect of diffraction and other important physical optics effects, corresponds to limiting the analysis to the domain of classical physics in the neglect of quantum effects.[50] As we have seen, there are profound differences between classical and quantum physics—the epistemology and ontology that each entails are strikingly different. In a sense, this neglect of physical optics (quantum physics) can be understood as marking the epistemological limit of science studies. There is more to nature than "nature-as-the-object-of-human-knowledge."[51] The latter constitutes a re-veiling (which provokes the seeming need for a revealing) of nature, yet again. Boundary-making practices do not merely pick out the epistemic object, backgrounding the rest. And scientific practices are not merely practices of knowing, and the knowledge produced is not ours alone. Even in direct challenges to Western philosophy's traditional conceptions of epistemology, there is a tendency to continue to think of knowers as human subjects, albeit appropriately hooked into our favorite technological prostheses. In the absence of a vigorous examination of the ontological issues, the locus of knowledge is presumed to be never too far removed from the human, and so the democratizing move is to invite nonhuman entities into our sociality. But the nature-culture dualism is not undermined by inviting everything into one category (man's, yet again). The point of challenging traditional epistemologies is not merely to welcome females, slaves, children, animals, and other dispossessed Others (exiled from the land of knowers by Aristotle more than two millennia ago) into the fold of knowers but to better account for the ontology of knowing.

Brittlestars literally enact my agential realist ontoepistemological point about the entangled practices of knowing and being. They challenge our Cartesian habits of mind, breaking down the usual visual metaphors for knowing along with its optics of mediated sight. Knowledge making is *not* a mediated activity, despite the common refrain to the contrary. Knowing is a direct material engagement, a practice of intra-acting with the world as part of the world in its dynamic material configuring, its ongoing articulation. The entangled practices of knowing and being are material practices. The world is not merely an idea that exists in the human mind. To the contrary, "mind" is a specific material configuration of the world, not necessarily coincident with a brain. Brain cells are not the only ones that hold memories, respond to stimuli, or think thoughts.[52] Brittlestars intra-act with their ocean environment and respond to differential stimuli made intelligible through these intra-actions, adjusting their positions and reworking their bodies in order to avoid predators or find food or shelter, all without brains or eyes. (Was the cell biologist Daniel Mazia being merely metaphorical when he remarked that "the gift of the great microscopist is the ability to think with the eyes and see with the brain"? Surely a plethora of statements about tacit knowing, including a wealth of testimonials offered by scientists, suggests some more literal, material meaning.)

"I think, therefore I am" is not the brittlestar's credo. Knowing is not a capacity that is the exclusive birthright of the human. The "knower" cannot be assumed to be a self-contained rational human subject, nor even its prosthetically enhanced variant. There is no res cogitans that inhabits a given body with inherent boundaries differentiating self and other. Rather, subjects are differentially constituted through specific intra-actions. The subjects so constituted may range across some of the presumed boundaries (such as those between human and nonhuman and self and other) that get taken for granted. Knowing is a distributed practice that includes the larger material arrangement. To the extent that humans participate in scientific or other practices of knowing, they do so as part of the larger material configuration of the world and its ongoing open-ended articulation.

Knowing is a specific engagement of the world where part of the world becomes differentially intelligible to another part of the world in its differential accountability to and for that of which it is a part. In traditional humanist accounts, intelligibility requires an intellective agent (that to which something is intelligible), and intellection is framed as a specifically human capacity. But in my agential realist account, intelligibility is an ontological performance of the world in its ongoing articulation. It is not a human-dependent characteristic but a feature of the world in its differential becoming. The world articulates itself differently. And knowing does not require intellection in the humanist sense, either; knowing is a matter of differential responsiveness (as performatively articulated and accountable) to what matters.

Crucially, knowing is not a matter of mere differential responsiveness in the sense of simply having different responses to different stimuli. Knowing requires differential accountability to what matters and is excluded from mattering. That is, what is required is differential responsiveness that is accountable to marks on bodies as part of a topologically dynamic complex of performances. As Rouse remarks, "There is nothing about the letters p-o-s-i-t-i-o-n or the po-'zi-shun that magically . . . connects them to what is disclosed in measurements using [an] apparatus with internally fixed parts; only their actual ongoing use in such circumstances, in reliably recognizable and normatively accountable ways, can account for their discursive significance" (Rouse 2004, 153). But recognition need not entail cognition in humanist terms. A brittlestar can recognize a predator and successfully negotiate its environment to elude capture despite the fact that it has no brain. A brittlestar is not some ideal Cartesian subject, but through specific practices of intra-active engagement, it differentially responds (not simply in the sense of responding differently to different things that are out there but) in ways that matter. There are stakes—life-and-death stakes—in getting it wrong.[53] Furthermore, "recognizability" is not a fixed and universal notion but obtains its meaning through its ongoing use in specific practices. What is at issue, then, is not mere differential responsiveness but normative differential responsiveness. Different material intra-actions produce different materializations of the world, and hence there are specific stakes in how responsiveness is enacted. In an important sense, it matters to the world how the world comes to matter.

Brittlestars are not merely tools that we can use to teach us about biomimesis and enhanced communication networks. Brittlestars are living testimony to the inseparability of knowing, being, and doing. On the one hand, we trust our eyes when it comes to believing that boundaries that we see are sharp inherent edges marking the limits of separate entities, even though upon closer examination the diffraction effects—the indefinite nature of those boundaries—become clear (which is not to suggest that there really are no boundaries or that what is at stake is a postmodern celebration of the blurring of boundaries; we have learned too much about diffraction to think in these simplistic terms). On the other hand, we don't trust our eyes to give us reliable access to the material world; as inheritors of the Cartesian legacy, we would rather put our faith in representations instead of matter, believing that we have a kind of direct access to the content of our representations that we lack toward that which is represented. To embrace representationalism and its geometry or geometrical optics of externality is not merely to make a justifiable approximation that can be fixed by adding further factors or perturbations at some later stage, but rather to start with the wrong optics, the wrong ground state, the wrong set of epistemological and ontological assumptions. Haraway's move away from her earlier "an optics is a politics of positioning" to her later "diffraction is an optical metaphor for the effort to make a difference in the world" signals the kind of shift that is required (Haraway 1991, 193; 1997, 16).

There is more to diffraction than meets the eye. As we have learned from our quantum mechanical studies of diffraction, it is a much more subtle and profound phenomenon than the classical understanding suggests. The phenomenon of diffraction does not merely signify the disruption of representationalism and its metaphors of reflection in the endless play of images and its anxieties about copy and original and displacements of the Same elsewhere. Diffraction is an ethico-onto-epistemological matter. We are not merely differently situated in the world; "each of us" is part of the intra-active ongoing articulation of the world in its differential mattering. Diffraction is a material-discursive phenomenon that challenges the presumed inherent separability of subject and object, nature and culture, fact and value, human and nonhuman, organic and inorganic, epistemology and ontology, materiality and discursivity. Diffraction marks the limits of the determinacy and permanency of boundaries. One of the crucial lessons we have learned is that agential cuts cut things together and apart. *Diffraction is a matter of differential entanglements. Diffraction is not merely about differences, and certainly not differences in any absolute sense, but about the entangled nature of differences that matter.* This is the deep significance of a diffraction pattern.[54] *Diffraction is a material practice for making a difference, for topologically reconfiguring connections.*

Brittlestars are not pure bits of nature or blank slates for the imprinting of culture. They are not mere resources or tools for human interventions. They are not simply superior optical engineers or natural inspirations for the enterprising ingenuity of humans. Brittlestars are phenomena intra-actively produced and entangled with other phenomena. They are agentive beings, lively configurations of the world, with more entanglements than arms. They are not merely objects of our knowledge-making and product-making projects. "Humans" and "brittlestars" learn about and co-constitute each other through a variety of brittlestar-human intra-actions. Biomimesis may be the goal of certain research projects that seek to appropriate the ingenuity of the brittlestar's lens system, but this practice cannot be understood as a process of copying the other. Nature is not a pure essence that exists "out there" or on a slide positioned under the objectives of our microscopes. In the game of geometrical optics would the brittlestar be the lens that we look at, or through, or with? Brittlestars are not gripped by the idea of mirroring, imitation, reflection, or other modes of the tropology of Sameness. These echinoderms don't reflect on the world; they are engaged in making a difference in the world as part of the world in its differential becoming, and so are we. The specific nature of our intra-actions with brittlestars matters. For all we have learned from our intra-actions with brittlestars, the issue is not whether or not we are willing to follow Nature's example. The attending ethico-onto-epistemological questions have to do with responsibility and accountability for the entanglements "we" help enact and what kinds of commitments "we" are willing to take on, including commitments to "ourselves" and who "we" may become.

It would be a serious error to mistake biomimesis for mere imitation. The emerging field of biomimetics is not about copies of originals or even copies of copies without beginning or end. On the contrary, biomimesis is a particularly poignant call for the incorporation of difference at every level in breaking the deadening and sinister symmetry of Sameness that uses the hall of mirrors to suck time, history, and matter into the black hole of stasis (leaving in its stead a culture of no culture and a nature of no nature).[55] The biomimetic-inspired study of the brittlestar reveals the limitations of the geometrical optics of mirroring and shows us that the crucial point is not mirroring but its creative undoing, not sameness reproduced without end but attentiveness to differences that matter. Contemporary practitioners of biomimesis do not claim to be making replicas of nature; rather, they are engaged in practices that use nature as inspiration for new engineering designs. Biomimetics honors Mother Nature as the primo engineer, but it doesn't promise to abide by her methods. It embraces new innovations, new materials, new techniques, new applications. Bringing the new to light is its highest principle. Of course, the new bio-info-nano-technologies embrace the new for very practical reasons: aside from the excitement and romantic overtones that inevitably accompany the story of the scientist as explorer breaking into new frontiers, and its obvious advertising benefits, without the new there is simply no copyright to be gained.

There's an important point to be made about the new in light of the entangled nature of spacetimematterings. As Hans-Jörg Rheinberger points out the new isn't the new until it is already not new—for the new "becomes a novelty only in a transformation which makes it a trace of something to which it has given rise" (1997, 177). Originals don't preexist as such and mimesis can't be the reproduction of what came before, not when time itself is constituted through the dynamics of intra-activity and the past remains open to material reconfigurings (see chapter 7). As we saw in chapter 7, the historiality of phenomena is written into their materialization, their bodily materiality holds the memories of the traces of its enfoldings; space and time (like matter) are phenomenal, that is, they are intra-actively produced in the making of phenomena; neither space nor time exist as determinate givens outside of phenomena. As a result of the iterative nature of intra-active practices that constitute phenomena, the "past" and the "future" are iteratively reconfigured and enfolded through one another: phenomena cannot be located in space and time; rather, phenomena are material entanglements that "extend" across different spaces and times. The production of the new can't be located and it certainly can't be owned. Neither the past nor the future is ever closed. It's not that the new is generated in time; rather, what is at issue is the intra-active generation of new temporalities, new possibilities, where the "new" is the trace of what is yet to come.[56] © is not a symbol of ownership of the right to copy, but rather of the responsibilities entailed in producing differences (for whom and at what costs?).[57]

Biomimetics is a nodal point around which nanotechnologies, biotechnologies, and infotechnologies are becoming more and more complexly entangled. This accounts for a great deal of the current fascination with biomimetics, the enthusiastic support it is receiving from government agencies, universities, and private industry, and the rapid growth of research centers that are fashioned on a model of hybridity (drawing together interdisciplinary, international, and interorganization teams) that cultural studies, women's studies, ethnic studies, and other critical social studies programs have been touting the advantages of for decades, but with little real structural or material support from the colleges and universities that claim to pride themselves on the interdisciplinary efforts that spur them on to the cutting edge of education and research.[58] As we entertain the possibilities for forming partnerships with brittlestars and other organisms for biomimetic projects, we are co-constituting ourselves into assemblages that "mimic" (but do not replicate) the entanglements of the objects we study and the tools that we make. The entanglements we are a part of reconfigure our beings, our psyches, our imaginations, our institutions, our societies; "we" are an inextricable part of what gets reworked in our R&D projects. The ethical questions that we will want to consider are not only about how nonhuman animals are being appropriated for human desires but also about how our desires and our beings are co-constitutively reconfigured as well.

One very important lesson we have gained from our intra-actions with brittlestars (where the objective referent here is the phenomenon, not some allegedly pure bit of nature) is that ethics is not simply about the subsequent consequences of our ways of interacting with the world, as if effect followed cause in a linear chain of events. Ethics is about mattering, about taking account of the entangled materializations of which we are a part, including new configurations, new subjectivities, new possibilities—even the smallest cuts matter. Biomimesis is not about making copies but about enacting new cuts and reconfiguring entanglements. We are much more intimately connected than the notion of mimesis connotes. We don't have the distances of space, time, and matter required to replicate "what is"; in an important sense, we are already materially entangled across space and time with the diffractive apparatuses that iteratively rework the "objects" that "we" study. The ethical practice of biomimesis will require specific case-by-case accountings for marks on bodies. Technoscientific practices are about making different worldly entanglements, and ethics is about accounting for our part of the entangled webs we weave.

ENTANGLED GENEALOGIES

> The ultra-fast computers of the future will be based on beams of light that exploit the strange properties of the sub-atomic or quantum mechanical world. Using light and quantum mechanics offers the prospect of computers trillions of times more powerful than we have today. The first, tentative but encouraging, steps have been made towards primitive quantum computers.
>
> —DAVID WHITEHOUSE, "Q&A: Teleportation," *BBC News*, June 14, 2004

> New paradigms will use advances in quantum computation and molecular and nano-electronics to devise radically faster computers to solve problems previously described as "uncomputable," such as full-scale simulations of our biosphere or surgical simulations. Viewing cells as computational devices will help enable the design of next generation computers that feature self organization, self repair, and adaptive characteristics that we see in biological systems.
>
> —NSF TESTIMONY TO CONGRESS, March 1, 2000

Testifying before Congress, a National Science Foundation officer explains "quantum entanglement" to our government representatives: "Two particles can have linked spins even though they are at a distance [and appear to be completely separate entities]. Manipulating one particle and then reading the spin of the other, linked, particle is the basis of quantum information teleportation."[59] Is this the late-night hallucination of a physics student cramming for an exam? A skit on *Saturday Night Live*? Or a national news report on yet another incident of wasted government spending slotted for the "Fleecing of America" segment? Surprisingly, the answer is none of the above. This statement on quantum entanglement is from actual testimony, important testimony regarding research funded by a host of government agencies. As discussed in chapter 7, quantum entanglement—which challenges the presumed ontological separability of seemingly individual particles—is a phenomenon that lies at the heart of quantum physics. But why are the National Security Agency (NSA), the Defense Advanced Research Projects Agency (DARPA), the National Reconnaissance Office (NRO), and other U.S. federal agencies including the Army, Navy, and Air Force, the Advanced Research and Development Agency (ARDA), the National Aeronautics and Space Administration (NASA), the National Institute of Standards and Technology (NIST), and the Department of Energy (DOE) interested in quantum entanglement?[60]

For decades, questions about the meaning and implications of quantum theory, foundational issues that cut to the very core of our understanding of the theory's nature, were considered "merely philosophical," that is, of no practical import. The impassioned debate between Bohr and Einstein belonged to the dustbin of history, and students who wanted to know something more about quantum theory than how to use it as a tool for doing calculations were directed, with an obligatorily pejorative tone, to seek counsel in the philosophy department, where questions of whether trees that fall in forests in the absence of listening subjects still make noises would not fall on deaf ears. The implication was that if one was seriously interested in the meta-physical issues, one could, and indeed one should, leave the serious endeavor of physics and pick up a career in history or philosophy of science. There were a few exceptions; a scant number of researchers in the field of the foundations of quantum mechanics were hired in physics departments or already had tenure in physics departments, but by and large the physics community just wasn't interested. In the past decade or so, things have changed. Now, all of a sudden, "metaphysical" issues have surfaced as a topic in physics, sparking the interest not only of physicists but also of a host of government officials, computer scientists, international bankers, and entrepreneurs around the world.[61] We have entered what the National Academy of Sciences calls the "Second Quantum Revolution."

The basis for the new quantum revolution is quantum entanglement, an idea that has been around since the mid-1930s but has only very recently been acknowledged as the very essence of quantum physics. Unlike the original quantum revolution, the new one is not so much a revolution in ideas (at least it is not widely acknowledged as such) but a revolution in technological potential. In the 1990s, physicists began to take quantum entanglement seriously as they realized its extraordinary potential as the basis for new technological endeavors including quantum computing, quantum cryptography, and quantum teleportation. Let's take a brief look at each of these innovations.[62]

Quantum computers are touted as a major contender for increased computing power in the postsilicon era. They have the potential to accelerate computations and solve problems that have heretofore been resistant to solution, including the factoring of large integers, the acceleration of combinatorial searches, and the simulation of complex physical systems. This anticipated "quantum leap" in computing power is due to quantum computers' intrinsic massive "parallelism," which enables them to perform many operations simultaneously.[63] The point was made to the U.S. congressional representatives in this way:

> Since the invention of the silicon integrated circuit in 1961 to the present, the number of devices that can be placed on a single silicon chip has roughly doubled every 12 to 18 months. This means that every ten years, the number of devices on chips increases about a thousand-fold. This is done by shrinking device sizes and is achieved by constant improvements in chemistry, photolithography, clean rooms, and other efforts. This doubling rate is known as Moore's law. For the computing industry, the shrinking devices and increasing density [have] enabled the information technology revolution through staggering increases in speed and functionality of computers accompanied by astonishing decreases in costs. We know that this cannot continue for long—the size of atoms is a very hard limit and very close in time. . . . If we are to continue to see improvements in the performance and cost of computing, we must go beyond silicon.

Quantum computing represents an important possibility for maintaining our competitive edge.

But quantum computing promises more than additional computing

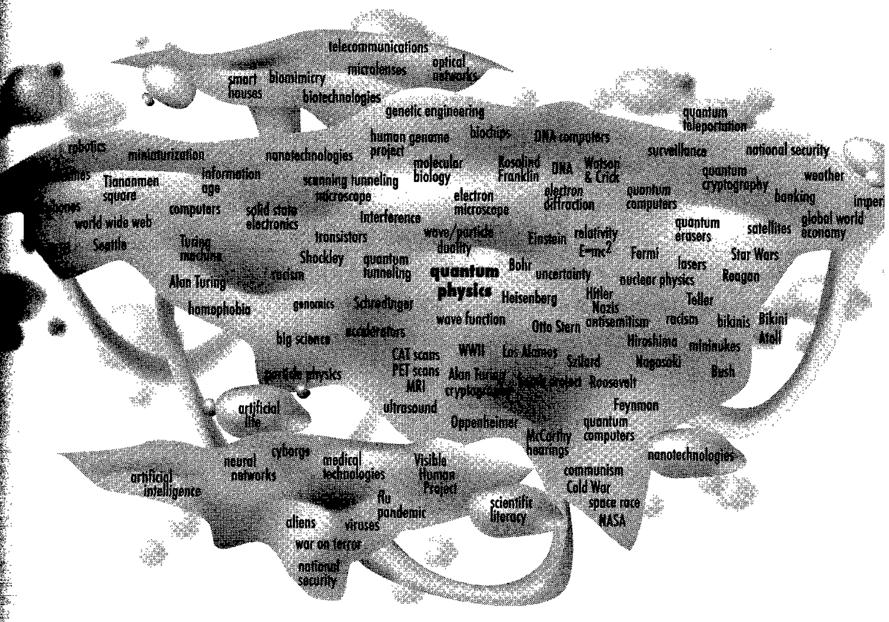
power, for the project is entangled with issues that cut to the heart of national security and control of global information systems. Though it may seem as if the factoring of large integers would be of interest only to a group of mathematicians who revel in the innocent pleasures of playing with numbers, factoring is the basis of encryption systems that seek to keep banking transactions secure. In theory, a powerful-enough quantum computer could pose a threat to the international banking system as well as to national security. Perhaps it isn't surprising, then, that overall support for Quantum Information Science (QIS) in the United States has risen from about $1 million in fiscal year 1995 to over $30 million in fiscal year 2000.[64] In fact there has been an explosion of such efforts throughout the so-called first world. Currently, "quantum computers are the focus of a mammoth research effort by a consortium including several universities in Australia and the U.S., as well as Los Alamos, leading those in the field to dub it the 'Manhattan Project of quantum computing.'"[65]

Quantum cryptography is an emerging technology that promises the secure transmission of information between distant locations (e.g., between two satellites). Significantly, the security of quantum crytpographic transmissions is guaranteed by the laws of quantum mechanics such that not only would any attempt to tap such a transmission fail, but no attempt would be able to evade detection. While quantum computing may take decades to realize, quantum cryptography is already commercially available:

> Long before [a time when quantum computing may be realized], moreover, entanglement and superposition may find practical application in other technologies. For example, quantum cryptography has the potential to exchange information with guaranteed secrecy; commercial products already exist. Quantum entanglement may also permit more accurate and better synchronized atomic clocks, which in turn could improve GPS systems and mobile communications networks.
>
> And of course, that is just the beginning. Attempts to tame the quantum realm are also opening up new possibilities for nanoscience and other areas of physics, and are certain to lead to technologies that today's physicists cannot even fathom.[66]

A third research area is quantum teleportation. Although it may not lead anytime soon (if ever) to the realization of a *Star Trek*–style transporter that makes an object dematerialize in one place and rematerialize in another (or at least its replica), quantum teleportation is a method by which physicists can transport the properties of one object to another even if the objects are on opposite sides of the galaxy (at least in principle). Even if scientists do find a way to handle the vast information that is a human being, the prospect of teleporting beings is rather grim, for, as Charles Bennett and his colleagues have shown, it means destroying the original and replacing it with a replica (Bennett et al. 1993). The teleportation of quantum information has been realized in the laboratory, and though it won't replace air travel in the near future, it will most likely have uses in quantum computing and quantum cryptography. No wonder quantum entanglement has gotten more people's attention than a few metaphysicians and a small group of die-hard physicists and philosophers intent on figuring out the deep mysteries of the quantum theory.[67]

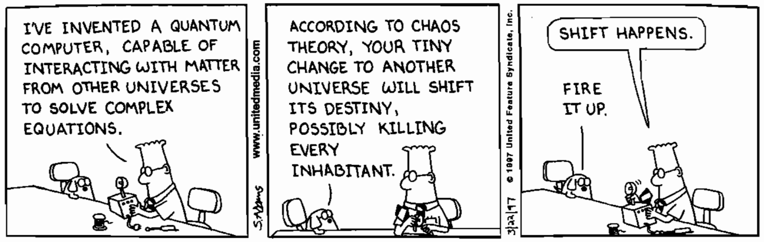
Quantum physics is part of a complexly entangled web of phenomena that include scientific, technological, military, economic, medical, political, social, and cultural apparatuses of bodily production, to name but a few. Figure 34 shows an illustration that attempts to offer some sense of this complex and lively manifold of entangled and changing practices and possibilities. The illustration is wholly inadequate, impressionistic at best, but hopefully of some use for the reader who shares my yearning and struggles to see, feel, touch, taste, smell, hear, and otherwise sense phenomena with the mind's eye (and it's not only the last word in this sentence that strives to give some sense of this material practice of grasping phenomena that ought to be put in scare quotes; of course, "grasping" is a material-discursive practice that intra-acts rather than interacts with its object). For one thing, the complex manifold of connections in question is an ever-changing multidimensional topological manifold *of* spacetimematter, not a three-dimensional object (assuming you'll grant that) located in space with the barest hint of time thrown in for good measure, that not only comes across as spatialized but is literally represented spatially (by the perhaps all-too-subtle suggestion that some "blobs" are in the process of materializing while others are becoming less substantial). The wormholes, the array of handles connecting nonproximate points that (only) seem distant or disconnected, barely hint at a much denser and more complex set of entanglements that could not be placed on the diagram without obscuring the image. Furthermore, the illustration fails to convey the dynamic set of changing relations and multiple en/foldings that are part of its ongoing reconfiguring. How to represent not merely the limits of representationalism (in the tradition of Velázquez or Magritte, for example) but the agential realist notions of causality and agency that are entailed in entanglements is a question that one simply can't wrap one's mind around (by definition). In particular, the notion of entanglement needs to be under-



34 Entangled genealogies. *Illustration by Nicolle Rager Fuller and Karen Barad.*

stood in terms of the relational ontology of agential realism. While the illustration gives the impression that the manifold is an assemblage of individual events, entities, and sets of practices, but the fact is that these apparatuses of bodily production are intra-acting with and mutually constituting one another; that is, what is at issue is the primacy of relations over relata and the intra-active emergence of "cause" and "effect" as enacted by the agential practices that cut things together and apart. All in all, perhaps at best the illustration conveys some sense of the multiplicity of apparatuses that are part of these entangled genealogies, but even at that the labels don't do justice to the nature of these different and differently connected changing materialities. Or maybe all that it is able to hint at is some sense of the need to read genealogies for their constitutive exclusions. But then again, representations are not (more or less faithful) pictures of what is, but productive evocations, provocations, and generative material articulations or reconfigurings of what is and what is possible.

Recall that apparatuses are themselves phenomena—the result of intra-actions of material-discursive practices—and the enfolding of phenomena



35 Shift happens. From Dilbert, © Scott Adams, dist. by United Feature Syndicate, Inc.

into subsequent iterations of particular practices (which may be traded and mutated across space, time, and subcultures, in the iterative reconfiguring of spacetimematter itself) constitutes important shifts in the nature of the intra-actions that result in the production of new phenomena, and so on. Which shifts occur matter for epistemological as well as ontological reasons: a different material-discursive apparatus of bodily production materializes a different configuration of the world, not merely a different description of a fixed and independent reality. We are responsible for the world of which we are a part, not because it is an arbitrary construction of our choosing but because reality is sedimented out of particular practices that we have a role in shaping and through which we are shaped. (The Dilbert cartoon in figure 35 offers a different illustration, a different way of conveying the crucial point that in our entangled engagements with and as part of the universe each shift matters.)

What we need is an understanding of the material-discursive practices by which these connections are formed and reformed, not in space and time but in the very configuring and reconfiguring of spacetimematter. In particular, the responsible practice of science requires a full genealogical accounting of the entangled apparatuses or practices that produce particular phenomena.[68] In contrast to more traditional conceptions of objectivity, which are only responsible to the norms of correct practice as narrowly conceived (e.g., the correct operation of equipment, the production of determinate marks on bodies, the following of standards of interpretation to produce intelligible results, the following of correct procedures for reporting results), objectivity in an agential realist sense requires a full accounting of the larger material arrangement (i.e., the full set of practices) that is a part of the phenomenon investigated or produced. (To do otherwise is to misidentify

the objective referent.) Hence objectivity requires an accounting of the constitutive practices in the fullness of their materialities, including the enactment of boundaries and exclusions, the production of phenomena in their sedimenting historiality, and the ongoing reconfiguring of the space of possibilities for future enactments. The point is that more is at stake than "the results"; intra-actions reconfigure both what will be and what will be possible—they change the very possibilities for change and the nature of change. Learning how to intra-act responsibly as part of the world means understanding that "we" are not the only active beings—though this is never justification for deflecting our responsibility onto others.[69]

TOWARD AN ETHICS OF MATTERING

Proximity, difference which is non-indifference, is responsibility.

—EMMANUEL LEVINAS, *Otherwise than Being, or Beyond Essence*

For Emmanuel Levinas, responsibility is not a relation between two subjects; rather, the otherness of the Other is given in responsibility. "Responsibility is "the essential, primary and fundamental mode of subjectivity. . . . Ethics . . . does not supplement a preceding existential base; the very node of the subjective is knotted in ethics understood as responsibility" (Levinas 1985, 95). Ethics grounds human experience (not the other way around).

Levinas rejects the metaphysics of the self that serves as a foundation for conventional approaches to ethics. Subjectivity is not a matter of individuality but a relation of responsibility to the other. Crucially, then, the ethical subject is not the disembodied rational subject of traditional ethics but rather an embodied sensibility, which responds to its proximal relationship to the other through a mode of wonderment that is antecedent to consciousness. As the feminist theorist Ewa Plonowska Ziarek explains, the "ethical significance of the body is crystallized in the figure of touch and sensibility, in 'the quite simple attempt to touch the other, to feel the other' " (Ziarek 2001, 56). Ziarek emphasizes that, for Levinas, embodiment is neither a passive surface for the inscription of culture nor the biological body:

> Levinas rethinks embodiment not only as the condition of relations to objects but also as a prototype of an ethical experience. In contrast to the transcendence of the body in self-reflection, "oneself," or ipseity, signifies for Levinas an embodied self—a prelogical, presynthetic entwinement of thought and carnality, or what Levinas calls "being in one's skin." (49–50)

Being in one's skin means that one cannot escape responsibility: the prior ethical relation of "having-the-other-in-one's-skin" conditions the constriction of embodiment, which "does not unify the ego but, on the contrary, inscribes the noncoincidence with oneself within the lived body and makes it the basis of the ethical relations to others" (55). Before all reciprocity in the face of the other, I am responsible.

But if responsibility is not a commitment that a subject chooses but rather an incarnate relation that precedes the intentionality of consciousness, "an obligation which is *anachronistically* prior to every engagement," then it seems we cannot ignore the full set of possibilities of alterity—that "having-the-other-in-one's-skin" includes a spectrum of possibilities, including the "other than human" as well as the "human." And if ethical relations extend to the other-than-human, then the "noncoincidence with oneself" is clearly not a singular feature of human embodiment. Responsibility—the ability to respond to the other—cannot be restricted to human-human encounters when the very boundaries and constitution of the "human" are continually being reconfigured and "our" role in these and other reconfigurings is precisely what "we" have to face. A humanist ethics won't suffice when the "face" of the other that is "looking" back at me is all eyes, or has no eyes, or is otherwise unrecognizable in human terms. What is needed is a posthumanist ethics, an ethics of worlding.

Levinas argues that "culture does not come along and add extra axiological attributes, which are already secondary and grounded, onto a prior, grounding representation of the thing. The cultural is essentially embodied thought expressing itself, the very life of flesh manifesting" (quoted in Ziarek 2001, 53). What would it mean to acknowledge that this is true of nature as well (as culture)—that nature expresses itself, that nature is not the other of thought or speech?[70] What if we were to acknowledge that the nature of materiality itself, not merely the materiality of human embodiment, always already entails "an exposure to the Other"? What if we were to recognize that responsibility is "the essential, primary and fundamental mode" of objectivity as well as subjectivity?

In my agential realist account, matter is a dynamic expression/articulation of the world in its intra-active becoming. All bodies, including but not limited to human bodies, come to matter through the world's iterative intra-activity—its performativity. Boundaries, properties, and meanings are differentially enacted through the intra-activity of mattering. Differentiating is not about radical exteriority but rather agential separability. That is, differentiating is not about othering or separating but on the contrary about making connections and commitments. The very nature of materiality is an entanglement. Matter itself is always already open to, or rather entangled with, the "Other." The intra-actively emergent "parts" of phenomena are co-constituted. Not only subjects but also objects are permeated through and through with their entangled kin; the other is not just in one's skin, but in one's bones, in one's belly, in one's heart, in one's nucleus, in one's past and future. This is as true for electrons as it is for brittlestars as it is for the differentially constituted human. (Electrons, like brittlestars, are complex phenomena that are lively and enlivened; memory and re-member-ing are not mind-based capacities but marked historialities ingrained in the body's becoming.) Just as the human subject is not the locus of knowing, neither is it the locus of ethicality. We (but not only "we humans") are always already responsible to the others with whom or which we are entangled, not through conscious intent but through the various ontological entanglements that materiality entails. What is on the other side of the agential cut is not separate from us—agential separability is not individuation. Ethics is therefore not about right response to a radically exterior/ized other, but about responsibility and accountability for the lively relationalities of becoming of which we are a part.

Rejecting the metaphysics of individualism that serves as a foundation for traditional approaches to ethics, agential realism proposes an alternative meta/physics that entails a reworking of the notions of causality and agency. Traditional conceptions of causation are concerned with the causal relationship between distinct sequential events. In my agential realist account, causality is rethought in terms of intra-activity. Intra-actions do not simply transmit a vector of influence among separate events. It is through specific intra-actions that a causal structure is enacted. Intra-actions effect what's real and what's possible, as some things come to matter and others are excluded, as possibilities are opened up and others are foreclosed. And intra-actions effect the rich topology of connective causal relations that are iteratively performed and reconfigured. This is a reworking of causality that not only goes beyond its classical conception but also goes beyond that of complex systems theory as well: "emergence," in an agential realist account, is dependent not merely on the nonlinearity of relations but on their intra-active nature (i.e., on nonseparability and nontrivial topological dynamics as well). Events and things do not occupy particular positions in space and time; rather, space, time, and matter are iteratively produced and performed. Traditional conceptions of dynamics as a matter of how the values of an object's properties change over time as the result of the action of external forces won't do. The very nature and possibilities for change are reworked.

With each intra-action, the manifold of entangled relations is reconfigured. And so consequentiality, responsibility, and accountability take on entirely new valences. There are no singular causes. And there are no individual agents of change. Responsibility is not ours alone. And yet our responsibility is greater than it would be if it were ours alone. Responsibility entails an ongoing responsiveness to the entanglements of self and other, here and there, now and then. If, as Levinas suggests, "proximity, difference which is non-indifference, is responsibility," then entanglements bring us face to face with the fact that what seems far off in space and time may be as close or closer than the pulse of here and now that appears to beat from a center that lies beneath the skin. The past is never finished once and for all and out of sight may be out of touch but not necessarily out of reach.[71] Intra-active practices of engagement not only make the world intelligible in specific ways but also foreclose other patterns of mattering. We are accountable for and to not only specific patterns of marks on bodies—that is, the differential patterns of mattering of the world of which we are a part—but also the exclusions that we participate in enacting. Therefore accountability and responsibility must be thought in terms of what matters and what is excluded from mattering.

The point is not merely that there is a web of causal relations that we are implicated in and that there are consequences to our actions. We are a much more intimate part of the universe than any such statement implies. If what is implied by "consequences" is a chain of events that follow one upon the next, the effects of our actions rippling outward from their point of origin well after a given action is completed, then to say that there are consequences to our actions is to miss the full extent of the interconnectedness of being. Future moments don't follow present ones like beads on a string. Effect does not follow cause hand over fist, transferring the momentum of our actions from one individual to the next like the balls on a billiards table. There is no discrete "I" that precedes its actions. Our (intra)actions matter—each one reconfigures the world in its becoming—and yet they never leave us; they are sedimented into our becoming, they become us. And yet even in our becoming there is no "I" separate from the intra-active becoming of the world. Causality is an entangled affair: it is a matter of cutting things together and apart (within and as part of phenomena). It is not about momentum transfer among individual events or beings. The future is not the end point of a set of branching chain reactions; it is a cascade experiment.

In his autobiography *Disturbing the Universe*, the physicist Freeman Dyson takes up the haunting question of J. Alfred Prufrock—"Do I dare disturb the universe?" T. S. Eliot's protagonist holds the question at arm's length, afraid

[redacted]

of what it might mean to give it voice. Caught in inaction, indulging instead in endless reflection, mirrors upon mirrors, he watches his life from a distance, afraid to face all but the most petty self-conscious instances: "Shall I part my hair behind? Do I dare to eat a peach?" On the other hand, Dyson grabs hold of the question and considers it in relation to matters on the grandest scales and potentially of the gravest consequences. "Do I dare work on the hydrogen bomb?" is an inversion of "Do I dare eat a peach?" Prufrock's extreme self-consciousness—his compulsive indulgence in interminable reflections designed to keep himself inside his own head, endless worries upon endless worries stacked up like dirty dishes crafted as a distraction, a prophylactic against facing the really difficult questions in life—does not amount to responsible reflection about the consequences of the choices life holds. On the contrary, it adds up to nothing more than his pitiable inability to be in his life, to sing his love song to the universe. By contrast, Dyson's life is filled with decisions and actions that are deeply consequential. Dyson knows that the very survival of humankind may rest on some of the decisions he faces. He confronts the really tough questions, questions of life and death, and his reflections are subtle and informed. Ethics and science go hand in hand for this self-reflexive scientist (who—rather paradoxically, it seems—never met a technological project he couldn't find justification for working on). Dyson puts his moral stances on the table: his firm belief that "knowledge implies responsibility," his insistence that "it makes no sense to separate science from technology, technology from ethics, or ethics from religion," his realization while working on the design of a nuclear bomb at Livermore that "it is not possible to make a clean separation between peaceful and warlike bombs, or between peaceful and warlike motives," his belief in an ultimate "covenant between nature and man," even his dream about finally meeting his maker, which reveals the ultimate secret that we hold the future in our own hands. And yet, despite all his thoughtful considerations, Dyson's ethical questioning remains eerily faithful to the logic of Prufrock's question. The image is inverted, but the mirror remains in fact. The structure that separates reflections from actions and observer from observed is left in place.

"Do I dare disturb the universe?" What can such a question mean? Shall we stand outside the universe and just let it "run"? Shall we take the side of Newton or Leibniz in the debate about whether the clockwork must be rewound periodically or whether it will continue in a satisfactory fashion without intervention? How best to design a clockwork? What position is this to occupy? Can we assume the position of the perfect modest witness and merely observe the universe without disturbing it? When faced with an ethical choice about working on a new technological or scientific project, can we get that kind of distance? Enough to detach ourselves from responsibility? Can we simply follow our passion to know without getting our hands dirty? Or if we cannot stand back, and we find ourselves needing to intervene now and again to keep things in alignment or make an adjustment here or there, if we honor our responsibility by helping to shape the future, what kind of distance shall we presume is the right amount to get a good perspective on things? How many light-years away do we need to stand to make wise choices? Shall we use the universe as a toy model, tweak a few things, and see what happens?

What fantasy of distance is this? What notion of responsibility is presumed? "Do I dare disturb the universe?" is not a meaningful question, let alone a starting point for ethical considerations. Disturbance is not the issue, and "dare" is a perverse provocation. There is no such exterior position where the contemplation of this possibility makes any sense. We are *of* the universe—there is no inside, no outside. There is only intra-acting from within and as part of the world in its becoming.

A delicate tissue of ethicality runs through the marrow of being. There is no getting away from ethics—mattering is an integral part of the ontology of the world in its dynamic presencing. Not even a moment exists on its own. "This" and "that," "here" and "now," don't preexist what happens but come alive with each meeting. The world and its possibilities for becoming are remade with each moment. If we hold on to the belief that the world is made of individual entities, it is hard to see how even our best, most well-intentioned calculations for right action can avoid tearing holes in the delicate tissue structure of entanglements that the lifeblood of the world runs through. Intra-acting responsibly as part of the world means taking account of the entangled phenomena that are intrinsic to the world's vitality and being responsive to the possibilities that might help us and it flourish. Meeting each moment, being alive to the possibilities of becoming, is an ethical call, an invitation that is written into the very matter of all being and becoming. We need to meet the universe halfway, to take responsibility for the role that we play in the world's differential becoming.

APPENDIX A

Cascade Experiment

ALICE FULTON

Because faith creates its verification
and reaching you will be no harder than believing
in a planet's caul of plasma,
or interacting with a comet
in its perihelion passage, no harder
than considering what sparking of the vacuum, cosmological
impromptu flung me here, a paraphrase, perhaps,
for some denser, more difficult being,
a subsidiary instance, easier to grasp
than the span I foreshadow, of which I am a variable,
my stance is passional towards the universe and you.

Because faith in fact can help create those facts,
the way electrons exist only when they're measured,
or shy people stand alone at parties,
attract no one, then go home and feel more shy,
I begin by supposing our attrition's no quicker
than a star's, that like electrons
vanishing on one side
of a wall and appearing on the other
without leaving any holes or being
somewhere in between, the soul's decoupling
is an oscillation so inward nothing outward
as the eye can see it.
The childhood catechisms all had heaven,
an excitation of mist.
Grown, I thought a vacancy awaited me.
Now I find myself discarding and enlarging
both these views, an infidel of amplitude.

Because truths we don't suspect have a hard time
making themselves felt, as when thirteen species
of whiptail lizards composed entirely of females
stay undiscovered due to bias