CHAPTER 6

INVERTEBRATE VISIONS: DIFFRACTIONS OF THE BRITTLESTAR

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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.

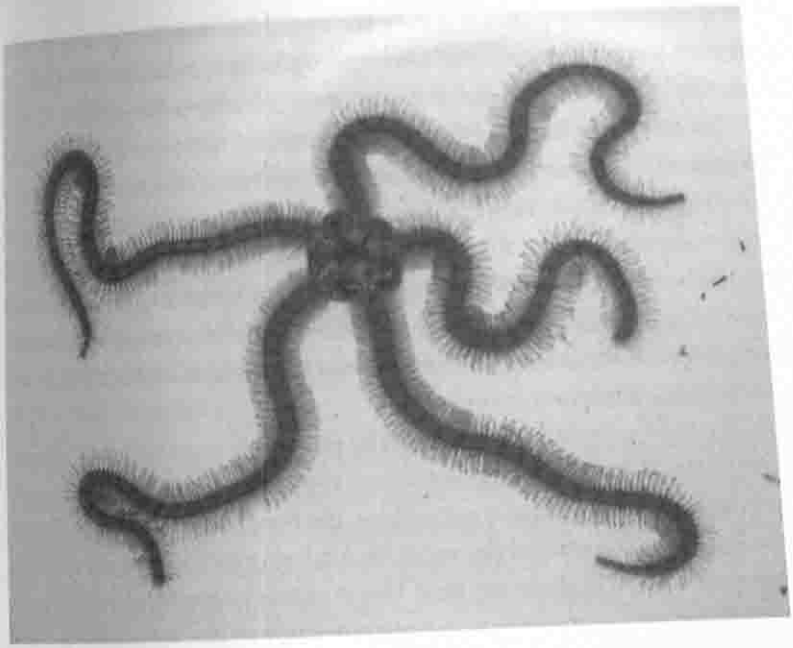
—Donna Haraway, "Situated Knowledges"

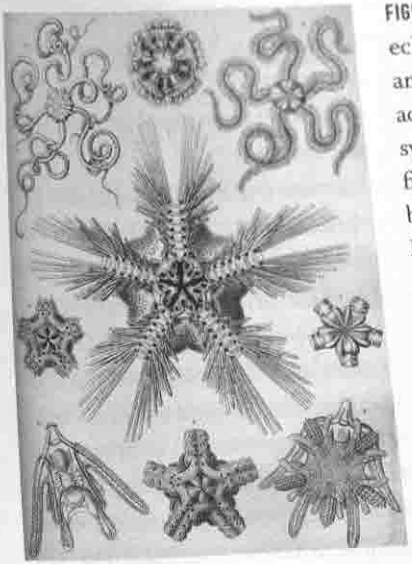
Diffraction patterns record the history of interaction, interference, reinforcement, difference. Diffraction is about heterogeneous history, not about originals. . . . Diffraction is a narrative, graphic, psychological, spiritual, and political technology for making consequential meanings.

—Donna Haraway, *Modest_Witness@Second_Millennium .FemaleMan_Meets_OncoMouse*

"Eyeless Creature Turns Out to Be All Eyes" announces the *New York Times*.[1] An international team of material scientists, theoretical physicists, chemists, and biologists were featured in the *Times* for their amazing finding that a 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. The ability of this critter to reconfigure the boundaries and properties of its body is prompting technology enthusiasts to reimagine what it means to be human. This multi-limbed sea creature is being enterprised up for new computer designs and telecommunications optical networks (giving new meaning to the AT&T slogan "Reach Out and Touch Someone"). Summarizing the results of a study published in the August 23, 2001, issue of the scientific journal *Nature*, Jonathan Abraham, the author of the *Times* article, continues: "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."[2] The researchers found that the approximately ten thousand spherically domed calcite crystals covering the five limbs and central body of the brittlestar function as micro-lenses. These micro-lenses 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 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." "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, Brighton.[3]

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.[4] 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. At first glance, this evolutionary strategy seems ill conceived, since it increases their visibility to predators. But if the brittlestar's goal is increase its vision (the better to avoid predators), to collect





FIGURES 6.1–6.2 Brittlestars, like other echinoderms (sea urchins, starfish, and sand dollars) are organized according to principles of radial symmetry. These organisms have five identical segments. Blue-lined brittle star (*Ophiothrix lineocaerulea*). Photograph by Ria Tan, http://www.wildsingapore.com. The illustration is from Ernst Haeckel, *Kunstformen der Natur* (1904). See multispecies-salon.org/barad.

as much light as possible during the night, and likewise to protect its visual system from oversensitivity, overexposure to light, during the day (think sunglasses), then the process of evolutionary selection seems justified.

To test their hypothesis that "these calcitic microstructures might have a function in directing and focusing the light on photosensitive tissues," the researchers at Bell Labs used a technique called optical lithography, a process that is 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* was cleansed of organic tissue, and a low-magnification scanning electron micrograph (SEM) of its dorsal surface was recorded as a reference image."[5]

The lensing system was analyzed by placing the prepared sample on a silicon wafer. Mimicking the process used to engrave circuits optically on a silicon wafer in the making of microchips, the researchers shined light through the lenses, which etched the wafer. By analyzing the etchings, the researchers were able to deduce the focal length of the lenses. This was compared with a transmission electron microscopy study of thin sections of decalcified dorsal arm plates, which revealed bundles of nerve fiber located at the focal plane of the lens system. On the basis of this finding, the researchers suggested 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."[6]

In talking with the press, Joanna Aizenberg, a Bell Labs scientist and the lead author of the study, likens the brittlestar to a digital camera that builds up a picture pixel by pixel.[7] 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."[8] In summary, the remarkable finding of this international multidisciplinary team of scientists is that the brittlestar's skeletal system is composed of an array of micro-lenses, 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 corresponds 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).

Physicist Roy Sambles, who works on optics and photonics at the University of Exeter in Britain, expressed his enthusiasm for this brainless creature's ingenuity this way: "It's astonishing that this organic creature can manipulate inorganic matter with such precision—and yet it's got no brain." Crystals emerge from the right chemical environment, they are self-organized, rather than engineered by careful top-down control. "It's starting with a soup of chemicals and pulling out this wonderful microstructure," says Sambles, who fantasizes about emulating the process "in a bucket in a corner of the lab."[9] Further, Sambles writes:

> 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.[10]

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."[11] (So what makes it "primitive" again?)

While this discovery is a fantastically interesting scientific result, it is probably fair to say that the excitement surrounding this finding and the wide reporting of this story has more to do with its potential applications than pure amazement at the ingenuity of this creature's bodily know-how. 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."[12]

Understatement (or, at least, reserve) is considered good professional etiquette in scientific publications. Summaries such as the ones in the "News

and Views" section of *Nature* allow quite a bit more leeway, but statements to the popular press follow a different set of rules altogether. So it perhaps is not surprising that a *Discover* magazine reporter juxtaposed 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.'"[13]

As might be expected, the press releases from Bell Labs (owned by Lucent Technologies) are very upbeat about the discovery. In a press release titled "Bell Labs Scientists Find Remarkable Optics in Marine Creatures That May Lead to Better Microlenses for Optical Networks," dated August 22, 2001, Bell Labs 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 more recent achievement, published in the journal *Science*: "the creation of the world's first micro-patterned crystals inspired by bioengineering found in nature."[14] The summary phrase, set as a boldface subtitle 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, Aizenberg explained the project this way: "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 brittlestar's optical system is different in kind from the visualizing systems that many science studies and cultural studies scholars are fond of reflecting on.[15] The history of Western epistemology displays great diversity and ingenuity in the generation of 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.[16]

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 do not *have* eyes. They *are* eyes. That is, it is not merely the case that its 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. It does not suffer the Cartesian doubts of an alleged mind-body split. Knowing is entangled with its mode of being.[17]

Brittlestars are not fixated on the illusion of the fixity of "their" bodily boundaries, and they would not entertain the hypothesis of the immutability of matter for even a moment. Dynamics is not merely matter in motion to a brittlestar when matter's dynamism is intrinsic to its biodynamic 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 a predator, 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 bodily boundaries. *Its discursive practices*—the boundary-drawing practices by which it differentiates between "itself" and the "environment," by which it makes sense of its world—*are materiality enacted*.[18] Its bodily structure is a material agent in what it sees/knows. 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.

The very substance of the brittlestar is morphologically active and generative—playing an agentive role in its differential production, its ongoing materialization. That is, *its differential materialization is discursive.* This dynamics entails causal practices that reconfigure boundaries and properties that matter to its very existence.[19] The ongoing reconfiguring of its bodily boundaries and connectivity are intra-active material-discursive practices through which the agential cut between "self" and "other" (e.g., "surrounding environment") is differentially enacted. The neologism "intra-action" (in contrast to the usual "interaction") signifies the mutual constitution of entangled agencies.[20] Agential cuts are the result of specific intra-actions.

On one agential cut, a given arm is part of the former; on another, it is part of the latter. The ability to distinguish "self" from "other"—to track and dodge predators, for example—is a requisite for the brittlestar's survival. But this does not imply that categories need to be fixed. On the contrary, the survival of these critters depends on their capacity to discern the reality of their changing and relational nature. Intelligibility and materiality are not fixed aspects of the world but, rather, are 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, is part of the brittlestar's biodynamics. This apparatus serves as both 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 multifunctional 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 *of* the world. Location for a brittlestar is not about occupying a determinate position in a given environment, although it may be usefully (con)figured as *specific connectivity.*[21] Objectivity cannot 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 in history. The importance of the body as a performance, rather than a thing, can hardly be overemphasized.

Brittlestars offer us resources for rethinking conventional conceptions of space and time. The brittlestar's bodily dynamism resists the familiar notion that space is a preexisting container, a stage on which actors take their places, and that time is the mere uniform ticking of a clock. Spacetime does

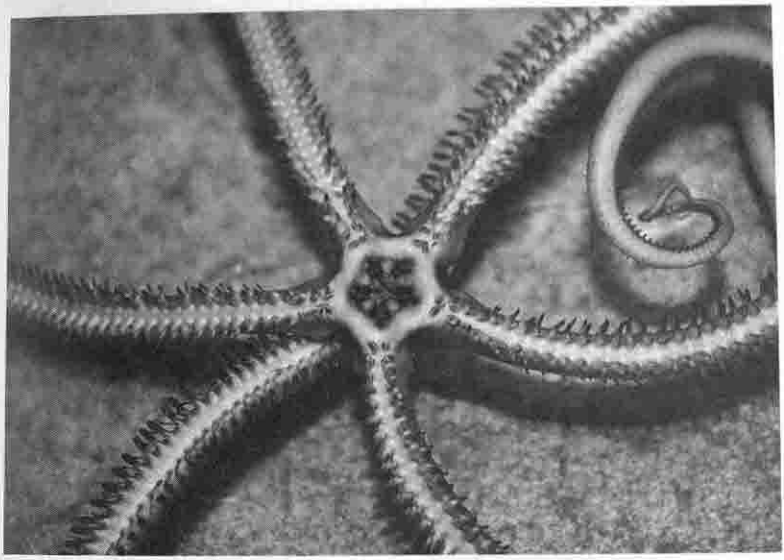


FIGURE 6.3 Close-up of an ophiuroid brittle star showing its fragile arm. Photograph courtesy of the National Oceanic and Atmospheric Administration Photo Library. See multispecies-salon.org/barad.

not sit still while bodies are made and remade. The relationship of space, time, and matter is much more intimate.[22] Matter does not move in space and time. Matter materializes and dynamically enfolds different spatialities and temporalities. Bodies are among the differential performances of the world's dynamic reconfiguring. No-thing stands separately constituted and positioned inside a spacetime frame of reference, and no divine position for our viewing pleasure exists in a location outside the world.[23] There is no absolute inside or absolute outside. There is only exteriority within—that is, *agential separability*.[24] Embodiment is a matter not of being specifically situated in the world but, rather, of being of the world in its dynamic specificity.

Some brittlestars 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 being helping out? If the detached limb's continuing movements are judged to be mere reflex, on the basis of the fact that the fragment has no brain, what of the original organism? Shall we deny the liveliness and ingenuity of this smart material without a brain, a living contestation of the organic-inorganic

binary? (Watch the antics of an autonomous brittlestar arm online at http://multispecies-salon.org/barad.)

Brittlestar species exhibit great diversity in sexual behavior and reproduction. Some species use broadcast spawning, and others exhibit sexual dimorphism. Some are hermaphroditic and self-fertilize while 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 it is 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. 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 surely will require rethinking psychoanalysis, as well.

Negotiating complex sets of changing relations concerning bodily boundaries, brittlestars are evolutionarily attuned to processes of differentiation and visual recognition. In fact, brittlestar optics help sharpen some of Donna Haraway's insights about diffraction. Haraway suggests that diffraction can serve as a useful counterpoint to reflection: Both are optical phenomena, but whereas the metaphor of reflection reflects the themes of mirroring and sameness, diffraction is marked by patterns of difference.[25] Troubling the notion of reflection as a pervasive trope for knowing, brittlestar optics challenge some key assumptions about visuality (and epistemology) that are based on the optical model of reflection. Indeed, brittlestars impress on us the need to pay greater attention to our assumptions about epistemology, particularly in its relationship to ontology. Brittlestars are attentive to different optical effects all at once. The tiny lenses that make up the brittlestar's skeletal system are susceptible to significant diffraction effects. As the size of a lens decreases, the diffraction effects increase. Lens makers are attentive to the optical trade-off between resolution and diffraction effects. Insects with compound eyes are also on to this optical trade-off. Diffraction effects limit the ability of a lens (or a system of lenses) to resolve an image. The greater the diffraction effects, the less determinate are the boundaries of an image. This is a fundamental physical limit (not merely a practical one) to light microscopes and other visualizing systems.[26] Brittlestars thus live at the edge of being diffraction gratings. These living, breathing, and mutating animals also offer an opportunity to rethink the nature of relationships.

Diffraction is not about any difference but about which differences matter. The brittlestar illustrates the possibilities for differentiation without individuation. Brittlestars have evolved in intra-action with their environment. Intra-action marks the relational nature of the world in its intra-active becoming. There are no independently existing things that precede their intra-action. Rather, differences are materialized through a dynamics of iterative intra-activity. It is through specific intra-actions that the boundaries and properties of agents become determinate. Brittlestars' micro-lenses are optimized to maximize visual acuity (for the discernment of predators, hiding places, and other important phenomena). They seem to have evolved in a creative tension, a trade-off, between the resolution of detail and diffraction effects, between geometrical and physical optics.

The focus of the analysis in the *Nature* article about brittlestars is exclusively on geometrical optics. There is no discussion of possible physical optics effects, such as diffraction. But diffraction effects, which limit the resolving power of a lens, are significant for lenses as small as the brittlestar's. (The smaller the lens, the greater the blurring of the image by diffraction.) This is also an important factor for small animals such as insects. In fact, it is the reason they do not have the kind of eyes that the human or octopus has. If the human eye were scaled down to fit an insect, the insect would be unable to resolve things on the scale that matters to it because the diffraction effects would be so significant. Insects thus use a different optical system—namely, compound eyes.[27] Compound eyes use bundles of very small optical detectors to form an image. The ability of the compound eye to resolve details increases as the individual detectors become smaller and more numerous, much like a computer monitor with large numbers of pixels per unit area. The price is that the smaller the lens, the greater the diffraction effects. How that tension is negotiated clearly matters: The possibilities for survival are at stake in an organism's ability to differentiate boundaries in its surroundings.[28]

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 science studies and cultural studies scholars fancy. These epistemologies too often figure visualization as a matter of geometrical optics, leaving important factors of physical optics aside. But this approach 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.[29] In the

absence of a vigorous examination of the ontological issues, the locus of knowledge is presumed never to be 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 women, slaves, children, animals, and other dispossessed Others (exiled from the land of knowers by Aristotle thousands of years ago) into the fold of knowers. The point is to better account for the ontology of knowing.

Brittlestars literally enact my onto-epistemological point about the entangled practices of knowing and being, a central element of agential realism.[30] 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.[31] Brittlestars intra-act with their ocean environment. They respond to differential stimuli made intelligible through intra-actions, adjusting their positions and reworking their bodies 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"?[32] 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, or 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 traditional 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.

In traditional humanist accounts, intelligibility requires an intellective agent (a that to which something is intelligible). Intellection is thus conventionally framed as a specifically human capacity. But in my agential realist account, intelligibility is an ontological performance of the world in its ongoing articulation. Intelligibility 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 to what matters.

Knowing, however, 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. As Joseph 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 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."[33] 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. Life and death are at stake.[34]

Brittlestars are not merely tools that we can use to teach us about how to build enhanced communication networks and principles useful to biomimesis—an approach used by scientists, engineers, and designers that explores possibilities of making novel designs by copying existing forms of life. 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 we see are sharp, inherent edges marking the limit of separate entities. Yet on closer examination, the diffraction effects—the indefinite nature of those boundaries—become clear. I am not suggesting 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 do not 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 repre-

sentations than in matter, believing that we have a kind of direct access to the content of our representations that we lack toward that which is represented. Representationalism involves the wrong optics, the wrong ground state, the wrong set of epistemological and ontological assumptions. Haraway's move away from optics as "a politics of positioning" (in "Situated Knowledges") to diffraction as "an optical metaphor for the effort to make a difference in the world" (in *Modest_Witness*) signals the kind of shift that is required.[35]

There is more to diffraction than meets the eye. As we have learned from quantum mechanics, diffraction is a much subtler and more 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. 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, and epistemology and ontology, as well as material and discourse. Diffraction marks the limits of the determinacy and permanence of boundaries. One of the crucial lessons we have learned is that agential cuts cut things together-apart (one move). *Diffraction is a matter of differential entanglements, where entanglement is not the intertwining of separate entities, but their very inseparability.*[36] This is the deep significance of a diffraction pattern. Differentiating is not about othering/separating. It is about making connections and commitments. What is on the "other side" of the cut is not separate from us. Agential separability is not individuation; the dynamics is one of differentiating-entangling. Ethics is not about the right response to the other but about responsibility and accountability in lively relationships. "We" are a part of these relationships; we do not stand apart.

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/product-making projects. "Humans" and "brittlestars" learn about and co-constitute one another 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 objective of our microscopes. Is the brittlestar the lens that we look at, or look through, or look with? Brittlestars are not gripped by the idea of mirroring, imitation, reflection, or other tropes of "sameness." These echinoderms do not reflect on the world; they are engaged in making a difference in the world. 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 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).

Brittlestars are *trans/materialities*. They transgress the sacrosanct divides between organic and inorganic, machine and animal, episteme and techne, matter and intelligibility, macro and micro. Brittlestars not only already know how to do nanotechnology (so beautifully that they have done away evolutionarily with optical aberrations in perfecting of their nanoscale designs), they live it. Indeed, brittlestars are an ancient nanotechnology that lives and breathes and repairs itself, marking a rather queer temporality that comes from the past and the future.

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. 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 for its own sake 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 does not 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 publicity benefits, without the new there is simply no copyright to be gained. But we should slow down in our unquenchable quest for the new. It is not so much newness as emergence that is at issue: With the intra-active generation of new temporalities, new possibilities, new subjectivities, the "new" has become the trace of what is yet to come. The copyright symbol © should be a sign not of the right to copy but, if anything, of the responsibilities entailed in producing differential materializations (for whom and at what costs?).[37]

Biomimetics is a nodal point around which nanotechnology, biotechnology, and information technology become more and more complexly entangled. As we entertain the possibilities for forming partnerships with brittlestars and other organisms for biomimetic projects, we are co-constituting ourselves into phenomena 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.[38] "We" are an inextricable part of what gets reworked in our research and development 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 how our desires and our beings are co-constitutively reconfigured.

Optical lithography is a prime example of how biomimetics has transformed not only the notion of mirroring but also our understanding of optics. Biomimetics is not interested in mirror images of the Same. It has a different optics in mind. Biomimetics involves bringing different difference patterns into existence. It is interested in running the rays of understanding back through the apparatuses of production to remake these very apparatuses. Optical lithography is used to study brittlestars' lenses, and then brittlestars' lenses are used as inspiration for improving optical lithography. Tools are used to rework tools.[39] Enfolded into the apparatuses of bodily production, these phenomena contribute to their constitution as nanotechnology phenomena. This is not simply the iteration of simulacra (copies from copies without originals); these dynamics have a much more complex topology. Differences are incorporated at each level. Reflexive analyses do not cut it. We need to understand diffraction effects. How are differences constituted and enfolded? Which differences matter, how do they matter, and to whom?

NOTES

This essay was originally written in 2004 in honor of Donna Haraway, an invited contribution for an "un-Festschrift" that, unfortunately, has yet to materialize. In the meantime, much of this material was published as part of chapter 8 of my *Meeting the Universe Halfway* (Duke University Press, 2007). It is presented here with revisions in response to two peer reviewers. Thanks are due to Eben Kirksey for suggestions to make it more accessible. I dedicate the chapter to my dear friend and colleague Donna Haraway, with deepest gratitude.

Epigraphs: Haraway, "Situated Knowledges," 583; Haraway, *Modest_Witness@Second_Millennium.FemaleMan_Meets_OncoMouse*, 273.

1. Jonathan Abraham, "Eyeless Creature Turns Out to Be All Eyes." *New York Times*, September 4, 2001.

2. Abraham, "Eyeless Creature Turns Out to Be All Eyes."

3. Land quoted in Whitfield, "Eyes in Their Stars." *Nature*. Available at http://www.nature.com/news/2001/010823/full/news010823–11.html.

4. Photosensitive species of brittlestars exhibit responses to their environment that are superior to those of other marine organisms and seem to entail visual functioning. For example, they move out of the way of predators and run into crevices they spy from a distance. The existence of photosensitivity was linked to diffuse dermal receptors in previous studies.

5. Aizenberg et al., "Calcitic Microlenses as Part of the Photoreceptor System in Brittlestars," 820.

6. Aizenberg et al., "Calcitic Microlenses as Part of the Photoreceptor System in Brittlestars," 822.

7. Whitfield, "Eyes in Their Stars."

8. BBC News Service, "Can We Learn to See Better from a Brittlestar?" December 16, 2002.

9. Sambles quoted in Whitfield, "Eyes in Their Stars." *Nature*. Available at http://www.nature.com/news/2001/010823/full/news010823–11.html.

10. Sambles, "Optics," 783.

11. National Public Radio, "Sea Creature Sight," August 22, 2001, available at http://www.npr.org, accessed on February 26, 2014.

12. Aizenberg et al., "Calcitic Microlenses as Part of the Photoreceptor System in Brittlestars," 821.

13. Weinstock, "A Thousand Eyes without a Face."

14. Aizenberg et al., "Direct Fabrication of Large Micropatterned Single Crystals," 1205.

15. What is at issue is not the geometrical optics model that positions representation as the lens that mediates between the object world and the mind of the knowing subject. That kind of optics reflects a geometry of absolute exteriority between ontologically and epistemologically distinct kinds.

16. This is not to say that language, culture, technology, and labor do not matter. Surely they do. The point is to question the assumption that they serve a mediating

function. My notion of agential realism rejects the geometrical optics metaphor of lenses and mediation and offers an alternative (nonrepresentational) understanding of *how* these factors come to matter: see Barad, *Meeting the Universe Halfway*, chap. 4.

17. 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 representationalism.

18. I draw on and further elaborate Michel Foucault's notion of discursive practices. According to Foucault, discursive practices are not the same thing as speech acts or linguistic statements. Rather, discursive practices are the material conditions that define what count as meaningful statements: Foucault, *Power/Knowledge*, 194. For my elaboration, see Barad, *Meeting the Universe Halfway*, chap. 4.

19. This is to suggest not that matter and discourse are equivalent but, rather, that the relationship is one of mutual entailment. Similarly, one cannot draw a distinction between the brittlestar's skeletal system and its visualizing system. There is no skeleton without the calcite crystals that also make up the visualizing system, and vice versa.

20. The notion of "interaction" assumes that there are separate individual agencies that precede their interaction. In contrast, "intra-action" recognizes that distinct agencies do not precede but, rather, emerge through their intra-action. It is important to note that agencies are only distinct in a relational sense, not an absolute one. It is through specific intra-actions that the boundaries and properties of "agents" become determinate. That is, agencies are only distinct in relation to their mutual entanglement; they do not exist as individual agents. For a more detailed discussion of the key agential realist notion of intra-action, see Barad, *Meeting the Universe Halfway*.

21. Haraway does not take location to be about fixed position (although, unfortunately, many readers who cite Haraway conflate her notion of "situated knowledge" with the specification of one's social location along a set of axes referencing one's identity). She reiterates this point in different ways throughout her work. For example, she writes, "Feminist embodiment, then, is not about fixed location in a reified body, female or otherwise, but about nodes in fields, inflections in orientations, and responsibility for difference in material-semiotic fields of meaning. Embodiment is significant prosthesis; objectivity cannot be about fixed visions when what counts as an object is precisely what world history turns out to be about": Haraway, "Situated Knowledges," 181. Situated knowledges are not merely about knowing/seeing from somewhere (as in having a perspective) but about taking account of how the specific prosthetic embodiment of the technologically enhanced visualizing apparatus matters to practices of knowing. See also Barad, *Meeting the Universe Halfway*, 470n45.

22. For more details, see Barad, *Meeting the Universe Halfway*, esp. chaps. 4, 6–7. See also Barad, "Nature's Queer Performativity (the Authorized Version)"; Barad, "Quantum Entanglements and Hauntological Relations of Inheritance."

23. Erwin Schrödinger nicely sums up the difficulty of the spectator theory of knowledge. "Without being aware of it, and without being rigorously systematic

about it, we exclude the subject of cognizance from the domain of nature that we endeavor to understand. We step with our own person back into the part of an onlooker who does not belong to the world which by this very procedure becomes an objective world": Schrödinger, *What Is Life?*, 127.

24. "Agential separability" is a key concept in agential realism: Barad, *Meeting the Universe Halfway*, 140.

25. Diffraction is a phenomenon exhibited by waves. Waves bend around edges and overlap with one another, making diffraction patterns. This essay only offers a glimpse into my much more extensive elaboration of diffraction. For a detailed discussion of diffraction as it is understood from the point of view of classical mechanics, see Barad, *Meeting the Universe Halfway*, chap. 2. For a further elaboration of this physical phenomenon (including its far-reaching implications for understanding quantum physics) and the profound epistemological and ontological shift produced by a quantum understanding of diffraction, see Barad, *Meeting the Universe Halfway*, index, s.v. "diffraction (interference)."

26. This optical limit is called Abbe's law. In theory, the diffraction limit can be mitigated (i.e., the diffraction effects can be reduced) by taking advantage of certain features of the phenomenon of quantum entanglement, but a limit exists nonetheless for any finite number of entangled photons: see, e.g., Boto et al., "Quantum Interferometric Optical Lithography," and the cautionary comments in Ole Steuernagel, "Comment on 'Quantum Interferometric Optical Lithography.'"

27. The compound eye of insects is made up of many individual units called ommatidia. Each ommatidium is a simple light detector (a light pipe) that points in a different direction. The insect's ability to resolve images depends on a large number of small ommatidia in its eye. Resolution increases with smaller and more numerous ommatidia. But if the ommatidia are too small, then blurring caused by diffraction becomes significant. The optimal size of insect ommatidia is a compromise between these competing effects. For example, for a wavelength of .5 micron (yellow-green), the optimal diameter of an ommatidium is 27 microns. Interestingly, the individual lenses of the brittlestar have a diameter of approximately 20 microns, so it seems that the brittlestar has also engineered a good trade-off between resolvability and diffraction. For a discussion of the optics of the compound eye, see Feynman et al., *The Feynman Lectures on Physics*, 1:36–38. See also Alexander, *Optima for Animals*.

28. Brittlestars are living breathing (liminal) diffraction gratings. Their very being is a flexible distributed growing and regenerating multi-oriented shape-shifting topologically variant dynamical system of diffraction gratings.

29. There is a profound distinction between classical and quantum physics—the epistemology and ontology that each entails is 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" (to borrow a phrase from Sandra Harding), but she is not alone in this insistence). 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, consigning the rest to the

background. 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: see Harding, *Whose Science? Whose Knowledge?*, 147.

30. Elsewhere I have presented a relational ontology that rejects the metaphysics of *relata*, of "words" and "things." In an agential realist account, it is possible to acknowledge nature, the body, and materiality in the fullness of their becoming, without resorting to the optics of transparency or opacity, the geometries of absolute exteriority or interiority, and the theorization of the human as either pure cause or pure effect while at the same time remaining resolutely accountable for the role "we" play in the intertwined practices of knowing and becoming: see Barad, *Meeting the Universe Halfway*.

31. "Holding," "responding," and "thinking" are all intra-active engagements with and as parts of specific configurations of the world.

32. Mazia quoted in Wayne, *Light and Video Microscopy*, 219.

33. Rouse, "Barad's Feminist Naturalism," 153.

34. "Recognizability" is not a fixed and universal notion. Rather, it also 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.

35. Haraway, *Modest_Witness@Second_Millennium.FemaleMan_Meets_OncoMouse*, 16; Haraway, "Situated Knowledges," 193.

36. See Barad, *Meeting the Universe Halfway*, esp. chap. 7.

37. "This is an excellent reminder as to why the recent uncritical embrace of the 'new' [a trend to which the academy has not been immune] might well give us pause. Although in [some important (philosophical)] sense there may be nothing but the new, this point should not deflect our attention from the fact that the uncritical embrace of the new (the brighter, shinier, lighter model) fits all too comfortably with capitalism's reliance on the continual production of new desires including a desire for the new": Barad, *Meeting the Universe Halfway*, 473n57. Significantly, the methodology of diffraction does not do away with the old in favor of the new—indeed, they are always already threaded through one another. I wrote this well before I had any inkling that my work was to be dubbed "new materialist." While it is exciting to be a part of a current *re*-turn to materialism, I also have some reservations about the framing and a sense of discomfort that derives from precisely this kind of concern: that the old not be discarded for the new, and that attention be given to the ways in which all the "news" (new turns, new programs, new fee structures, new forms of digital education, and the like) feed neoliberalism's grip on the academy. To my mind, the "old" materialism is not only an honored part of "new" materialism's inheritance. It is also a rich resource for feeding and informing the "new" materialism, especially now, when economic analyses are so urgently needed—hence, my desire to place poststructuralist and Marxist insights in conver-

sation with one another by reading them through one another rather than placing them at odds with each other. For other authors who are similarly committed, see, e.g., Rosemary Hennessey, Leela Fernandes, Miranda Joseph, Linda Alcoff. Of course, feminist science studies has always had a disloyal but honored relationship to historical materialism. Where would feminist theory in the twenty-first century be without Haraway's "A Cyborg Manifesto"?

38. *Entanglement*, in the quantum theory sense, refers not to the intertwining of separate states but, rather, to their inseparability. To put it another way, spatially separated particles in an *entangled state* do not have separate identities; they are instead part of the same phenomena. Empirical support for a relational ontology interpretation (such as the one offered by agential realism) has been amassing since the 1990s, when rapid technological advances made possible an increasing number of experiments that test fundamental questions about the nature of reality. For details, see Barad, *Meeting the Universe Halfway*, esp. chap. 7. There has been some confusion as to whether the existence of quantum phenomena has any relevance for thinking about the nature of human experiences, which occur at the macroscopic scales. But this insistence on quarantining quantum queerness is suspect for several reasons. For one thing, the notion of a "micro-world" does not hold up either theoretically or experimentally. That is, while there is much talk about a so-called micro-world, as compared with a "macro-world," Newtonian physics is thought to have been superseded by quantum physics. In particular, Newtonian physics happens to be a good approximation for relatively massive objects, but quantum physics is thought to be the fundamental theory. Furthermore, there is no empirical evidence of such a disjunction of ontologies at a particular scale. On the contrary, with each passing year new experimental evidence is gathering that flies in the face of the supposition that the world is divided into two—a "micro-world" that follows the laws of quantum theory and a "macro-world" that follows the laws of Newtonian physics. For example, in 2011, it was demonstrated that it is possible to entangle macroscopic bits in the form of diamond chips. "Our results show that entanglement can persist in the classical context of moving macroscopic solids in ambient conditions": Lee et al., "Entangling Macroscopic Diamonds at Room Temperature," 1253. As the quantum entanglement expert physicist Anton Zeilinger proffers, "Someday, we will actually be able to demonstrate that quantum uncertainty has its relevance also for macroscopic objects. This is a question of technology as it develops. There is no clue in sight telling us that quantum uncertainty must stop somewhere. . . . There is no reason *in principle* why it should not be possible to observe quantum superpositions of living systems someday. For example, there is no fundamental reason why one should not be able to observe a quantum double-slit experiment for an amoeba or a very small bacterium": Zeilinger, *Dance of the Photons*, 44, 249; emphasis added. In addition, according to agential realism, scale is intra-actively (re)configured in the ongoing intra-active becoming of space-time-mattering.

39. These creatures are reminiscent of the "living mutating differential gear assemblage": see Barad, *Meeting the Universe Halfway*, chap. 6.