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RESEARCH ARTICLE

Materials sovereignty: Pathways for shaping nanotechnology design

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People in contemporary industrial societies encounter countless novel materials that did not exist previously, many of which present risks to health and environment. In this article, we build on the concept of "materials sovereignty" as the right of people to use and be surrounded by environmentally benign, non-toxic, and renewing materials in their everyday lives. As a rights-based approach, materials sovereignty may help change the politics of governing materials. We suggest that social movements that explicitly base interventions into design on materials sovereignty may be better able to gain traction in changing industrial production. We consider the case of nanotechnology as a particularly challenging field for social movement intervention. We review several pathways that have been used by social movement organizations in attempts to influence the development of nanomaterials, but which have met with limited success. We more closely examine three participatory pathways through which social movements could intervene more directly into material design: participatory technology assessment, collaboration with industry, and co-design. We identify three key elements of materials sovereignty: participatory knowledge systems, which create multi-directional flows of knowledge and agency; the embedding of citizen voices into design processes; and building accountability systems. Of the pathways we examine here, co-design appears to be the most promising from a theoretical and ethical perspective, but there remain significant institutional and organizational challenges for bringing it into practice.

Keywords: Social movements; Nanotechnology; Materials sovereignty; Co-design; Participatory design

Introduction

Industrial societies face difficult quandaries in deciding how to deal with emerging materials, from teflon to bioplastics. Novel materials promise new capabilities and functions, including greater sustainability. Yet their use may result in harm to ecological and human health, or worsen economic inequality across societies. From perfluorinated compounds to flame retardants, seemingly "safe" industrial chemicals have turned out to harm reproduction and development in human bodies (Harremoës et al., 2013; Lanphear, 2017). Despite observing early warnings of these effects, corporations and governments have allowed problematic chemical uses to proliferate, while people have remained oblivious to the fact they are being exposed without their knowledge and permission. Do citizens have a role in helping shape the design and use of materials? What can they contribute to the design process, if anything, and how? What might be needed for more diverse voices to be represented in the development of material technologies?

To investigate such questions, we consider a class of materials that has emerged in the last 20 years: nanotechnologies, or substances designed with features at very small scales roughly between the molecular and the cellular (Ramsden, 2011). Examples include carbon nanotubes, titanium dioxide, and quantum dots. Their use in everyday consumer products is expanding rapidly and in relatively unseen ways. Nanomaterials may present novel risks to workers involved in production, to vulnerable populations, or to ecosystems. However, enormous uncertainty exists in estimating these risks because of how much is still unknown about nanomaterial use and hazards (Lai et al., 2018).

Nanomaterials present a challenge for citizen involvement in design. Engineering nanomaterials is a technically esoteric domain. Developing them—and scaling up to production capacity—entails sophisticated chemistry, quantum physics, material informatics, and manufacturing technologies. Furthermore, the global material production system ranges across large geographical, temporal, economic, and cultural distances between the designers of materials and the people using them or being exposed to their effects (Princen, 2002). As a consequence, there is little feedback from societal actors into the design process, except through market demand and legal liability (Nieusma, 2011). Companies primarily use economic and market analysis to decide whether to insert nanomaterials into their products. It would appear, then, that only

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scientists and corporate managers can legitimately decide on introducing this new class of materials into society, because they hold the requisite knowledge and expertise. In theory, material scientists can apply green chemistry principles to develop nanomaterials that are benign to human health and the environment (Anastas and Warner, 1998; Hutchison, 2008). In practice, very few actors in the nanotechnology industry are realizing these principles, mostly because they are not being held accountable by societies for their decisions. Yet nanomaterials are still at an early, if rapidly evolving, stage of development: intervention now could result in risk reduction later (van Broekhuizen and Reijnders, 2011).

Multiple civil society organizations are now striving to influence the development of nanotechnology. Together, they are attempting to build a new social movement around making nanomaterials safer, at a time when the technologies are still emerging—their forms still in flux, open to change. This did not happen with earlier generations of industrial chemicals, leading to what sociologists Woodhouse and Patton (2004) have described as technological somnambulism: societies sleepwalking through the rapid, unmonitored growth of the modern industrial chemical system, oblivious to the environmental and social costs of new substances. However, social movements have historically had only partial success in influencing technological fields (Hess, 2005; Hess, 2007).

We suggest that social movements can invoke what we call "materials sovereignty" as a basis for active intervention into the development of material technologies. Akin to food sovereignty, people can seek to create and assert rights to have a say in what materials are used in their products. But what materials sovereignty means, who can effectively invoke it, and its implementation in practice are uncertain. We use the challenging case of nanotechnology to begin fleshing out the concept of materials sovereignty, by comparing different pathways through which diverse voices could be incorporated (via social movements) into the design of new materials. The prevailing approach sees nanotechnology design processes as occurring largely within private firms and universities, even though they still reflect pervasive societal influences (Woodhouse and Patton, 2004). Investment, research funding, business models, regulations, intellectual property rights, and consumer culture are all examples of social systems that help determine how nanotechnologies take shape. The unintended consequences of technologies are often the result of not intentionally exercising "anticipatory" social governance over technologies (Barben et al., 2007). In contrast, we suggest, social movements may push for particular scientific research priorities, public policy interventions, or business practices to ensure that potentially risky technologies develop in ways that reflect broader public interests.

Materials sovereignty and social movements

We define materials sovereignty as the right of people to use, and be surrounded by, environmentally benign, nontoxic, and renewing materials in their everyday lives. The concept of materials sovereignty has a parallel in food sovereignty, a fast-coalescing discourse and practice in the food system worldwide (Wittman, Desmarais, and Wiebe, 2010; Claeys, 2012, 2015). Materials are diverse and pervasive in everyday life: they include plastics, metals, wood, stone, ceramics, and bone. In contemporary societies, people encounter countless chemical products that did not exist previously. Materials sovereignty builds on, but also goes beyond, the extensive STS literature on democratizing technology (e.g. Sclove, 1995; Kleinman, 2000; Woodhouse and Patton, 2004). It emphasizes the role of *sovereignty* in potentially changing the politics of chemicals and other materials in a context where decades of democratization discourse have struggled to transform the terrain on which design and production happen.

Materials sovereignty is arguably emerging through an array of new demands and actions taken by consumers, citizens, indigenous peoples, scientists, and NGOs that are centered on making materials safer. Examples include the NGO campaigns occurring in the United States to mobilize consumers to boycott cosmetics that contain phthalates and baby bottles that carry bisphenol A (Geiser, 2015). Communities in West Virginia and Minnesota have organized against DuPont and 3M Corporation respectively to stop their drinking water from being polluted with perfluorinated chemicals (Kozlowski and Perkins, 2015). European mothers have had their bodies tested for the presence of synthetic chemicals, such as flame retardants, in connection with the passage of the REACH law that transformed chemical controls in 2006 (Lyons and Illig, 2007). Indigenous peoples have linked the issues of sovereignty, self-determination, and human rights to struggles against chemical pollutants that contaminate their air, water, and food (Downie, Fenge, and Inuit Circumpolar Conference, 2003; Selin and Selin, 2008; Hoover et al., 2012). They have brought human rights petitions in international fora to demand the reduction of air pollutants that endanger climate stability in the arctic (Watt-Cloutier, 2015). Many of these efforts center on chemicals but others address metals and wood. While still far from being a settled "constitutional" norm, the concept of materials sovereignty helps gather these disparate efforts into a more cohesive form.

Materials sovereignty is rooted in human and democratic rights. Under this framework, people have the right, for example, to say they want products designed without endocrine disrupting chemicals—and made readily available, at affordable costs. Across millions of workplaces and households globally, people have the right to reject being exposed to harmful substances present in the consumer products, technologies, and infrastructures they use (c.f. Dinham and Malik, 2003; Westra, 2008; Arnold, 2010). They have the right to be free from building up a body burden of industrial chemicals through their lifetime (Hoover et al., 2012). They also have a right to say that materials should be sourced or manufactured without causing environmental degradation and damage to human health (e.g., not made from ore mined with destructive methods). This harm could occur directly to consumers through using products; it could also be felt indirectly through the spread of chemical contamination from factories and products around the planet (Lerner, 2010). Implicitly, therefore, people have the right to intervene in the materials production system in order to assure their health and well-being; and to have the precautionary principle implemented in chemical design, business decisions, and government policies where feasible (Kerns, 2001).

Many institutional, legal, knowledge, and political elements are necessary to support the capacity of people to exercise their right to use non-toxic and renewing materials. For example, people may need readily accessible knowledge about material ingredients and manufacturing; the science of chemical toxicity, ecological impacts, and body burdens; and the alternative safer materials that manufacturers could potentially use (Lambert et al., 2003). In turn, more protective laws, chemical testing and evaluation regimes, biomonitoring surveys, and readily searchable open-access databases may be needed to generate and provide such knowledge to the public. People may also need epistemic political changes in policy-making and scientific institutions that enable their local and societal expertise to be more widely recognized and used (Iles, 2007, 2011). They may need the re-configuration of chemical manufacturing systems to allow ready engagement with designers and corporate decision-makers.

Ultimately, materials sovereignty calls for attention to how the entire materials production system is built and operated—including research, design, regulation, and other forms of technological decision-making. In contrast with the rights framework of environmental justice, which attends to the effects of the industrial material system on people, materials sovereignty is about the construction of that system itself. Under this sovereignty, designers and industry can no longer unilaterally decide to introduce new materials or products without facing, and responding adequately to, societal scrutiny. Instead of leaving sovereignty to the makers of technologies, such as Apple or Dow Chemical, people have the social authority to decide *because* they are exposed to harmful substances and may face substantial risks; and because the environment more generally is heavily burdened with chemical pollutants that endanger human reproduction and development.

In this paper we focus on how the formation and work of social movements can influence material design, potentially incorporating diverse voices into the governance of materials. Social movements are networks or coalitions of people, organizations, and communities who come together around a shared goal or ethical position—such as eliminating toxic chemicals from human bodies, or calling on energy companies to leave fossil fuels in the ground (Tilly, 1978; Schlosberg, 2004; Woodhouse and Breyman, 2005). These movements represent collective voices raised from within civil society—the larger public existing alongside government and private-sector institutions. They may play particularly influential roles in catalyzing civil society responses to environmental and social problems, as in the Civil Rights era of the 1950s–1970s. Yet social movements may not always be cohesive (Della Porta and Diani, 2006). They can contain many strands with internal philosophical contradictions and political competition. They can be more democratic than the political system they work through or seek to change, but they can also lack democracy. A few particularly powerful organizations or individuals can hold outsized control over their direction. In short, the human frailties of social movements should not be forgotten.

Research on social movements reveals that they can have complex and influential roles in scientific and technological change. Analyzing social movements that focused on transforming the harmful effects of major industries, Hess (2007) has shown that they can be "generative"—influencing, promoting, or spreading alternative technological designs—rather than merely opposing industry. Hess theorizes social movements' impacts on technological fields as the incorporation and transformation of civil society demands or proposals into industrial systems. This often results in significant changes in the systems as well as the actors involved, although the original demands are usually only partially satisfied; the goals of the movement itself may be changed through the process. One key way that social movements intervene in technological designs is by identifying alternative research priorities that have been neglected, and demanding new science that might lead to the desired innovations or socio-technical change (Frickel et al., 2010; Hess, 2016).

For social movements to do this, they do not necessarily need to be mobilized around specific technological fields. Studies of health social movements organized around illnesses like asthma and breast cancer have shown how they can intervene in research agendas and public policy around environmental and occupational health by acting as "boundary movements" (Brown, Morello-Frosch, and Zavestoski, 2011). These movements engage strategically in both challenging and collaborating with scientists, redefining the boundaries of scientific knowledge, expertise, and authority. In the case of social movements organized around the health risks of consumer products, highly specialized activist organizations have crystallized out of the movement and developed considerable technical and analytical expertise that NGOs traditionally have not been associated with (Iles, 2007). Social movements can therefore mobilize a variety of scientific and political resources that have relevance to material design. This is why we focus on social movements as actors that could be instrumental in introducing materials sovereignty into the technological politics of nanomaterials.

A brief overview of nanotechnology issues

Nanotechnology is a broad category of technologies that involve engineering and manipulating materials at extremely small dimensions, typically 1–100 nanometers (Ramsden, 2011). At this scale, matter manifests physical, chemical, and biological phenomena not usually observed at larger scales where ordinary physical forces predominate. Nanomaterials offer novel physical, optical, and electronic properties that make them attractive for a variety of technological applications. Examples include carbon nanotubes, graphene sheets, quantum dots, and dendrimers. Many nanomaterials are nanoscale versions of common chemicals, such as silver or titanium dioxide. While nanoparticles occur naturally, we focus on materials that scientists, engineers, and manufacturers intentionally design and synthesize for use in consumer products.

Research suggests that normally benign substances can be toxic as nanoscale particles. Their small size means they can move around bodies readily and their large surface area-to-volume ratio makes them chemically and biologically reactive. A growing body of toxicological evidence suggests that nanomaterials present risks to human and environmental health (Gupta and Xie, 2018). Researchers have identified many adverse health effects from nanoparticles in experimental studies. These include respiratory diseases, cardiovascular inflammation, reproductive and developmental toxicity, and immune system effects (Zhang et al., 2014). Carbon nanotubes have been shown to cause pulmonary fibrosis, an irreversible lung disease (Pacurari et al., 2016). Many mechanisms of toxicity are being explored, but one of the most significant is the production of reactive oxygen species within living tissues. This can damage DNA and disrupt the work of mitochondria, the tiny energy-producing organelles found in every cell (Jain et al., 2018).

Nanomaterials have rapidly entered consumer product manufacturing chains. In 2006, the Woodrow Wilson Center's Project on Emerging Nanotechnologies (PEN) began tracking the use of nanomaterials across many product categories, cataloguing thousands products as they entered the market in their Consumer Product Inventory (Vance et al., 2015). Personal care products, cosmetics, and sunscreens comprise 29% of the total product inventory as of 2019; clothing products make up an additional 12% (Project on Emerging Nanotechnologies, 2019). People apply these products to their bodies directly, making human exposure to nanoscale ingredients almost certain (Katz, Dewan, and Bronaugh, 2015). Moreover, nanomaterials may become riskier by intentional choices made in their design and formulation. In personal care products, nanoparticles are often specifically engineered to more effectively penetrate the skin (Katz, Dewan, and Bronaugh, 2015). Many products also include 'permeability enhancers', substances that help active ingredients enter the skin (Mihranyan, Ferraz, and Strømme, 2012). Since people tend to use multiple personal care products on a daily basis, they may be exposed to many interacting sources of nanomaterials.

Manufacturers are bringing new materials into the market with little awareness amongst consumers, lax regulatory oversight, and negligible input from society as to whether the material is desirable (Bennett and Sarewitz, 2006). With very few exceptions, governments around the world rely on the same laws and regulations designed to govern industrial chemicals, drugs, and consumer products without giving special consideration to nanomaterials (Lai et al., 2018). Manufacturers have operated with very little transparency: some companies advertise the presence of nanoscale ingredients in products—even if the information they provide is incomplete (Vance et al., 2015)—while other companies make misleading claims or simply avoid disclosing that their products contain nanomaterials (Becker, 2013). Public consciousness of nanotechnology is still in the formative stages, even after 20 years of scientific research and debates amongst policy-makers over what to do about possible risks. Survey studies conducted by scholars and policy institutes since the early 2000s reveal a consistent pattern: for example, a meta-analysis in 2009 showed a largely uninformed, mostly undecided, yet optimistic public (Satterfield et al., 2009).[1] More recent studies have demonstrated that public views of nanotechnology are still highly malleable and context-dependent (Satterfield et al., 2013; see also van Giesen, Fischer, and van Trijp, 2018 for a review).

As a rapidly emerging new class of materials, nanotechnology is still in an early era of industrial development, when intervention in design choices could greatly improve environmental and health outcomes. Nanotechnology R&D decision-making remains opaque and confined to a relatively exclusive set of industry and scientific actors. A number of social movement efforts have already occurred to attempt to shape the introduction of nanomaterials into everyday consumer products. But simply following traditional activist strategies does not appear to work particularly well, given strengthening industry power and consolidation. Materials sovereignty could give social movements more political traction and authority, by asserting health and environmental rights in pressing for systemic change in design.

Pathways for social movements to exercise materials sovereignty

How can social movements can intervene at strategic points in the materials system to shape the design of nanotechnologies? To exercise materials sovereignty, social movements must understand, and act on, a complex industry in which agency in design decision-making is unevenly distributed. Within the ecosystem, certain agents have more concentrated power over how nanotechnologies are developed, and deliberately exercise this power.

In innovation networks, for example, investors who allocate financial resources for nanotechnology research can set agendas and priorities, or choose to support one possible vision of technology over others. Trends in funding can influence academic research programs, or corporate management—which in turn directly controls R&D within firms. Likewise, companies that dominate a given market sector have greater opportunities to introduce precedent-setting new designs. In industry chains, some companies may function as gatekeepers to supply or distribution networks; some retailers greatly influence which manufacturers get access to large consumer markets. Within companies, groups of designers, scientists, and business executives hold power over deciding what materials to use in making a product, and where and how to source these materials. Some institutional structures, such as laws and regulations, are also highly influential. In comparison, consumers, citizens, and environmental NGOs have historically not been part of the materials development and product design processes. Their values and arguments have mostly been excluded until the past 20 years.

Social movements, then, can direct their influence at the agents and structures that have the greatest potential to yield change. Systems analysts use the metaphor of *leverage points* to capture the idea that small changes at certain points may produce large shifts in overall system behavior (Meadows 2008, 145–65). Leverage points are effective places to intervene in a system. What are the most effective places to intervene in the nanotechnology system, and how can social movements use them to achieve their goals? The work of environmental, consumer, and health groups to identify valuable leverage points in what is still a novel, nascent, and fast-evolving industry has already yielded a diverse set of possible pathways, as seen in **Table 1**.

We briefly review the direct action, policy activism, and market mobilization strategies, discussing how social movements have experimented with these approaches and appraising their success to date in shaping nanomaterials. We pay attention to how materials sovereignty has been, or could be, integrated into these strategies. In the subsequent section we turn to the three remaining pathways that are our main focus: participatory technology assessment, collaboration with industry, and co-design.

Direct action and civil resistance

Social movements can act directly against new technological developments, attempting to physically stop research and design from proceeding. Inspired by successful protests against GMO field trials in Britain and France, a small number of civil resistance actions in Europe have targeted nanotechnology specifically.

One example is the effort in the early 2000s by the French group Grenoble Opponents to Necrotechnology (OGN) to oppose a new nanotechnology research center, Minatec, being built in Grenoble. OGN was critical not only of the risks of nanotechnologies to environmental and social well-being, but of how a complex of industrial, government, and military interests has controlled nanotechnology research. Activists in Grenoble tried many tactics to stop Minatec's inauguration (OGN, 2006). During the construction of the facility, activists occupied a crane in an attempt to stop the project. In 2006, OGN activists hurled insults and eggs at a reception for scientists celebrating the opening of Minatec; they occupied regional government buildings to protest the use of public funds to invest in the research center. They distributed magazines posing as official public education materials that contained scenarios of alarming nanotechnological interventions in daily life. Finally, activists disrupted a public forum on "Science and Democracy," organized by the local government, which OGN viewed as deceptive and hypocritical— "a talk show … aiming at making us accept decisions which had already been taken" (OGN, 2006). OGN's views on nanotechnology have likely been shaped by multiple movements worldwide, which are concerned with the relationships of material technologies to health, human-ecological sustainability, economics, and power. OGN's actions ultimately did not stop Minatec, which today is an "international hub for micro and nanotechnology research" (Minatec, 2016). Moreover, OGN failed to influence the design of nanomaterials more broadly.

Policy activism

Social movements often make demands for the reform or creation of public policy to force industrial change, such as activism around alternative energy and toxic waste in the US (Hess, 2007; Hess, 2010). Social movements can also aspire to engage in producing and debating policy-relevant scientific knowledge so that they can intervene in regulatory and policy-making processes or influence the risk assessments that government agencies do—often through the work of specialized professional organizations that develop in connection with the social movement (Iles, 2007; Brown, Morello-Frosch, and Zavestoski, 2011).

Many environmental NGOs and labor groups have therefore issued detailed calls for new or revised regulations (e.g., European Trade Union Confederation, 2008, 2010; European Environmental Bureau et al., 2014) or mounted legal challenges (e.g., Center for Food Safety, 2015) to push governments to control nanomaterials more effectively.

Table 1: Pathways for intervening in the nanotechnology system. DOI: https://doi.org/10.1525/elementa.410.t1

Pathway	Mechanism	Examples
Direct action and civil resistance	Demonstrate and enact opposition to nanotechnology research and deployment; raise public awareness	Anti-nanotech activists in Europe
Policy activism	Influence government regulations that play an important role in shaping technological design, manufacturing, and commercialization	NGOs advocating for product labeling laws and chemicals policy reform
Market mobilizations	Mobilize consumers to send market signals to technology developers, enabled by increased consumer knowledge and systems of corporate accountability	Skin Deep Cosmetics Database; campaigns about nano sunscreens; Campaign for Safe Cosmetics
Participatory technology assessment	Engage citizens in public deliberation about emerging technologies; allow citizens to participate in the governance of technological systems	National Citizens' Technology Forum (US); Project on Emerging Nanomaterials (US)
Collaboration between social movements and industry	Partner with companies to gain 'inside' influence and insert social movement concerns into design processes	EDF-DuPont Nano Risk Framework
Co-design/Participatory design	Open the technological design processes to direct participation by representatives from affected groups in civil society	Collaborative On-site Technology Exploration

Among numerous demands, calls for mandated product labeling schemes for nano-ingredients have received the most extensive consideration and debate by governments, NGOs, industry, and researchers. Labeling is one way to provide some information about nanomaterials to consumers at the point of purchase. Recent EU laws governing cosmetics and biocides require manufacturers to disclose nanoscale ingredients on product labels using the word "(nano)" and institute nano-specific requirements for safety screening and authorization (European Commission, 2017; European Chemicals Agency, n.d.). In the US, no laws yet require products to be labeled as regards the use of nanotechnology.

Consumer mobilizations through the market

Social movements can aim to mobilize citizens into campaigns, pressuring corporations to produce consumer goods using safer and healthier materials. Much evidence supports the idea that consumer behavior (or perceptions of demands) can influence manufacturers and retailers to change their business strategies, product designs, sourcing decisions, and operations (O'Rourke, 2005; Hall, 2006; Gulbrandsen, 2006). Manufacturers may find lucrative incentives in responding to, or foreseeing, consumer demands: they may not want to lose market share or risk damage to their brand reputation. Companies could also sell products at premium prices and create new markets for safe products. Numerous cases of effective consumer pressure include the electronics, seafood, apparel, and forestry product sectors (O'Rourke, 2005). Consumers may express their pleas through multiple, sometimes mutually reinforcing means: boycotting a brand or company, telling a company about their concerns, joining a social media campaign stigmatizing the firm, preferentially buying eco-labeled products, or lobbying governments for regulation.

Consumer demands may eventually feed back into research, design, and production. This may happen if firms identify these demands as pertinent to their financial and market performance. In response, they may pursue new design goals—even if incremental ones like removing specific chemicals of concern—with the expectation of increased market share. This can be a proactive approach based on foresight, or a reaction to negative publicity and stagnant sales. Either way, companies may end up redesigning their products, or requesting specific reformulations from their suppliers. This hypothetical market mechanism is a feedback loop that connects product design, consumers' expressed preferences, and the actual market performance of products—which is connected back to product design. The potential leverage of consumer mobilizations comes from driving this feedback loop to make product design as responsive as possible to consumer demands.

In the nanotechnology arena, consumer information campaigns and campaigns directed against brands and visible companies have been the most prominent to date.

Informing consumers

A common strategy is to provide information about chemical risks to consumers to allow them to evaluate products more critically and potentially change their buying behavior, thus sending signals to manufacturers and retailers. Information provision can occur in several ways: through NGO reports and press releases; through digital media and online resources; and through voluntary or mandated product labeling and eco-certification. Environmental Working Group's Skin Deep Cosmetics Database (Environmental Working Group, n.d.) allows consumers to search for and evaluate products based on EWG's analysis of the ingredients and their associated health effects, and includes limited information about nanoscale ingredients. Several other NGOs have engaged in consumer knowledge interventions around nanotechnology in personal care products specifically. Between 2006 and 2009, Friends of the Earth (FoE) published three reports warning consumers of the potential health risks of nanomaterials in personal care products (Friends of the Earth, 2006), presenting summaries of relevant scientific research, and arguing for a precautionary approach (Friends of the Earth, 2009). They guide consumers in choosing nanomaterial-free products and recommend that citizens express their concerns to manufacturers and to the US FDA (Friends of the Earth, 2007).

NGOs are providing these resources to mitigate an information asymmetry in the market: manufacturers do not reliably reveal nanomaterial content, and in general, they publicly disclose as little as possible about the ingredients of their products. If they voluntarily make any information public, they do so for marketing reasons. Product makers have made advertising claims about how nanotechnology enhances their products with special functions, especially in the cosmetics and textile sectors. But in terms of leveraging the feedback between consumer demands and product design, consumer knowledge interventions have generally failed to shape how consumers perceive differences between products on the basis of their design. They have relied on relatively uncoordinated and weak outreach by NGOs to consumers. They have also relied on a diffused campaign strategy that aimed broadly across product sectors, rather than targeting market leaders who would have the greatest power to translate consumer demand into changes in design, supply chains, and industry norms.

Targeting companies

Instead of trying to reach consumers, social movements can target brands and their supply chains directly. Since the mid-1990s, NGOs have organized many campaigns that invoke the threat of consumer activism against companies and brands. An example of a market campaign centered on chemical health impacts is the Campaign for Safe Cosmetics (CSC) (Safe Cosmetics Action Network, n.d.). Beginning in 2006, the US-based chapter of FoE—a founding member of the Campaign for Safe Cosmetics—led its own campaign targeting nanomaterials in sunscreens and cosmetics (Friends of the Earth, n.d.). In letters to 128 sunscreen manufacturers, FoE demanded information about the nanomaterial content of their products, and warned about the potential health risks of untested nanomaterials. Most companies refused to reply; FoE published the responses that they received from the nine manufacturers who answered that their products do not contain any nanomaterials. FoE has cited this very poor response rate as evidence that consumers are not adequately informed of, nor protected from, the risks of nanomaterials in products. However, it is unclear to what extent FoE's nano-specific campaign was integrated into the broader strategies of the CSC, and whether it benefitted from the CSC's effective consumer and business outreach strategies. Relatively few social movement efforts have aimed at supply chains to shape nanomaterial design and use.

Appraising existing approaches

Social movement efforts focused on the leverage points discussed above have not led to systemic change in how nanomaterials are designed and incorporated into everyday products. Resistance tactics have failed to dismantle the nanotechnology industry: in many forms, it continues to develop over the objections of civil society opponents. Industry can find it easy to depict certain forms of civil resistance as ill-informed, thereby dismissing the concerns being raised. The localized concerns of activists in France did not make a strong connection to nanotechnology as a global phenomenon for social movements to oppose, perhaps because of the many subtle and invisible ways in which it is being deployed. Perhaps, if highly public actions were mobilized in multiple, strategically chosen locations simultaneously—creating a coordinated front of resistance[2]—activists could potentially have created new accountability from industry and government, or forced greater interaction between researchers and concerned citizens.

Policy advocacy does not appear to have radically altered the regulation and governance of nanomaterials; social movements have not succeeded in using public policy to make nanotechnology researchers and designers accountable and responsive to their concerns (Hess, 2010). The degree of government control over the material economy—even its power to manage the health risks of materials on the market—is a deeply contested political issue, in which social movement activists must face off against powerful industry lobbies. In a global political economy that has grown more neoliberal in its culture since 1980, the default approach to introducing new technologies is now to let the market "decide."[3]

Consumer mobilizations represent an attempt by social movements to harness market forces proactively. But can market mechanisms really enable social movements concerned about nanomaterials to exercise their materials sovereignty? There are historical examples of consumers leading companies to redesign products through their user resistance, adaptation of products to their own preferences, and expression of values (Oudshoorn and Pinch, 2003; Kline, 2002; McCarthy, 2007). On the other hand, there are many difficulties with relying on mass consumer power. Consumers can only choose among already-existing alternatives, reflecting their exclusion from pre-market design and innovation. Moreover, consumers' ability to meaningfully exercise choice is impaired by poor and inaccessible information about the health and environmental risks of nanomaterials, or about what materials are actually in products. For example, despite some attention by environmental NGOs to nanomaterials in consumer products, the tendency has been for companies to simply manage consumer perceptions. Analysis in 2009 showed that some cosmetics makers, who previously vigorously endorsed their products as nano-enhanced, had reduced or stopped this publicity for the same products (EurActiv, 2009). The reasons are unknown, but may have little to do with changes in product formulation: manufacturers may be responding to NGO campaigns by hiding the presence of nanomaterials in their products. In 2012, FoE Australia successfully pressured a sunscreen maker to admit that their 'non-nano' product included nanoparticles (Friends of the Earth Australia, 2012).

Many dimensions of industrial production are structurally impervious to market influences. Materials production chains are often complex, geographically dispersed, and feature numerous, anonymous contract manufacturers (Smith, Sonnenfeld, and Pellow, 2006). Clothes and electronics exemplify these chains. Substances used in intermediate stages in the supply chain, produced as by-products, or sold between businesses, are invisible to consumers even though they affect workers and the environment. Because these materials are not identifiable in connection with specific products, brands, or companies, it is virtually impossible to launch a market-based campaign against them (O'Rourke, 2005).

More fundamentally, market-based campaigns transfer the work of health and environmental protection from industry and government onto individual consumers (Maniates, 2001), but consumers may have little influence over systems-level outcomes that emerge from the workings of markets. Market incentive structures tend to focus design in ways that benefit consumers with the greatest economic and social power—a tendency that can "materialize inequity" in the development of nanotechnologies just as it has in other sectors (Nieusma, 2011). Shoppers may not mobilize in a concerted way that is strong and focused enough to achieve systemic change in industrial production (O'Rourke, 2012). In a political economic system that fails to cultivate communal knowledge-making about products, people may identify with consuming, comfort, and materialism as their core values. As a result, truly *collective* consumer demands for health and environmental protection—for meaningful input into product design—have been sporadic and feeble (Szasz, 2007; Dauvergne and Lister, 2012).

Appraising these pathways in terms of creating materials sovereignty, they have tended to fall short. They rely on social movements exerting a weak and diffuse influence on technological design through many structural and institutional layers. We now turn to a deeper examination of participatory processes, which we argue hold greater promise.

Participatory pathways

What might be possible if social movements could participate more directly in processes that shape technological design? Instead of being passive recipients of knowledge, or being asked to sign off on knowledge, how could civil society and technoscientists collectively produce knowledge—a higher level of participation (Pretty, 1995)? In this section we look more deeply into three further pathways: participatory technology assessment, collaboration with industry, and co-design. We discuss how they might enable more meaningful social-movement-driven change in nanotechnology based on materials sovereignty. We discuss a collaboration between the DuPont chemical company and the Environmental Defense Fund (EDF) to create a framework for more environmentally and socially responsible development of nanomaterials in industry. Then, we explore the concept of participatory design, or co-design, using examples of participatory community development and community-led "exploration" of nanotechnology. We discuss how co-design practices could be applied in highly technical fields like nanotechnology to advance materials sovereignty.

Research on social movements suggests some general mechanisms by which collaborative and participatory interventions could happen. Intervention in the design of nanomaterials could follow a pathway like what Hess describes for alternative industry movements—such as those advocating zero-waste manufacturing and green buildings—which do not necessarily achieve a fundamental restructuring of socio-technical systems (Hess, 2016). Social movement organizations could work across the boundaries of science, building ties with collaborators "inside" scientific and industrial research communities and eventually gaining the capacity to influence research agendas—or even to fund and carry out research projects that they help to design. Following a pattern seen in health social movements (Brown, Morello-Frosch, and Zavestoski, 2011), social movements can strategically develop ties to technoscientists who feel an ethical responsibility to develop safer and more sustainable technologies. These scientists could potentially join with NGOs to provide needed expertise in design and hazard reduction. Or, social movements could engage in partnerships with companies or research labs that design and produce nanomaterials for commercial applications. Either way, the goal would be to influence design decision-making in consequential ways that might lead to materials sovereignty.

Participatory technology assessment

Instead of exerting leverage via market, regulatory, or industry mechanisms, social movements can attempt to intervene in the societal infrastructure through which technologies are introduced and governed. Considerable shaping of new technologies occurs through public and private investment in research—the measures that governments, universities, and large companies take to promote and advance new areas of science and technology. Social movements could try to intervene in processes of institutional agenda-setting and oversight regarding nanotechnology, specifically by influencing the analysis and reasoning about the proposed or imagined benefits, risks, and ethical implications.

Technology assessment (TA) refers to processes of inquiry into the societal implications—including risks, opportunities, and broader goals—of emerging areas of science and technology. Historically developed as a function of national-level governments, a range of TA approaches have been tested in the past several decades (Schot and Rip, 1997; Guston and Sarewitz, 2002). TA aimed to add a dimension of foresight to public decision-making, so that governments can potentially intervene in shaping new technologies toward desired outcomes. Traditional TA is centered on independent expert analysis—for example, setting up government bodies of experts that hold public hearings and seek input from selected witnesses (Federation of American Scientists, n.d.; Owens, 2012). In contrast, participatory technology assessment (PTA) refers to methods and activities that aim to be more democratic by eliciting the informed views of citizens or formally integrating public deliberation into the TA process. Examples of such processes include consensus conferences and scenario workshops, which have been used in Denmark since the late 1980s (Andersen and Jæger, 1999). Increasingly, a range of organizations besides national governments are undertaking various forms of PTA: academics, NGOs, research consultancies, think tanks, and citizen groups.

Can technology assessment be a mechanism for people outside of research and design—including social movements—to engage in such a broader discussion of the possibilities, goals, and visions of nanotechnology? Social movements could intervene in the processes of technology assessment, using them or working to change them. They can seek recognition as legitimate participants—alongside companies, scientists, and government bureaucrats—in the processes of inquiry, foresight, and long-term decision-making that shape technological systems. Participating in TA would afford social movements some influence over the human values and ethical positions that are brought into these processes. They could also seek to develop new institutions for multi-directional dialogue, through which citizens and lay publics can have greater input into setting broad policy directions for nanotechnology, and into product design processes more directly. In theory, this is a key leverage point: materials sovereignty could be embedded into the complex of policies, regulations, corporate governance, and scientific practice.

Public engagement

Questions of public engagement in the development of nanotechnology have attracted much attention in government and social sciences research. In the early 2000s, major governmental research organizations in the US, UK, and EU made recommendations or commitments to include public engagement as part of nanotechnology development strategies,[4] motivating a period of experimentation with PTA in which dozens of public engagement processes were convened. Efforts were made to incorporate public engagement "upstream" in nanotechnology development (Wilsdon and Willis, 2004). Several sources provide summaries of these diverse initiatives (Gavelin, Wilson, and Doubleday, 2007; Strandbakken, Scholl, and Stø, 2013; Guston, 2014; Foley, Wiek, and Kay, 2017). Critically, public engagement exercises have shown that ordinary citizens are able to articulate well-reasoned positions on nanotechnology issues, which often relate to materials sovereignty.

If they are given opportunities to educate themselves and overcome the barrier of gaining technical knowledge about nanotechnology, people demonstrate a significant capacity to reason about its social and political dimensions. They often want to be better informed—demanding the production and communication of greater knowledge, more studies of health and social impacts—and to become more involved in the making of nanotechnology (Schomberg and Davies, 2010). For example, American participants in a deliberative forum on nanotechnology and human enhancement expressed a range of concerns grounded in individual rights balanced with the safeguarding of the collective good (Philbrick and Barandiaran, 2009). They emphasized the importance of directing nanotechnology research towards meeting pressing social needs, rather than following agendas dictated by profit motives, authorities, or desires for a luxurious life.

Still, efforts to promote public engagement with science and technology harbor complex problems, as highlighted by numerous scholars (Stilgoe, Lock, and Wilsdon, 2014). There remains a tendency for experts in government, science, and industry to treat citizens simply as passive recipients of information, and to "correct" public misunderstandings of science and technology issues (Jasanoff, 2005). Experiments in PTA have likewise struggled to break down divisions between experts and "lay" publics, with some supposedly participatory processes effectively reenacting an outdated model of one-way science communication (Petersen and Bowman, 2012). Furthermore, institutionalized processes that bring together citizens, scientists, and policymakers often fail to acknowledge or balance power relations among these groups (van Oudheusden, 2011). Even if social movements with technically competent representatives participate, the resulting dialog may reproduce the dominant framing assumptions and discourses that already prevail among scientific experts and policymakers—intentionally or not. An effort to create broad consensus and a mutually agreeable plan of action may instead serve to silence social movement views that go against the dominant political framework. If the framing assumptions of PTA are set in advance, then citizens and social movements lose important opportunities to intervene in making the technological agenda. A public engagement program on nanotechnology in France achieved precisely this outcome. In 2009–2010, the French government convened panels of experts for a series of public debates on nanotechnology issues. However, the debates were criticized by activists and even opposed by civil society organizations that had relevant expertise (Arnold, 2010; Bensaude-Vincent, 2012). In their view, none of the fundamentally important questions were being opened to debate—such as the potential encroachment of nanotechnologies on private life. Protests escalated around the debates, eventually causing some of them to be cancelled.

NGO-led technology assessment

Government and academic sponsorship of public engagement activities has arguably not amounted to a deep reconfiguration of the role of citizens in shaping new technologies—even in Europe, where PTA has supposedly been institutionalized (Bensaude-Vincent, 2012). If governments are not adequately performing the functions of technology assessment despite persistent advocacy, then another strategy for social movements is to create alternative, non-governmental organizations to take the lead for this work. A few NGOs have indeed leveraged TA in the ways that we outlined above: pushing for and getting involved in PTA, or taking up technology assessment initiatives themselves. Important critiques have come from the Canada-based activist group, ETC Group, which has been highly active in international legal and political arenas pertaining to agricultural, biological, and environmental technologies (ETC Group, 2016). ETC Group was among the first civil society organizations to raise doubts about nanotechnology, and as a result, has played an influential role in framing political dialogue (ETC Group n.d.). The group has argued that there are no existing systems of governance capable of guiding the potential transformations that nano- and biotechnologies might bring to natural, technical, and socio-economic systems. In response to the history of unprecedented corporate consolidation of power in the agricultural biotechnology sector, ETC Group advocates a strongly precautionary position, calling for a worldwide moratorium on nanotechnologies until the dilemmas of governance and risks are solved. As part of a solution, they advocate for creating institutions of democratic technology assessment (ETC Group, 2003).

In the US, where citizen participation in technology assessment has lagged behind Europe (Sclove, 2010), non-governmental groups have lobbied the federal government to adopt participatory nanotechnology governance, or even generated multi-directional dialogue processes on their own. One such group, the Loka Institute, successfully advocated for including public engagement and PTA elements into the US National Nanotechnology Initiative (NNI), a major nanoscience funding program (Loka Institute, 2013). Loka has since criticized the US government for failing to fund and implement meaningful programs of public engagement. Another group, the Project on Emerging Nanotechnologies (PEN) at the Woodrow Wilson Center in Washington DC, worked in the vein of TA from 2005 onwards. Spanning the boundaries of government, academia, industry, and civil society, PEN performed several public-interest functions related to critically framing nanotechnology issues and introducing them to ever broader constituencies (Michelson, 2013). While the organization never aimed to be politically "neutral," PEN did not join environmentalist movements in their activism or lawsuits against the government. Instead, PEN chose to instigate cross-cutting channels of communication that allowed social movements, government, and industry to exchange their knowledge more effectively. Despite these important achievements, PEN remained a small entity funded by sympathetic foundations; its budget and activities appear to have dwindled since 2012, reflecting a lack of longer-term stability. Moreover, PEN did not have direct input into manufacturer and designer practices, nor did it created wide-ranging public participatory processes beyond opinion surveys.

Moving beyond assessment

Can PTA approaches enable greater materials sovereignty? While expressing an ambition to foster democratic processes in the development of new technologies, many PTA approaches are geared towards researching or experimenting with how public engagement can be promoted. To date, the trials in participatory assessment tend to be highly academic or bureaucratic in practice. They are usually one-off, small-scale, and institutionally fragile. They do not seek to create new conduits for social movements to directly influence the deliberations of companies and designers when making new materials. They sidestep questions of how to bind such actors to the choices and authority of citizens. Corporations responsible for the commercialization of nanomaterials are conspicuously absent from participatory and democratic dialogues. Given the potency of corporate power, civil society actors are understandably reluctant to include companies in their fora. However, this means that there are no mechanisms to include societal (not consumer) voices in product design processes.

Collaboration with industry: the Nano Risk Framework

Can social movement organizations attempt to collaborate with industry directly? While corporations regularly engage in voluntary initiatives aimed at environmental and social responsibility, public participation is usually absent from these (Muldoon and Nadarajah, 1999). Social movements therefore face a challenge of aligning corporate interests with their own to a sufficient degree to develop stable and productive partnerships. To do this, they may need to find particularly receptive companies and internal advocates within them. Even so, collaborators may face dual pressures from industry and from the movement if they have conflicting goals and interests—pressures that may compromise the possibilities for change.

In 2007, DuPont was a major chemical company involved in designing and commercializing nanomaterials (it has since merged with Dow Chemical and subsequently reorganized again). The company entered a seemingly unlikely partnership with EDF, a non-profit group that advocates strongly precautionary approaches to regulating chemicals and nanomaterials. As a social movement organization, EDF has cultivated technical competence among its staff and maintained close involvement with businesses.[5] In the late 2000s, the two organizations worked together to create a joint framework for structuring decision-making in organizations that conduct nanomaterial research and design (Environmental Defense Fund, n.d.b). The Nano Risk Framework (NRF)[6] "offers guidance on the key questions an organization should consider in developing applications of such materials, and on the critical information needed to make sound risk evaluations and risk management decisions" (Environmental Defense–DuPont Nano Partnership, 2007, p, 7).

The NRF is a system for organizing and tracking certain prescribed practices in the context of R&D involving any nanomaterial. It divides these practices into six steps and provides extensive guidance on each, borrowing in many respects from paradigms of chemical risk assessment, risk management, and life-cycle thinking. The six steps are as follows:

1. Describing the material and its applications. This includes the material's origins and characteristics, as well as how it is used, in what quantities, and why it is being used.
2. Generating sufficient information about the material's physical properties, health effects, environmental fate, and exposure potentials throughout its life cycle. Here, the NRF includes a detailed protocol for addressing data gaps and uncertainties in a precautionary manner.
3. Evaluating risks, including characterization of the data gaps, uncertainties, and assumptions.
4. Assessing risk management options, and developing a risk management plan.
5. Deciding on the organization's course of action pertaining to this nanomaterial. This involves deliberative analysis of the information produced in the preceding steps by a review team. It may result in the identification of problems, data needs, or new priorities. The organization must make and implement short-term decisions, engage in long-term planning, and plan when to revisit their conclusions in the future. Decisions made here are to be extensively documented and shared as broadly as possible.
6. Cycle through the framework, periodically reviewing decisions and adapting them in light of new knowledge.

The framework interlocks with typical corporate product development processes, i.e., systems of "milestones as a product moves through basic R&D, prototyping, pilot testing, test marketing, and finally to full-scale commercial launch" (Environmental Defense–DuPont Nano Partnership, 2007, 14). The responsibilities for implementing various parts of the NRF likewise fit naturally within a hierarchical leadership structure. The information gathering and evaluative steps of the NRF (i.e., steps 1–4) are likely to be performed in small technical teams working on a discrete project within the firm. Step 5, however, introduces a broader "review team" and gives them the opportunity to reflect on a new technology and influence the R&D processes that will take the project to its next milestone. DuPont and EDF recommend going through multiple iterations of the entire NRF whilst developing a single nanotechnological application, to ensure that this review process contributes substantially to the ultimate design.

The participatory potential of the NRF hinges on who is included in the review team and what actual influence the review process has. According to DuPont and EDF, "the review team facilitates interactions that might never occur if left to informal processes" (Environmental Defense–DuPont Nano Partnership, 2007, 78), because it intentionally assembles a cross-functional group of leaders for the critical assessment stage. The framework recommends including a workforce representative, as well as experts on safety, legal, manufacturing, and administrative aspects. These roles may be filled by people within the firm, or by external partners. Besides convening review teams, the NRF requires documenting the rationale for decision-making in each feedback cycle, and specifies an "output worksheet" format for encapsulating all of the relevant types of information to be documented. Moreover, the NRF recommends sharing these review results with successively broader groups of stakeholders and audiences as a product moves towards commercialization—even if it is a limited, guarded disclosure to protect the firm's R&D investments.

The NRF can be seen as a constructive intervention by one member of a social movement into the scientific and methodological process of risk assessment in corporate nanotechnology R&D. By helping to set the guidelines, protocols, baseline assumptions, and organizational priorities for nano-risk assessment and management, EDF has—to some extent—imprinted on the framework its own ethical understandings of how science should be used to protect environmental health. However, so has DuPont: the NRF does not venture very far from the chemical industry's established positions on matters of risk. In fact, through the very strategy of partnering with industry, EDF did not act as a representative of the broader social movement concerned with nanotechnology (Krabbenborg, 2013).[7] EDF has been seen as an outlier in its eagerness to compromise with industry (Leber, 2016). A group of 20 environmental NGOs, including FoE, Greenpeace, and ETC Group, publicly rejected the NRF (Hess, 2010). They did not see collaboration with industry on a voluntary initiative as an ethically tenable substitute for societal oversight.

Still, a variety of corporations, industry associations, government agencies, and NGOs have reviewed and "endorsed" the NRF, and three organizations have implemented it in their own practices (Environmental Defense Fund, n.d.a). DuPont used it to guide and track the development of nanomaterials in three cases, sharing the output worksheets with the public and with the US EPA. A greater number of firms—namely General Electric, Procter & Gamble, Lockheed Martin, and Lloyd's—have chosen to incorporate elements of the NRF into their own practices. Which elements they used, and to what extent they implemented provisions for stakeholder participation and transparency, remains unclear.

Can such a voluntary initiative enable social movements to exercise materials sovereignty over how nanomaterials are developed? In principle, the DuPont-EDF framework can embed citizen perspectives into the heart of the design process—something that has been missing from the majority of experiments with increasing societal oversight. The framework can also create direct accountability between a company and its chosen civil-society representatives, provided that they are willing and able to play this role. Nonetheless, efforts to infuse participatory processes into intact hierarchies of corporate authority and expertise face inherent challenges.

One key critique of the Nano Risk Framework is that it does not provide an *adequate* participatory approach to addressing the potential health risks of nanomaterials. It does not contribute to creating new multi-directional dialogue between designers and social movements, maintaining instead a traditional linear vision of technology development in which "stakeholders" are involved mostly at the end. The Loka Institute, an US-based NGO working to develop participatory technology assessment, publicly expressed "disappointment … about the relatively slight attention in the framework to the urgency of directly involving the general public and workers—whose livelihoods and safety are most at stake—in assessing and reducing nano risks" (Loka Institute, 2007). The cross-functional review teams that comprise the main mechanism of high-level analysis and evaluation would very likely be drawn from a limited group of elite insiders, dominated by high-ranking company staff and experts. Even if the review team were eventually broadened to include outside stakeholders—such as community representatives or citizen panels—the closed, specialized group developing the product will have already carried out their own evaluation of risks and assessment of risk management options (steps 3 and 4 of the framework). These risks and options will be framed and selected in advance of the broader review. Similarly, as a new technological application takes shape and approaches its market-ready state, its fundamental design will become markedly less responsive to influence by outside contributions. Finally, the firm's communication with public and other stakeholders is conceptualized as one-way "transparency" rather than multi-directional engagement.

Second, the NRF focuses too narrowly on the environmental fate, toxicity, and exposure issues of nanomaterials, lacking an entry point for questions of materials sovereignty. Even if practitioners are addressing the entire product lifecycle, this is still narrow because it does not consider the broader relationships of the technology to social systems. The functions of a nanomaterial—the practical reasons for using a material—are established and documented in the first step of the NRF, presumably within a purely technical scope. There is no attention to why the material is being used, in a wider sense. Who needs it, and who stands to benefit from its use? Might particular applications of nanotechnologies affect individual autonomy, privacy, or economic empowerment?

The NRF may be adept at assessing the toxicological risks of materials, but it does not equip organizations with tools for asking questions of equal or perhaps greater concern to social movements. The NRF authors recognize that they built the framework with a focus on their own limited areas of expertise, and invite others to develop ways of addressing broader issues (EDF-DuPont, 2007, 12–13). To date, there have been no further efforts from within the NRF network to connect the framework to other civil society dialogues. This situation simply underscores the need for public participation. It is not that the available technical expertise is too limited; the deficiency is rather an unwillingness within powerful institutions of research, design, and development to broaden the discussion of organizational goals and visions for nanotechnologies.

Co-design approaches

How can we advance models of technological governance that are more multi-directional, directly shape the design process, and hold industry and scientists accountable for their choices? We suggest that approaches based on co-design, or participatory design, offer one way toward strengthening the capacity of social movements to exert their materials sovereignty. Participatory design encompasses several strands of theory and practice in the overarching spirit of citizen involvement in the design of objects, spaces, and technological systems (Schuler and Namioka, 1993; Sanoff, 2008; Simonsen and Robertson, 2013). A rich variety of techniques can be used to realize co-design—including dialogue, deliberation, story-telling, participatory mapping, and many other methods of eliciting and sharing knowledge. Co-design has been applied in a range of domains including health information systems, architecture, urban planning, and education. One prominent strand of participatory design originated in the context of Scandinavian labor movements responding to the computerization of manufacturing work and asserting their rights to be involved in the development of technologies that affect workers' livelihoods. This rights-based framing resonates with our current framing of materials sovereignty.

Co-design holds promise as a way to assert materials sovereignty, because it fundamentally recognizes that citizens should have opportunities to question and shape the basic directions of technological design. In the case of nanomaterials, such questions might include: What are the goals of developing specific nanomaterials or nano-enabled products? Are these goals truly best served by nanotechnologies, or would non-nano alternatives be preferable? What technical functions are desirable—or superfluous? How are nanotechnologies being introduced, and how can we monitor their effects in the world? Are nanomaterials actually being designed to be safer? Do systems exist to recycle nanomaterials securely? What values are missing from green nanoscience—or from the larger social discourse on nanotechnology? Citizen involvement in design can lead to criticisms of the agendas and framing assumptions of technologists, and this is something that many scientists and company staff fear because they imagine public opposition as a barrier to innovation. Materials sovereignty implies that citizens should have a degree of decision power that includes the right to refuse nanotechnologies based on their informed participation—or refusal to participate—in co-design. Yet this can actually be useful to technology developers, since early public engagement could diagnose issues that may arise later in the form of even stronger opposition or regrettable harm, after flawed technical systems have been allowed to develop (e.g., Harremoës et al., 2013). Co-design would seem to present the most potent leverage point for social movements to intervene in an industry that is only beginning to consider whether nanotechnologies are really delivering their promised benefits to society.

Co-design can also play an instrumental role in creating technological alternatives, which social movements can then advance through the process of incorporation and transformation theorized by Hess (2007). Shaping technological fields through social movement action has typically involved the making and use of technological objects that can compete with incumbent systems—objects such as functional prototypes, alternative designs, and visions of alternative socio-technical systems; objects that can be shown to "work." Taking two of Hess' historical examples: alternative energy movements advocated for solar and wind technologies on the basis of existing technical artifacts that were already being developed and commercialized. In contrast, 20th century social movements opposing the toxic hazards of industrial manufacturing were largely focused on ways to reduce exposure through waste management, leaving industry to pursue (or not) more "upstream" technical innovations like product and process redesign (Hess, 2007). Even now, the limited development of safer alternative *chemicals* is almost wholly pursued by the chemical industry and academic researchers, with NGOs contributing expertise mainly in the assessment of alternative technologies.[8] This highlights the need for co-design to create alternative nanotechnologies: new technological objects that social movements could advance together with research programs and startup firms, to eventually challenge or displace the incumbent forms of nanotechnology that they find problematic. It could even make social movement participants "users" of innovative nanotechnologies that "materialize" (Nieusma, 2011) the forms of equity and sustainability that they demand.

A particularly relevant group of scientists and engineers for social movements to collaborate with would be those already engaged in a professional movement sharing some of the same goals—i.e., materials that are benign by design. Green chemistry, articulated in the 1990s as a set of principles for chemists (Anastas and Warner, 1998), is one such movement. It is now an established research field with dedicated peer-reviewed journals, conferences, and professional networks. Broadly, the practices of green chemistry aim to reduce waste, pollution, resource use, and toxicity in chemicals throughout their life cycles. At the University of Oregon, James Hutchison has applied green chemistry principles to nanotechnology, coining "green nanoscience" to describe his work (Hutchison, 2008). Hutchison and colleagues call on scientists to develop design strategies, informed by nanotoxicology, for making new nanomaterials that are inherently non-toxic and environmentally benign (Gilbertson et al., 2015). Nonetheless, social movements cannot assume that they will find allies among green nanoscientists, just as manufacturers should not assume that they can engineer all nanomaterials to be safe. These scientists may form a new disciplinary field and a movement in their own right, but maintain minimal or skeptical relations with civil society organizations—as seems to be the case with green chemistry (Woodhouse and Breyman, 2005; Maxim, 2018).

However, "green" technology fields have tended to develop in a technocratic manner rather than adopting participatory design practices (Howard, 2004). This is particularly true in the design of "sustainable" synthetic materials—as exemplified by green chemistry, which has developed largely following entrenched structures of research funding and dominant framings of policy issues (Maxim, 2018). As we have noted, many aspects of how chemicals and nanomaterials are designed present structural and cognitive challenges to intervention and participation by civil society. Social science scholars have urged that design processes should incorporate intentional input from civil society, with the same level of attention as is given to the contributions of technical professionals (Woodhouse and Patton, 2004). But they have largely left open the questions of how this can be accomplished, especially when advanced materials require highly interdisciplinary and technical expertise.

Nieusma (2011) presents a detailed analysis of how and why nanotechnology should incorporate participatory design to address the problem of materialized inequity—in which technological design creates, reinforces, or fails to counteract systems of oppression. Intentionally shaping nanotechnologies to be socially equitable must proceed on multiple fronts simultaneously, requiring "a combined effort by nanotechnology experts, representatives of the social groups subjected to materialized inequities, and policy makers committed to experimenting with new decision-making protocols" (Nieusma, 2011). Policy-makers and nanotechnologists need to actively seek out and institutionalize the involvement of said social groups, with technology designers paying particular attention to groups whose needs would be ignored or undermined by relying on market signals alone to shape design. Once identified, these civil society representatives must be invited to participate with in the work of universities, agencies, firms, and other actors that "translate" nanomaterials out of labs and into society.[9] However, Nieusma is unclear about what the specific roles and capacities of these representatives would be in technological design, besides providing their perspectives in a general sense. He is also unclear on how the representatives would actually contribute to design processes and what the practical challenges might be.

What elements might be needed to make co-design effective as a pathway for social movements to achieve materials sovereignty? The implications of Nieusma's analysis for co-design are clear on one point: it must entail "systematically reconsidering who participates in nanotechnology decision making and on what terms" (Nieusma, 2011). This means reshaping the distribution of decision-making power and epistemic authority. How can this be done? Although we are not focusing on methodological issues specifically, looking at how co-design might happen in practice is critical for investigating the overarching question that we pose. There are many examples to follow in the practice of participatory design (Simonsen and Robertson, 2013), but examples of co-design approaches being applied in nanotechnology are very few. Most efforts to involve citizens in this field have focused on deliberation about macro-level social and ethical issues, rather than the particulars of technological applications. Still, some academics are experimenting with bringing nanoscientists and representatives of civil society together in participatory ways. We look at two examples that provide possible models for nanotechnology. One example deals with nanoscience specifically, while the other example is about sustainable infrastructure and energy systems—we include it because it exemplifies several important features that we would like to highlight and relate to nanomaterial design. After briefly discussing these examples, we turn to the needs and challenges for participatory pathways.

Nanotechnology in urban sustainability

Researchers at the Center for Nanotechnology in Society at Arizona State University (CNS-ASU) have approached participatory design by working at the intersection of nanotechnology and urban development (Wiek, Foley, and Guston, 2012; Wiek et al., 2013). An approach reported recently by Foley, Wiek, and Kay (2017) deploys co-design principles with notable attention to the particular challenges of engaging citizens in nano-design. Their approach, called "collaborative on-site technology exploration" (COTE), situates participatory technology assessment practices within citizen-guided walking tours of urban neighborhoods. Representatives of local citizen groups lead small groups of nanoscientists and citizens through parts of the city, exploring specific social challenges faced by local communities, and discussing how nanotechnologies might play a role (or not) either in solving or exacerbating the problems. These challenges are identified through partnerships between the COTE facilitators (university researchers) and civil society organizations. Likewise, potential nanotechnologies of relevance are identified in collaboration with the participating scientists. In the COTE engagements reported by Foley and colleagues, the participants considered the challenges of energy vulnerability, public health impacts of chronic diseases, and water contamination in the US city of Phoenix. The participants readily linked these challenges to broader systemic problems, and some lines of "exploration" led to later interventions having to do with nanotechnology while others did not. Even if COTE participants fail to identify relevant and workable nano-solutions to high-priority problems, that in itself is a valuable learning outcome and an insight for scientists and technology designers.

This co-design approach has several aspects that suggest a potential for integrating materials sovereignty. First, intentional steps are taken to destabilize conventional configurations of power between technoscientists and "lay" citizens. By locating the exercise in the urban environment rather than in labs or conference rooms, and by giving civil society participants the role of guides, COTE aims to put all of the participants on the same level of epistemic authority. Indeed, it is designed to encourage humility in the scientists who find themselves not only on an equal footing, but on the home turf of urban residents. Second, the COTE model sets up much needed interactions between the disparate knowledges of citizens and technoscientists—although not without difficulty. The facilitators must intentionally orchestrate and mediate these interactions, while also fostering multi-directional dialogue and learning rather than a simple exchange of information. For example, facilitators at CNS-ASU helped prepare the citizen guides by briefing them on the nanoscience topics that they had identified as relevant. Scientist participants were likewise familiarized with the problem framings of urban challenges. These knowledges may not resolve or coalesce, but rather meet in an unpredictable and generative dialogue, as the facilitators "attempt to reconcile the ways of knowing and making sense of the complex urban challenges and nanotechnologies" (Foley, Wiek, and Kay, 2017). Furthermore, the encounter might invite reflection in each participant on their "own values and other people's normative positions regarding fairness, moral claims, harms and risks, and value conflicts (or trade-offs)."

Sustainable infrastructure in a tribal community

Although this second example of co-design does not address nanotechnology, several of its features contribute to our analysis of how co-design can enable social movements to seek materials sovereignty. In a recent UC Berkeley-based participatory study, Ryan Shelby led a team that explored the potentials of co-design through a project in partnership with the Pinoleville Pomo Nation (PPN), a Native American tribe in Northern California (Edmunds et al., 2013). The project sought to meet community-identified needs for renewable energy and culturally appropriate housing infrastructure, which would replace existing natural gas systems and prefabricated homes. The underlying principle of the engagement was that community members "are considered to be experts on their needs and therefore should co-design solutions with designers and engineers… The voice and point of view of the user community is at the forefront" (Shelby, Perez, and Agogino, 2012, 801). It is up to the community whether they will accept the solutions that the co-design process has produced.

The PPN participants engaged in collective story-telling over how they defined a sustainable way of life. They shared their previous history of negative experiences with US government officials and academic researchers. Supported by a technically expert PPN employee, David Edmunds, participants from both UC Berkeley and PPN generated graphic concepts for the design of self-sufficient housing, water, and energy systems, via multiple rounds of workshops. This co-design approach contrasted with conventional technology-driven approaches to sustainability, in which "little or no time is spent on understanding the needs of the Native American communities and building trust" (Shelby, Perez, and Agogino, 2012, 796).

In an iterative process that combined ongoing community participation with technical analysis and design activities performed by UC Berkeley students, community members oversaw the design, engineering, and construction aspects of the project. For example, Berkeley researchers would build several prototype building models based on community input, and bring them back to the tribe (Edmunds et al., 2013). Tribe members would critique these models and imagine how the buildings might fit into their life. They would have materials at hand to make their own models. The PPN-Berkeley partnership yielded locally situated and culturally sensitive designs, which were constructed on-site, and led to further sustainable development efforts in the community. Importantly, the co-design process did not rest on any prior, unquestioned assumptions of what constitutes sustainability. Nor did it require participants to arrive at any definite conception of sustainability. Rather, the focus was on understanding the values underlying design. As a result, the value of cultural sovereignty was understood to be profoundly intertwined with ecological sustainability. The tribe could not be sustainable without also having cultural self-determination.

Needs and challenges for participatory change

What principal elements are needed to provide participatory pathways to materials sovereignty? And what are the main challenges to meeting these needs? Based on our review of participatory pathways, including theory and experimentation in public engagement with nanotechnology, we propose that three overarching elements are central to achieving substantive materials sovereignty. We present these elements, their components, and associated challenges as a hypothesis to guide future research in materials sovereignty. We summarize the following sections in **Table 2**.

Participatory knowledge systems

Materials sovereignty requires creating multi-directional flows of information, knowledge, and agency—in other words, participatory knowledge systems—centering on materials. Conventional models of the public understanding of science rely on drawing lines between technical experts and lay people, between scientific/technological and popular/experiential knowledge, between policy-makers and citizenries (Jasanoff, 2005). Such models assume that lay people are passive recipients of knowledge radiating from

Table 2: Needs and challenges for materials sovereignty. DOI: https://doi.org/10.1525/elementa.410.t2

Key elements	Challenges
Participatory knowledge systems · Knowledge sharing, collaboration, and commons · Enable complex and multi-directional dialogues between knowledges · Epistemic humility	· Cognitive constraints of citizens and designers · Gaps in knowledge · Epistemological, methodological, and political tensions · Citizens' independent time and resources · Organizational resources
Embedding civil societies into the design process · Upstream engagement with publics · Intentional inclusion of citizen representatives · Practical mechanisms for engagement	· Accessibility of upstream R&D processes · Appropriate selection of representatives from civil society · Corporate behavioral norms · Organizational capacity for engagement
Building broad-based accountability systems · New or reinforced social norms · Policies giving more power to citizens · Institutionalized societal oversight	· Industry power and commercial incentives · Weak existing institutions · Political climate favoring deregulation and free markets

technical experts, and that scientific and technological developments flow linearly into policy-making. By contrast, numerous cases of citizen science and socially robust knowledge-making attest to the potential capacity of lay people to contribute significant expertise on environmental issues (e.g., Nowotny, 2003; Corburn, 2005; Brown, Morello-Frosch, and Zavestoski, 2011). People not only need to be informed, they need to be empowered to be knowledge-making agents in their own right.

Developing participatory knowledge systems will require addressing the cognitive challenges and barriers that various actors face. Citizen groups will need technical expertise to be able to participate in the assessment and co-design of material technologies—to evaluate material design issues, and to judge alternative designs. Successful efforts to intervene in industrial environmental activities, from pollution prevention at chemical plants to toxics reduction programs, have often entailed citizen groups working with scientists and engineers who volunteer to help or who are paid as consultants. Such experts can help bridge the large knowledge gaps that citizens have regarding industrial operations. Finding experts willing and able to collaborate with social movements as the leaders can be challenging, as can finding ways to finance the use of those experts. Bringing in technical experts who do not share the goals and values of movements can undermine the pursuit of real change (Ottinger, 2013). Mobilized citizens can sometimes feasibly develop enough familiarity with technical knowledge to be able to participate in knowledge-making. For example, AIDS disease activists in the US acquired enough expertise in clinical pharmaceutical research to insist on their equal involvement in co-designing drug trial protocols (Epstein, 1996). Other citizen science examples can be seen in design for pollution monitoring (Rey-Mazón et al., 2018) and agricultural technologies (Bishaw and Turner, 2008). Academic institutions and NGOs can contribute to "building capacity" (Guston, 2014) for public participation around nanomaterial issues. Nonetheless, few citizens have thus far had the time, resources, or interest to develop particular expertise in green nanotechnology that could inform actual design choices. The lack of active public interest is evident in the gap between people's largely uninformed and malleable views about nanotechnology on the one hand, and the nuanced understandings and critiques that citizens develop while participating in "capacity-building" PTA exercises on the other (e.g., Guston, 2014). If it appears that people do not care, this may be because they are poorly informed and resourced to do so.

Even within expert knowledge communities, technology designers face substantial cognitive and technical barriers to developing safer materials. For example, green nanoscience calls for even more highly specialized technical knowledge than already is involved in nanomaterial design. Designers must more carefully characterize the physical and toxicological properties of their materials, among other challenges (Harper et al., 2011). Yet there is a lack of information that would enable them to do so, and corporations are not obliged to generate environmental data on nanomaterials. Green nanoscientists will also need to choose which environmental impacts and risks are most important to reduce, but few ethical or policy guidelines exist to govern their thinking. This underscores all the more why participatory knowledge sharing can improve design outcomes.

One way to work towards participatory knowledge systems is through practices of sharing and collaborative creation of knowledge—the development of knowledge commons (Hess and Ostrom, 2007). These might include databases, libraries, or informal networks for sharing knowledge. Some starting points already exist to develop knowledge commons about nanomaterials and their health, environmental, and social dimensions. An international network of nanoscientists and toxicologists has collaboratively developed an information system called eNanoMapper (Kilic et al., 2016), which enables the publication and open sharing of scientific data about the environmental health effects of nanomaterials. While eNanoMapper makes important contributions to the capacity of scientists to share knowledge and assess nanomaterial health risks using agreed-upon standards and conceptual agreements, it primarily addresses expert rather than civil society knowledge needs. Taking a different approach, researchers at CNS-ASU have begun assembling a range of knowledge resources about nanotechnology applications in city environments, creating the online database NICE (Center for Nanotechnology in Society, 2019). They were able to leverage this database in their facilitation of COTE engagements on urban nanotechnology issues (Foley, Wiek, and Kay, 2017). Of course, these efforts demand significant investments of organizational resources and citizens' time (Kleinman, Delborne, and Anderson, 2011).

Participatory knowledge systems must enable complex and multi-directional dialogues between knowledges—and for this, scientists and designers must exercise epistemic humility. For example, in the PPN-Berkeley partnership, researchers made efforts to catalyze new information flows within the tribal community while allowing the tribe to maintain decision-making authority regarding building materials, design, and renewable energy technologies. The designers were willing to communicate across what can be profound epistemological, political, methodological, and language divides in transdisciplinary work (Lélé and Norgaard, 2005). Both the community and researchers were open to learning from each other, treating each other with mutual respect. The COTE methodology also requires this willingness. Epistemic humility is needed (Jasanoff, 2003), especially in science and engineering, where no single knowledge predominates. Likewise, efforts to build shared knowledge resources—like databases and product standards—should be participatory themselves, recognizing the capacity of information systems to embed and codify values (Bowker, 2000).

Embedding civil society in design processes

Material sovereignty demands embedding civil society representatives into the design process. Instead of keeping design practices enclosed, societal actors need ways to directly and authoritatively communicate their values into materials design (Woodhouse and Patton, 2004; Howard, 2004). Technical experts, in turn, must be willing to allow lay people and social movements to define the values and needs that are embedded into a material or product. This needs to occur "upstream" in the design process, at points where technological applications are still coalescing and before path-dependencies set in (Wilsdon and Willis, 2004). Working through the market, for example, may be circuitous: can companies actually learn about social preferences from buying patterns? Can citizens truly overrule design choices already made and rendered as manufactured products? For direct engagement to exist, civil society actors must be regarded as epistemically and socially legitimate fellow participants in the design process. They cannot be seen as token representatives of diverse social voices. New institutions and social norms need to develop through which material design can only have legitimacy if it has included civil society review.

But who are civil society "representatives," and how should they be selected—and by whom? This is one of the most difficult challenges to address in imagining co-design as a broadly applicable strategy and pathway to materials sovereignty. Nieusma (2011) points out that unlike traditional examples of participatory design integrating user input, nanomaterial design should also consider the wide range of *affected non-users* of the materials, such as people exposed to pollution or otherwise impacted by the introduction of specific technologies. Seeking a broad set of participants is therefore of critical importance. This includes equitable representation of the diversity of civil society—in terms of gender, disability, race, class, and other dimensions—which is likely to be challenging with co-design methods that typically involve only small groups of participants. We suggest that another important aspect of representation, especially in concerns materials sovereignty, is the intentional inclusion of representatives of social movement groups that have organized around focal interests—such as local community pollution, product-specific issues (e.g. nanomaterials in cosmetics), or other technology issues. As *mobilized publics* (Hess, 2016), these groups may have clearly articulated concerns and demands that would be much more difficult to elicit from representatives selected from the general public. On the other hand, co-design processes cannot be allowed to be overrun by self-nominated representatives of industrial or political interest groups.

The legitimate selection of co-design participants may require new organizational functions not usually associated with technological design. For example, CNS-ASU facilitators needed to identify and invite civil society organizations into an ongoing dialogue, before inviting specific representatives to serve as COTE guides. Similarly, they partnered with scientists and engineers who were interested in engaging with broader challenges in their research. This required extensive research, outreach, and relationship-building on the part of the facilitators. In short, co-design requires a clear recruitment strategy and significant organizational capacity and credibility to implement it. Given the innumerable private-sector design processes happening at any given time, how such processes could be institutionalized and financed at a larger scale is one of the question that future research in co-design needs to address.

For civil society and social movement concerns and knowledges to be embedded into design, practical mechanisms—like co-design or PTA techniques—are also needed to facilitate encounters and interaction with designers. This requires nanotechnologists to be accessible to the people whose lives are affected, but this requires them to be willing to cede some of their structurally-accorded power and privilege. Pragmatic approaches like those used in COTE—taking scientists and designers outside of labs and conference rooms, letting citizens lead them for a while—might be effective, if they can be institutionalized. Indeed, rather than design occurring purely inside industrial laboratories, nanotechnologists could venture out into community spaces to share their potential ideas via prototypes for feedback. Companies and research institutes could internalize citizen perspectives by developing new design tools and protocols that incorporate broader evaluation alongside traditional performance criteria and toxicity data. Such practices would contravene long-held industry norms of secrecy, competition, and intellectual property. Nonetheless, such behavioral norms are arguably obsolete in an era of proliferating ecological and human health degradation.

Accountability systems

Finally, realizing materials sovereignty would require building a broad-based accountability system for assuring actual practice. As Hess has observed, social movements aiming to influence industry rarely achieve their goals fully, instead becoming "caught up in a more complex dance of partial success and cooptation" (2007, 236). Corporations can readily promise to make their materials safer, only to make compromises in design, or ultimately subside into their familiar profit-seeking culture. They must be made accountable for their materials choices. Similarly, scientists and government regulators may be at a distance from the populations whose lives they are affecting. Weber (2003) suggests that accountability is "a system, or set of mechanisms designed to make sure promises are kept, duties are performed and compliance is forthcoming." In other words, a substantive standard can be defined, and then accountability can be assured through assessing whether that standard is being met, enforcing performance, and imposing sanctions. Some empirical evidence suggests that corporations are more likely to adopt ethical design choices if they face questioning from citizens about their rationale, or when governments require rigorous, highly public tracking of progress in making materials safer (Geiser, 2015). New institutions and laws may be required to support a web of accountability relationships that can work more effectively in complex materials production systems.

How might co-design happen in institutional terms? If designers are, in fact, willing to accept and work with the other elements of materials sovereignty, accountability systems may be created jointly with civil society participants and may rely on conventional social norms—such as academic standards of research conduct. The Berkeley researchers working with PPN were held accountable for their design choices, and for including tribe members in the process, through rolling report-backs and presentations of prototypes for feedback. They were sensitive to how power was distributed across their team and throughout the R&D process (see also Schattman et al., 2014). Another possibility is that green nanoscientists and designers may develop a vested interest in the participatory process itself, either through incentives for research funding or through their own ethics and politics. Like the computer scientists who eventually originated the free software movement, nanotechnologists could develop a "moral and technical order" of collaboration and sharing with society (Kelty, 2008). If the history of free software is any indication, though, such an order might be fragile and easily commodified by companies.

Public policy changes may be needed to institutionalize accountability in technological design. One way might be for government to mandate that new nanotechnologies or nano-products can only be approved if authentic citizen engagement has occurred. This could take the form of participatory technology assessment structures that enable people to collaborate with designers in their many locations within start-ups, large multi-national corporations, and university institutes. Decentralized, site-specific organizations could be created to facilitate dialogue with social movements. Using taxes on the ecological and health effects of materials, governments could fund open access to technical expertise—as well as new institutions for participatory research (e.g., Woodhouse and Breyman, 2005). Governments could give citizens the power to require design changes, or new development could be held up or even vetoed through lawsuits or product suspensions against companies. All proposals that depend on asserting government power over the private sector, of course, face serious challenges in the current neoliberal political climate. Finally, civil society can seek accountability through careful and sustained oversight of nanomaterial issues in a global forum—a collective form of participatory technology assessment—as Jasanoff and colleagues have argued should be instituted for human gene editing technologies (Jasanoff and Hurlbut, 2018).

Much of the preceding discussion has been exploring the premise that social movements' goals can include changing the design of nanomaterials, in the vein of "sustainable materialism" (Schlosberg, 2019). But we also recognize that the goal of some social movements may, in fact, be full resistance to nanotechnology—and perhaps also resistance to the attendant material cultures of consumption and corporate control. Materials sovereignty could still form the basis for such demands, and all of its key elements could contribute to an "informed refusal" (Benjamin, 2016) of nanotechnology. That is: an alternative vision of just and sustainable material systems *without* nanotechnology should be open to social movements and societies.

Conclusions

Nanotechnologies in many ways exemplify emerging technologies that could cause an array of ecological and health damages, if they are not designed with sustainability in mind. Yet we face fundamental problems in governing such emerging technologies. Green nanotechnology is now being developed as a way to make nanomaterials safer through rational design, but nanotechnologists do not uniformly recognize any obligation to attend to societal concerns and only limited obligations to address environmental health and safety issues (Corley, Kim, and Scheufele, 2015; Johansson and Boholm, 2017).

Against this background, the new concept of materials sovereignty is arguably emerging in the practices of social movements for health. Materials sovereignty is the right of people to use, and to be surrounded by, environmentally benign, non-toxic, and renewing materials in their everyday lives. In this paper, we have begun to sketch how and why materials sovereignty matters in the governance of emerging technologies. We suggest that social movements using the idea of materials sovereignty can bridge between technological designers and ordinary citizens. Far from the passive audiences that surveys portray, citizens are likely to be feeling disempowered because of their lack of agency and lack of access to information about the (nano)materials present throughout their environments, workplaces, homes, and bodies. The relatively few instances of participatory citizen analysis of nanotechnology suggest this.

We have examined how materials sovereignty might be achieved in the case of nanotechnologies by targeting leverage points within the industrial materials system. We have discussed five examples of such pathways: direct resistance; market-based approaches; policy activism; participatory technology assessment; voluntary partnerships between industry and NGOs; and co-design approaches. We have analyzed these pathways in terms of their theoretical and practical contributions to materials sovereignty. Based on this analysis, we identified three key elements of materials sovereignty: participatory knowledge systems creating multi-directional flows of knowledge and agency; the embedding of citizen voices into design processes; and building accountability systems.

We conclude that most of the pathways we have analyzed are lacking as regards one or more of these elements. Still, we suggest that all of the pathways are essential to realizing materials sovereignty; they are not mutually exclusive and they can complement each other. Co-design appears to be the most promising pathway from a theoretical and ethical perspective, but there remain significant institutional and organizational challenges for bringing it into practice.

Therefore, further research and experimentation is needed to determine whether co-design processes can intervene effectively in materials design. To begin with, action-research projects—such as Arizona State University's COTE endeavor—can gather scientists, citizens, NGOs, and companies together in structured experiments to develop safer nanomaterials for specific uses. Such projects can evaluate mechanisms to assure that citizen and social movement participants are fully representative, and test practical methods for enabling dialogue and sharing of power between civil society actors and designers. They can make it more 'normal' for civil society to be directly part of materials development. These projects can also be used to seed, and gradually expand, a shared infrastructure for recruiting participants, pooling and financing accessible technical expertise, and making designers accountable for their choices. Based on the results, governments may need to enact laws that mandate participatory design as a precondition for marketing new materials.

As social movements increasingly apply pressure on multiple leverage points in the global materials system, we hope that our analysis may help guide strategies to maximize the beneficial effects of interventions in technological design. Materials sovereignty can provide a way to integrate societal perspectives into material design for the benefit of humans and ecosystems.

Data Accessibility Statement

No new data was generated and all data used is cited and publicly available in searchable databases and online sites.

Notes

1. 51% of respondents in 11 different studies in North America, Europe, and Japan reported knowing nothing about nanotechnology. Studies that asked respondents to weigh the perceived benefits and risks of nanotechnology consistently showed a prevalence (by about three-fold) of people seeing greater benefits versus greater risks; however, a significant proportion of respondents (almost half on average) were unsure (Satterfield et al., 2009).
2. This strategy has been used by organizations such as 350.org and Fridays for Future on the issue of climate change.
3. Although market decision-making itself is complex: Polanyi (1944) pointed out that markets typically rely extensively on laws.
4. For example, in the US, the 21st Century Nanotechnology Research and Development Act of 2003 required that the national R&D program ensure "ethical, legal, environmental, and other appropriate societal concerns… are considered during the development of nanotechnology" by various means, including "public input and outreach… by the convening of regular and ongoing public discussions, through mechanisms such as citizens' panels, consensus conferences, and educational events" (United States Congress, 2003). In the UK, public engagement was recommended by the Royal Academy of Engineering (Royal Society and Royal Academy of Engineering, 2004).
5. For example, in 2017, EDF funded detailed hazard assessment studies on sixteen chemicals used as preservatives in consumer products, and made the results public to provide a basis for further research in safer alternatives (Environmental Defense Fund, 2017)—effectively conducting research that industry should itself be doing.
6. This project is no longer active, but the NRF is still available online (Environmental Defense Fund, n.d.b).
7. This case highlights a crucial (and often ignored) point: the people and organizations most active within social movements may or may not be representative of the people they purport to speak for. NGOs frequently claim moral and political authority because they stand for the interests of their constituencies (Wapner, 2002). They may aggregate the resources of people who otherwise lack the time and capacity to participate in an issue. Yet, NGO staff may make decisions and express views that do not necessarily reflect the experiences, priorities, and values of those who are supporting them through memberships. NGOs and movements can also lack democracy: a few particularly powerful individuals can control their direction.
8. Environmental NGOs and government agencies, as well as various consumer product firms, have worked together on developing methods for the assessment of safer chemical alternatives (such as Lavoie et al., 2010). But the alternative molecules are typically new products developed by the chemical industry in response to regulatory pressure (e.g. Harmon and Otter, 2018).
9. The term "translate" is quoted here from Nieusma (2011) but also recalls the sense of Latour (1987).

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Author contributions

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- Contributed to acquisition of data: AK
- Contributed to analysis and interpretation of data: AK, AI
- Drafted and critically revised the article: AK, AI
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