Public Value Integration in Science and Innovation Policy Processes

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> "What really counts when it comes to public values flowing from science policy is not so much the budgetary level of effort as the institutional, cultural, political, and economic contexts in which science is produced and applied" (Bozeman and Sarewitz, 2005).

Introduction

Demonstrating the public value of science and innovation policy (SIP) programs is important for ensuring prudent investments in research, for guiding its conduct, and for justifying public trust and support for science (Guston, 2000; Wilsdon et al., 2005). Public values, and other societal dimensions of research, are particularly important in the case of emerging science and technologies, which are increasingly likely to occasion complex public contestations. Public value integration (PVI)—the elucidation and consideration of public values during research conduct and evaluation—seeks to bolster the capacity of SIP practitioners to systematically take into account the uncertain yet pressing social and value aspects of science while it is still under development.

Establishing a sound basis for analyzing and reflecting on public values is challenging. Public value integration therefore addresses both practical and methodological challenges. It does this by elucidating the public values at stake in specific SIP programs and by simultaneously expanding the decision spaces that take them into account. PVI helps reveal the complex manner in which capacities to achieve public value are embedded in the knowledge creation process, distributed across multiple SIP actors and—most interestingly—are amenable to incremental amelioration by practitioners at nearly all levels who engage in reflective exercises.

PVI is built upon two separate approaches that have been supported by the National Science Foundation's Science of Science and Innovation Policy (SciSIP) program. Together, these two approaches help PVI address two distinct "value metric gaps." The first gap has to do with evaluation. The metrics, or language, of SIP justifications and SIP evaluations are, quite often, incommensurable. Although SIPs are typically justified in terms of a broad range of public values, available models and tools for evaluating them mostly address only economic activity and scientific productivity. Public value mapping (PVM) was developed in an attempt to address this evaluation gap.

The second gap has to do with performance. SIPs are implemented by scientific practices that routinely exclude value considerations as a matter of principle.

Shifting political pressures have triggered more explicit demands for research practitioners to take into account broader economic, ethical and other societal dimensions of research (Gibbons et al., 1994). Legislative mandates and agency rules have formalized these demands, but R&D practitioners lack the skills and training to effectively implement them (Fisher and Miller, 2009; Owens, 2010; Roberts, 2009). Socio-technical integration research (STIR) was developed to address this performance gap.

As demonstrated by the case study presented in this paper, PVI can reinforce the core rationales that justify SIP programs by helping practitioners synergistically consider them in light of the more prevalent instrumental values that are associated with the use and scientific quality of research. After a brief summary of the PVM and STIR approaches, the paper explains how these are combined in PVI activities and provides empirical support for its practical effectiveness. It concludes with a summary of PVI strengths and policy applications and offers reflections on strengthening the approach through further research.

Public Value Mapping (PVM)

Public value mapping was developed as an alternative to economic and bibliometric evaluation of SIPs, as these are posited as insufficient for assessing the capacities of SIPs to achieve public values. As stated, PVM posits a gap between the metrics used to justify SIPs and those used to evaluate SIPs. The primary rationales for PVM are thus twofold: (1) SIPs are often justified in terms of a broad range of end-state social goals and public values—from improved health and better environmental quality to more equitable distribution of sciences' benefits; and yet (2) available models and tools for evaluating SIPs mostly address only economic activity and scientific productivity, which only imperfectly take these values into account.

PVM defines a society's "public values" as those providing normative consensus about the rights, benefits, and prerogatives to which citizens should (and should not) be entitled; the obligations of citizens to society, the state and one another; and the principles on which governments and policies should be based (Bozeman, 2007). Specific public values are selected to justify government actions, including SIPs, so there is no difficulty in finding public values; rather, the difficulty is understanding them in some analytically useful form (Bozeman, 2007).

Proceeding through a case study model, PVM specifies and applies general "public value failure" criteria to guide assessments across multiple, disparate SIPs of whether the public values associated with a given SIP are being advanced. It employs a "public value grid," a two-by-two matrix that classifies SIP outcomes in light of their relative market success/failure, and their relative public success/failure (Fig. 1).

An NSF SciSIP project[1] has developed and tested the PVM model for assessing the linkages between SIPs and a range of non-economic public values. The project built on previously developed foundational theory and method (Bozeman 2007; Bozeman and Sarewitz 2005), and yielded several important results: PVM theory and method can be applied with some consistency across a disparate set of SIP cases, including climate change, natural hazards mitigation, green chemistry, cancer research, technology transfer, and nanotechnology. These individual case studies led to the development of formal criteria for assessing SIP capacity to achieve those public values that motivate them. Furthermore, evidence suggests that the internal consistency of the public values articulated within a given SIP and/or program may help to predict the capacity of that SIP/program to advance those values.

Socio-Technical Integration Research (STIR)

Socio-Technical Integration Research (STIR) was developed in order to enhance the capacity of research performers to productively reflect upon the societal dimensions of their work in real-time. STIR posits an incommensurability between the language of SIP justifications and the practices utilized by the research performers who implement SIPs. In other words, public values—ranging from equity, security and health to environmental quality—characterize SIP authorizations, but these very social considerations are typically excluded from research and development activities themselves.

Historically, the exclusion of social considerations during research has been justified on the grounds that such considerations would compromise the quality and productivity of scientific research (Brush, 1974; Leshner, 2005; Polanyi 1962). Recent calls, however, at the highest levels of American (US Congress, 2003) and European (European Commission, 2007) government for the "responsible innovation" of new and emerging technologies such as nanotechnology, explicitly call for the "integration" of social considerations and concerns *during* research (Barben et al., 2008; Fisher, 2007).

STIR utilizes a decision protocol that was developed in collaboration with laboratory participants during a 33-month pilot study (Fisher, 2007). The protocol (Fig. 2) facilitates broader reflection by research practitioners while they are in the process of making research decisions. Successive passes through the protocol's four decision components—opportunity, considerations, alternatives, outcomes—tend to produce a spiral of unfolding value considerations. Initially, SIP practitioners are concerned only with research value; over time, the same decision spaces can become expanded to include social, ethical, environmental and public value considerations. At the same time, the protocol's focus on alternatives increases the chances of perceiving new potential alignments between research value and public value.

[1] NSF award #0738203, PI: Daniel Sarewitz, Co-PI: Barry Bozeman.

The NSF-supported STIR project[2] coordinates over 20 laboratory engagement studies in a dozen countries to assess the capacities of research laboratories to integrate broader societal considerations into their work. The project's studies demonstrate that semi-structured collaborations between social and natural scientists can enable a richer variety and quality of research outcomes, without sacrificing research quality or productivity (Fisher 2010).

Public Value Integration

Both the PVM and STIR projects have developed and tested practical tools for helping decision makers—ranging from agency program managers and Congressional staffers to university research administrators and laboratory scientists—identify and respond to broader contextual factors that are latent in science and innovation decision making processes. The PVM and STIR methods were initially combined for two reasons: (1) to provide a credible normative baseline to inform and assess productive integrative activities during research; and (2) to increase the resolution of public value mapping by extending PVM to the lab scale and applying data mining techniques to elicit values across a broad but coherent field of endeavor. Combining their approaches provides SIP practitioners with credible intelligence and allows them to creatively respond to underlying public value structures that extend across all levels of a science and innovation policy endeavor.

PVI Case Study: The Photon Project

> "Science and technology policy rarely gives much recognition to the R&D laboratory as a social and political institution" (Crow and Bozeman, 1998).

This case study presents three distinct, yet interrelated modules of public value integration: First, it reviews key value considerations that were documented during an interactive observational study of a scientific research laboratory. Second, it presents outcomes from a deliberative workshop that fed these findings back to the laboratory team in order to stimulate their responses. Finally, to support future deliberations, it describes the results of an effort to quantitatively map the public value structures that underlie the US nanotechnology SIP.[3]

Value Considerations in the Laboratory

The Center for Single Molecule Biophysics (SMB) is one of several centers within the Biodesign Institute at Arizona State University. Its main workspace is stocked with long, shining arrays of off-white laboratory benches, chemical hoods, computers, and all manner of experimental equipment and supplies. Two floors down are many

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[2] NSF award #0849101, PI: Erik Fisher, Co-PI: David Guston. Project website: http://cns.asu.edu/stir/.

[3] The modules can be employed synergistically, as they are here, or independently of one another—depending on the policy maker's needs.

more desks and smaller, dedicated microscopy rooms. The laboratory, home to several research groups, is typically neat, tidy and bustling with graduate students. Across the spacious corridor that runs from one side of the institute's brightly lit, platinum LEED-certified building to the other, and that separates the laboratory space from the faculty and administrative offices, I sit with center director Stuart Lindsay.

We are discussing one of the center's flagship projects, a multi-disciplinary, multi-team, NSF-funded endeavor that focuses on "using nanotechnology to improve solar cell technology." The "Photon project" consists of four different research groups comprising a dozen or so team members, half of whom conduct their research in laboratories elsewhere on campus. Lindsay—also the project's principal investigator (PI)—recalls how the research began to take shape five years earlier, with interactions among various professors of physics, chemistry, biochemistry and electrical engineering—all of whom are now either PI or Co-PIs on the $1.1 million grant. When I ask him "what comes to mind" when he thinks about the project's outcomes, he closes his eyes and folds his arms behind his head. "Cheap and clean solutions to the energy problem," he responds. He pauses and then adds, "I hope." These two additional words signal the high stakes associated with the envisioned outcome. They also indicate that innumerable uncertainties could influence the project's success, uptake and public value.[4] The question that we contemplate over the next year then becomes: *How can a research group increase the likelihood of the public value success of a given scientific project?*

As a preliminary step towards clarifying this question, I become increasingly embedded in the project's and center's activities. For instance, I am supplied with desk space, on the project email list, have full access to the laboratories (after I take two lab safety classes), attend the group meetings of the center's main projects and, eventually, receive an honorary research appointment in the center. My conversations—with PI, co-PIs, post-docs and graduate students—seek to identify possible connections between concrete research decisions (for instance, whether to use gold or silver nanoparticles in the device the group hopes to produce) and more abstract policy rationales (for instance, ensuring the nation's energy security). I employ a modified version of the STIR protocol to better understand how daily decisions about scientific research could more consciously take into account the broader public values that warrant its funding. The protocol helps to elicit both the research values and the public values at stake, including the potential tensions and trade-offs among them. In this way, interviews that focused heavily on technical details (for example, nano-scale photonics, electronics, microscopy, etc.) could eventually give rise to broader topics (for example, research management,

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[4] We can classify these uncertainties in terms of three variables, which are increasingly dependent upon the previous variable: the project's success as a research project ("scientific excellence"), its broader uptake ("technology transfer"), and—ultimately—its public value contribution ("cheap and clean solutions to the energy problem").

interdisciplinary education, resource acquisition, environmental and safety concerns, etc.)(Fig. 2).

Ideally, to inquire into the obligations of SIP performers to take public values into account, at least two conditions must be met: (1) there should be reasonable clarity regarding what public values are at stake are, and (2) SIP performers must actually have opportunities to make decisions that entail public value implications. In an effort to establish these two conditions, the qualitative methods of ongoing semi-structured interviews, participant-observation and archival research were used to document value tensions were at three SIP levels: public policy (macro-level), funding program (meso-level) and research conduct (micro-level).

Macro-level Value Tensions. A given SIP program or project is likely to be justified in terms of a rich diversity of public value statements, not all of which logically or operationally reinforce one another. The case of the Photon project is particularly illustrative in this regard, since the project seeks to advance objectives associated with two different established SIP programs: Solar energy research and nanoscale research. Given the inevitable uncertainties surrounding the project, the continual need to reaffirm or adjust the direction of the research, it was necessary to develop a working understanding of the public values that this research was in theory obligated to take into account.

An initial search of House Science Committee reports from the 106th to the 110th Congresses revealed a plurality of objectives associated *not only between but also within* each of the two SIP program. While some objectives diverged from one another, there was some overlap between the two programs (Fig. 3).[5]

A total of 24 public policy objectives were identified for nanotechnology and for solar energy SIPs. Of these, eight overlapped to create four shared objectives between the two programs: energy efficiency, economic growth, solar energy cost, and economic competitiveness. While "objectives" are not the same as "public values" (public values underwrite or anchor objectives), they do provide a general sense of the diversity of values and objectives involved and of the challenges for explicitly considering values during decisions about research funding, conduct and evaluation.[6]

Meso-level Value Tensions. The Photon project receives resources from two separate National Science Foundation interdisciplinary award mechanisms.[7] One of these is meant to advance nanoscale research, and the other is intended to promote academic-industry collaborations. As in the macro-level case of the dual focus on nanoscale and solar research, the project's duality of funding sources also

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[5] Thanks to Derrick Anderson for his help in searching for and compiling the SIP objectives.

[6] As is explained below, close collaborations with laboratory practitioners led us to further refine this list, focusing on underlying public values and making it more representative.

[7] The project is funded by both the Nanoscale Interdisciplinary Research Team (NIRT) and the Grant Opportunities for Academic Liaison with Industry (GOALI) award programs.

introduces the possibility of value tensions: should nanotechnology in this case be pursued for the sake of its centralized/decentralized renewable energy potential, or for the sake of commercialization, which could take any number of forms unrelated to renewable energy?

Documents produced by the laboratory allude to both of these application objectives. On the one hand, the project proposal states, "this grant focuses on renewable energy," and it notes that the research could potentially demonstrate that "nano-engineered materials…could contribute a new approach to the generation of renewable energy." On the other hand, the center's public website characterizes the project team's goal in slightly different terms, namely, "to create tiny, nanoscale devices for higher efficiency solar energy *and* photonics applications" (emphasis added). In other words, solar energy and photonics applications are not mutually inclusive. Photonics applications can include consumer equipment (printers, scanners, and readers; remote control devices) and infrared technology for military and other applications (for instance, firefighting).

Micro-level Value Tensions. At the micro-level, considerations of use and public value must also compete with pressures on the research leaders to demonstrate that the project has research value or "scientific excellence," even at the expense of an envisioned application or device. As the Center director stated when I asked him how likely it was that he will have a device at the end of the project,

> So, here's the difference between successful and unsuccessful research groups: Unsuccessful research groups stick with an untenable goal forever. Successful groups know how to make lemonade from lemons.

Put differently, if a research group or its director lacks confidence in the value of a particular research direction, that direction is likely to change.[8]

But what happens when there is uncertainty over research value? For instance, it is quite possible to have multiple interpretations of research value, especially in a multidisciplinary team. In the following exchange, two of the Photon project members push the PI to change the direction of the research, given slow progress with nanoparticles that has plagued the group for months:

> Electrical Engineer: [We have a] problem measuring the [electrical charge] of the [metallic nano]particles...
>
> Chemist A [*speaking to the other chemist*]: Another idea is to [use porphyrins].
>
> Chemist B: We were supposed to be doing that anyway.
>
> [*Two of the graduate students smile at each other—they recognize what seems to be a longstanding debate.*]

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[8] At least, if one has NSF funding, which allows such deviations for the sake of obtaining fundamental knowledge.

Physicist: Trouble is that gets away from the metal sphere idea.

Chemist A: So far we have not observed any Plasmon shift yet?

Physicist: No.

The physicist, as the project PI, is the most senior member of the team. Chemist B arguably carries most weight after him. Once Chemist A, who is less established, gains the support of Chemist B, he challenges the PI directly on the grounds of too little research progress. This challenge is reminiscent of what the PI said to me earlier about knowing how to make lemonade from lemons.

However, whether one is looking at a lemon or a lime may depend on who's doing the looking. Disciplinary training and area of expertise can influence how one assesses research value. The engineering group has been pushing for months to construct a nanoscale antenna made of silver or gold particles, while the chemists are used to working with porphyrins (organic compounds). Differences in experience, training, and desired outcomes help shape not only the disagreement over research value, but also the disagreement about what the group is obligated to do. For Chemist B appeals to what was promised in the proposal as the primary source of authority. Two weeks later, the negotiation continues. There is disagreement about what "the plan was" in the grant proposal.

To summarize this first section of the case study: the macro-level raised questions about what constitutes public value, the meso-level raised questions about what constitutes use value, and the micro-level raised questions about what constitutes research value. The significant complexities and uncertainties involved in establishing the value of research are daunting. However, as the next section of the case study suggests, it is possible—and useful—to employ these very complexities and uncertainties as a creative resource for enhancing learning and innovative thinking.

Public Value Deliberations

One year after initiating participant-observation activities, the author organized a workshop to specifically explore the relations between the Photon group's research and public values. The workshop brought project members from the various labs into contact with representatives from industry (Microchip, a US based semiconductor producer), civil society (the Loka Institute, an NGO dedicated to public participation in science) and energy policy (Dr. Frank Laird, University of Denver).

Twenty people participated in the workshop, which was divided into two half-day sessions (the second day was reserved for Photon graduate students). Of these participants, 10 were members of the Photon project. This included three of the four project PIs and at least two representatives from each of the four project sub-groups. To put this turnout into perspective: over the course of the previous year, of the 18 people who had showed up at least once during the project meetings, six of these had attended no more than twice. Thus, to have most of the "regular" members show up was an encouraging sign, especially considering that the event was voluntary and had been only minimally advertised, without significant lead-time.

The workshop centered on the question, "Can public values affect the direction of laboratory research?" The agenda included background talks on the Photon project, the role of public policies and public values[9] in science, and industrial and lay public perspectives on academic research. It presented project members with findings from the participant-observation phase of the case study, followed by an open discussion between two of the project PIs and the author, and it ended with a series of "challenge" exercises. Participants were prepared for the exercise by means of several graphic depictions of research and innovation processes that contained prompts about how laboratory choices might relate to licensing, manufacturing, use and social significance of the envisioned technological device (for example, see Figs. 4 and 5).

Another diagram—termed a "forking roadmap"—presented equally plausible yet diverging technological trajectories that linked lab-level decisions to conflicting public value outcomes (Fig. 6).

[9] Public values were defined as rights, benefits, and prerogatives of citizens (examples: clear air, security, participation in governance decisions).

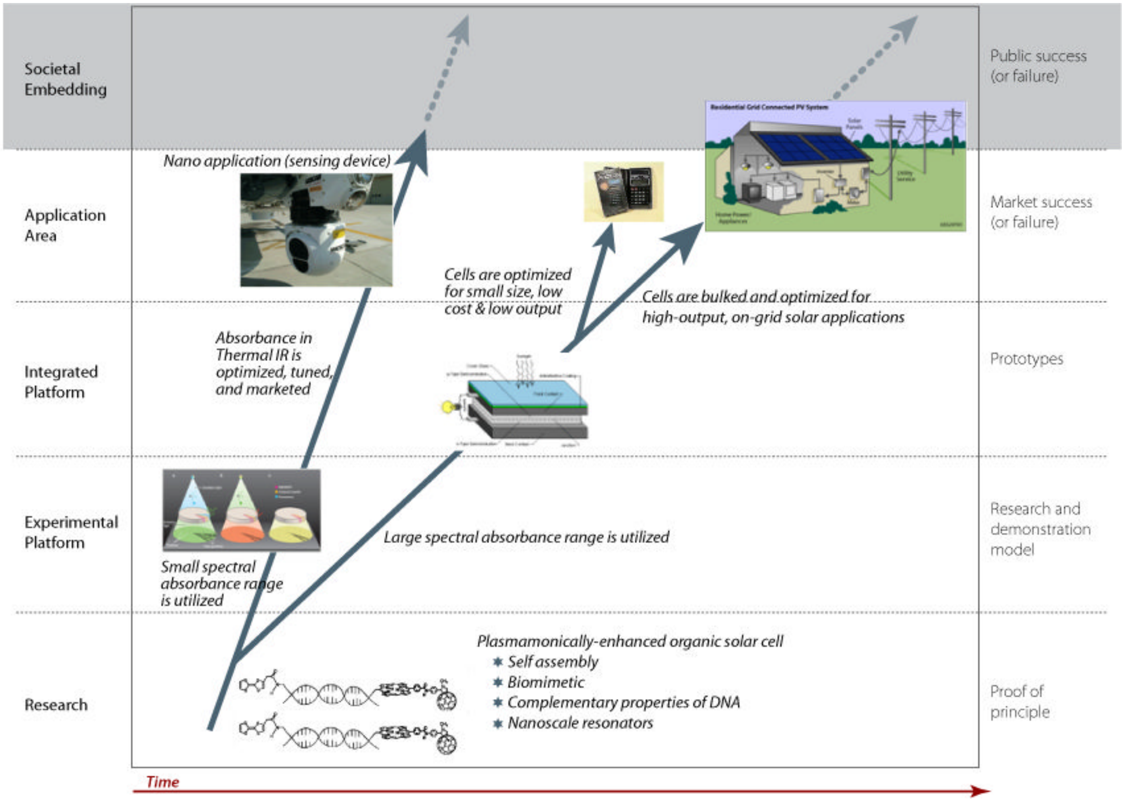

Figure 6: Forking Roadmap of Nanosolar Applications *(this figure is inspired by Robinson and Propp 2008).*

The "forking roadmap" was accompanied with the following provocation: *think about how lab-level decisions might potentially favor one pathway over another. This suggests that a research group can "lock in" to a trajectory without realizing it. However, some paths are potentially more desirable than others. We can't know in advance what the effects of lab-level choices will be, but reflecting on them from time to time is a way to practice due diligence.*

In order to help participants reflect on the public value implications of potential "forks in the road" in their own research, they were asked to identify current and impending research challenges—for each group and for the project as a whole—and to evaluate the public value utility of at least two possible responses to each challenge (Fig. 7).

Workshop Outcomes. Although initially skeptical about the value of the workshop, most of the laboratory researchers who attended it reported that either the concepts, the open discussions about research decisions, or the deliberative activities proved to be valuable. Several stated that these helped them shift their perspectives on how their own decisions relate to the broader innovation system. In fact, both faculty and graduate student researchers requested "more meetings like this" in the future. The "challenge" exercise, while extremely difficult at first for participants, turned out to "actually be useful" (as the PI told me the following week). Specifically, two faculty members and one junior researcher reported that the exercise led to two technical "breakthroughs" for synthesizing nanoparticles and one novel idea for structuring an antenna. A graduate student group was less successful; they struggled with the idea of using less toxic substances, attempting unsuccessfully to identify a more benign set of chemicals. In the end, this experience inspired two of them to seek funding to attend a "green chemistry" workshop. Two other graduate students stated that the workshop had provided them with new perspectives on the potential value of their work for practical applications beyond the laboratory, which they reported to have been inspiring. Graduate students were particularly vocal about the value of listening to their professors discuss the broader dimensions of the research projects to which they contribute. Overall, the lab participants expressed a desire for more such interactions, and it was resolved that we would meet quarterly on the public values agenda. (These group meetings did not, in the end, come about; but the author did arrange to have one embedded humanist and one embedded social scientist join the lab in his place.)

General Reception by Scientific Collaborators. On the one hand, Researchers seem reluctant to notice, let alone consider, either in group meetings or during one-on-one interviews. On the other, there was a notable degree of cooperation and reception at all levels of the project team and among all groups. One of the graduate students took a science and technology studies (STS) class and accompanied the author to a conference out of state to present a poster. A second graduate student contributed to a science policy research project and presented a posted at a meeting of the Center for Nanotechnology in Society at ASU. As stated above, the workshop led to several significant outcomes, including novel ideas for research. There were differences of opinion as to why these ultimately did not end up being employed in the original form, but according to the PI, "they did stimulate discussions that led to other ideas." Three of the four sub-groups welcomed two more social scientists—Ph.D. students in philosophy and in STS—who began working in my place, took part in preparations for experiments, followed closely the interpretation of experimental data, and introduced broader questions using the STIR protocol. One of these students took a course on quantum mechanics from the PI, who agreed to pursue joint funding that would allow this student to devote more of her time to the laboratory engagement.

End-to-End Public Value Mapping

As a result of the experience of facilitators and participants in the deliberative workshop, it was clear that more comprehensive, systematic and reliable information about the public values of the solar and nanoscale SIP programs were required. In the words of one Photon project participant, "[the public values listed in Fig. 3] should be weighted appropriately to allow us to see what to do when two conflict." Public documents that promote, justify and fund SIPs are numerous and can be found in many venues. Thus, there is no shortage of federal and federally authorized documents produced by stakeholders that may serve as sources for public value statements and public value rationales.[10] But given the plurality of sources—and the inevitable diversity of public value statements associated with a given SIP—the challenge was to determine which public values have been formally associated with a given SIP program.

Accordingly, in order to appropriately weight public values, a team of social scientists, with the help of laboratory practitioners and policy actors who assisted in the selection of dozens of search terms, undertook a massive electronic content analysis of a comprehensive set of public documents produced by nanoscale and solar SIP stakeholders from the years 2000-2008. The decision was eventually made to concentrate solely on nanoscale documents.

The feasibility of this approach was demonstrated in Fisher et al. (2010a), which extracted value statements related to federally funded nanoscale research from over 1,000 documents (over 100,000 total pages), concentrating at the lab scale (NSF funded proposal abstracts), but also including NSF program funding solicitations and Congressional reports. After extracting value statements produced by laboratories, funding agencies and legislatures over an eight-year period, electronic content analysis and data reduction methods revealed a multi-factor structure of public values that has been consistently cited by a range of actors in an NSE policy network.

Principle components analysis of 84 search terms yielded three factors with eigenvalues greater than 1.00 and a contribution of at least 5% to the variance explained. The first two factors, termed "Society and Economy" and "Security and Defense" account for 33 and 10% respectively of variance explained. A third factor, termed "Energy and Environment" explains 8.6% of the variance. A given search term was retained in each factor if it met the following conditions: loads at 0.50 or higher on the factor, does not load higher than 0.50 on more than one factor, constitutes highest factor loading for the term and is conceptually relevant. Factor 1 (Society and Economy) had 26 terms, Factor 2 (Security and Defense) had 6 terms and Factor 3 (Energy and Environment) had 7 terms. The internal consistency coefficients for the factor structure were also analyzed. The subscales, "Society and Economy," "Security and Defense," and "Environment and Energy" demonstrated good to excellent internal consistency with Cronbach alphas of 0.798, 0.792 and 0.927, respectively.[11]

The credible and reliable information that the PVI team was able to generate was envisioned as an aid in assessing the public value of a given scientific research

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[10] For example, preliminary explorations by CSPO graduate students reveal over thirty congressional committee reports referencing solar energy in the current (111th) congress alone. Meanwhile, over 300 solar energy-related Department of Energy project descriptions are available from the Office of Scientific and Technical Information (OSTI; www.osti.gov) dating back to the 1980s.

[11] This paragraph largely reproduces material from Fisher et al., 2010a.

endeavor—whether that endeavor happened to be a single research project, or an entire SIP program. Given the uncertainties facing the Photon project, and the need to resolve disputes and determine next steps, it was deemed necessary to identify which public values researcher could reasonably be expected to take into account when operating under conditions of uncertainty. Such information could, it was reasoned, also help establish which public values should be considered to translate into obligations, once a research performer formally agrees to accept research funding.[12]

Conclusion

Twelve months of PVI participant-observation yielded a multi-level analysis of value tensions that need to be taken into account by any stakeholder who insist on a plausible program of responsible innovation. Furthermore, against an explicitly normative backdrop of public values, PVI workshop activities generated novel research ideas among laboratory researchers and administrators, demonstrating, contrary to persisting norms, that "efforts to enhance scientific creativity and societal responsiveness can be mutually reinforcing" (Fisher et al. 2010b). Finally, which were derived from public legislative records was subsequently refined and expanded into a systematic and credible analysis of over 1,000 documents, which produced a reliable assessment of the underlying value structures that justified eight years of funding, allocation and performance of the US nanoscale research endeavor.

Several conclusions can be derived from the PVI pilot case study: (1) value and choice elucidation at the (micro) project level can be significantly aided and guided by reference to (macro) program-level. This mitigates the unreliability of mere "personal ethics" and insists that SIP actors take up publicly sanctioned statements, goals, values, concerns and rationales as a basis for their local decisions. This supports the finer grained and context-specific analysis required to conceptually link micro decisions to anticipated meso and macro scale outcomes. (2) Not only can individuals carry out STIR exercises over time and in an ongoing manner, as they are in STIR project studies, but larger groups can also conduct them in concentrated bursts. Furthermore, they exercises can enhance the value of research decisions that are made by managers as well as by bench scientists. (3) End-to-End PVM can establish credible, robust and reliable information about the underlying value structures that comprise a SIP endeavor that can be verified by external sources. This information thus establishes general baselines for what public values are most consistently cited by a range of SIP stakeholders over time, in turn providing a rational basis for "weighting" values during deliberations.

Similarly, the applications of PVI to SIP processes can be summarized as follows: As an investigative tool, PVI activities can reliably identify public and research values at stake, mapping their hierarchies and tensions. As a performance tool, PVI can help

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[12] As Vannevar Bush, the principal architect of US science policy, himself argued (Guston 2000).

bring identified public values to bear on decision processes—both decisions about science and scientific decisions themselves. Finally, as an evaluative tool, PVI can assists PVM by tracking outcomes at multiple levels and by developing a more nuanced and multi-level map of the public values in play and authorized by the authorization, allocation and peer review processes that constitute SIP program areas.

These conclusions and applications suggest that PVI techniques can be useful to science policy makers and evaluators for three general purposes: Policy makers can employ STIR exercises to enhance their own deliberations, whether as individuals or in groups; Policy makers can encourage research performers to employ the STIR exercises; and, finally, evaluators can commission End-to-End PVM studies of specific SIP programs. End-to-End PVM can be carried out either for the sake of a comprehensive analysis of the public value structures that underlie a given SIP program, or in order to obtain a more focused analysis of the components that constitute a specified subset of values that are determined to warrant analysis for specialized purposes.

Several steps are required to further develop, refine and test PVI methods. One obvious step is to apply the combined STIR-PVM approach to other SIP areas, for instance, solar energy research, in order to explore the utility of PVI in more established fields as well as to continue to expand a demonstrable ability to provide valuable intelligence and decision support functions to SIP practitioners. Another next step for PVI is to complement the quantitative analysis with more fine-grained textual analysis, interviews, and participant-observation. Specifically, PVI will need to develop methods to construct value hierarchies that explain in more (probably qualitative) detail the comprehensive underlying value structures that emerged from quantitative analysis. This could also encompass the development and testing of hypotheses that posit research value as an independent variable and use value and public value as dependent variable. Additionally, it would be extremely useful to sponsor and document a variety of events that challenge SIP practitioners to employ PVI techniques or variations thereof in order to further test the utility of reflecting on seemingly intractable value considerations. This would eventually aid in the development of best practices for facilitating and conducting deliberations and in the development of sound criteria for evaluating them. In the case of graduate science and engineering education that takes place in research settings, this has been recommended by Fisher and Lightner (2009) for the sake of building the capacities of "scientists in the making," and it is further supported by the experience of some of the Photon project graduate student.

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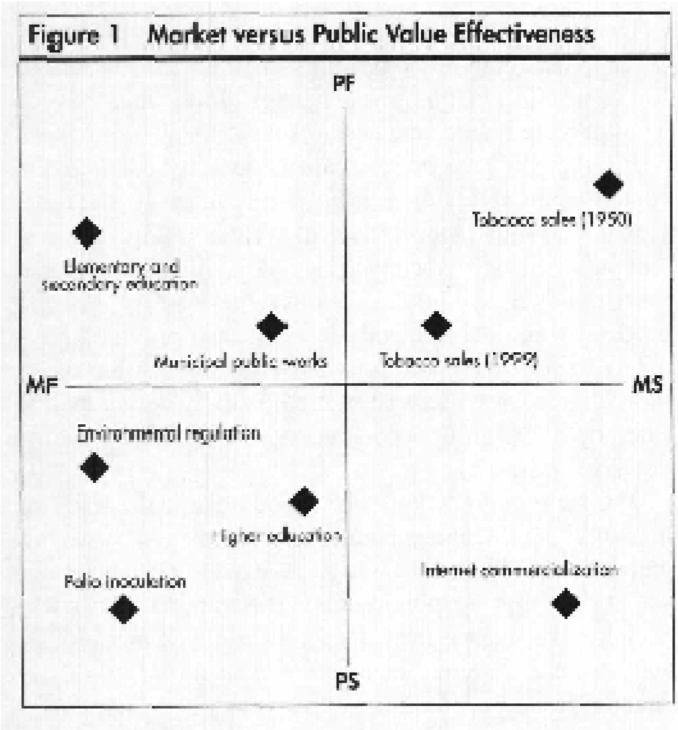

Figure 1: Public Failure Grid (Bozeman 2002)

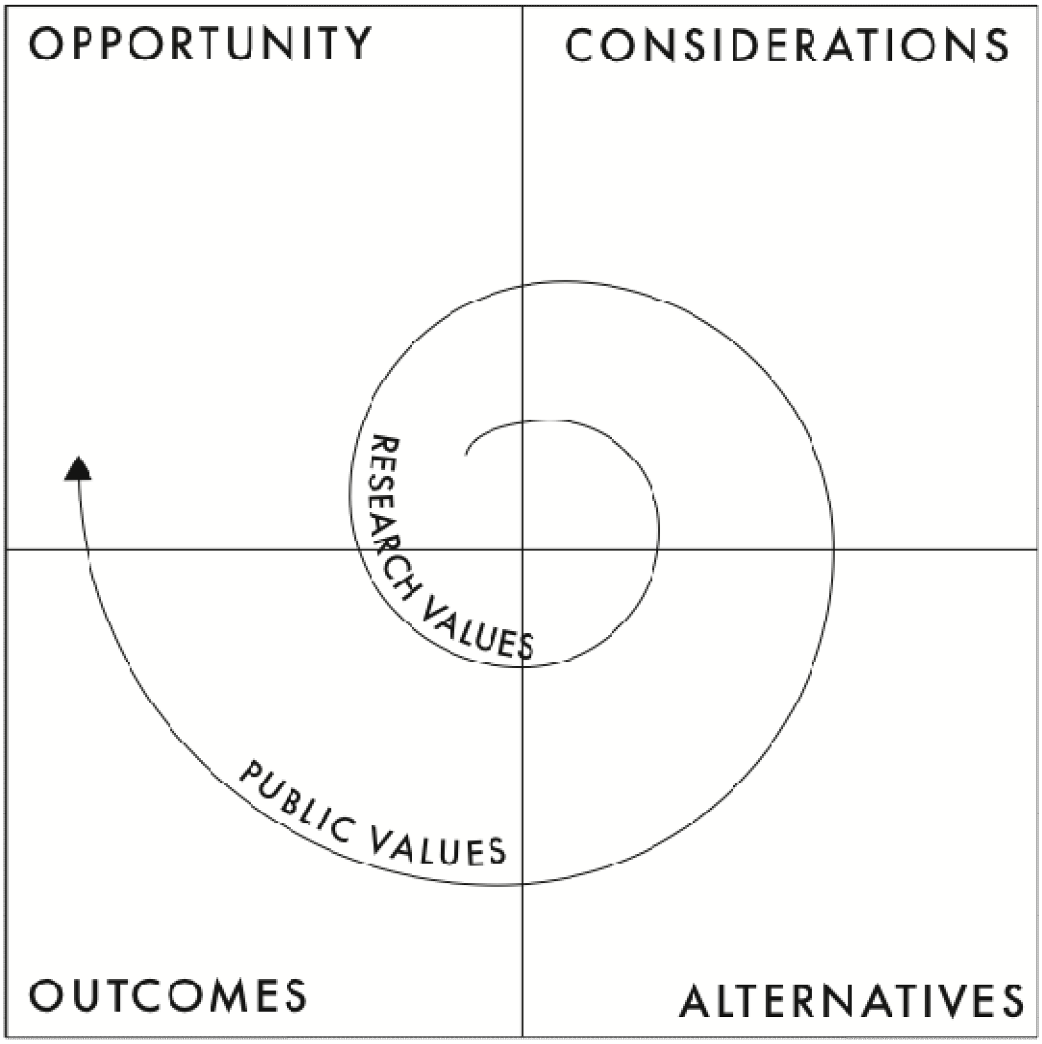

Figure 2: STIR Decision Protocol

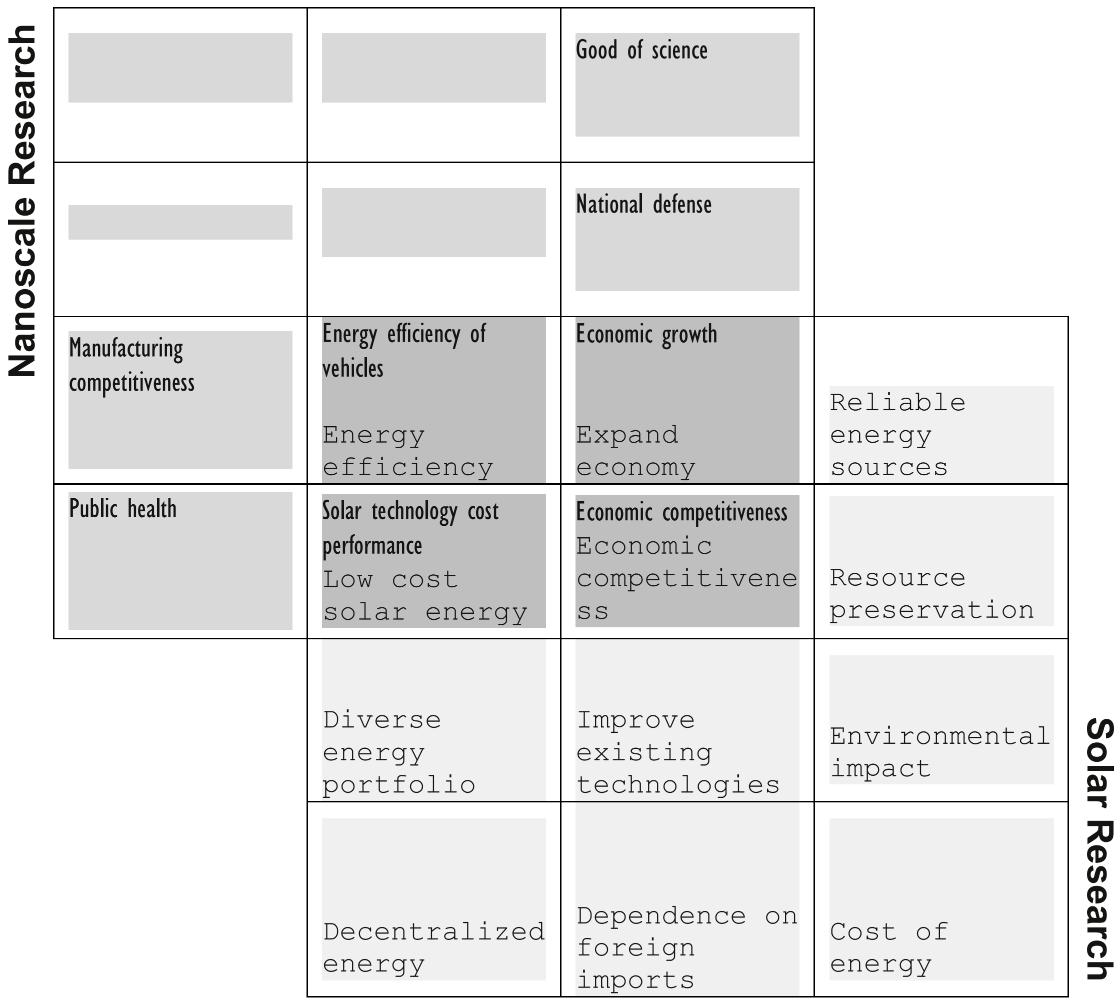

Figure 3: Public Policy Objectives for Nanoscale and Solar Research

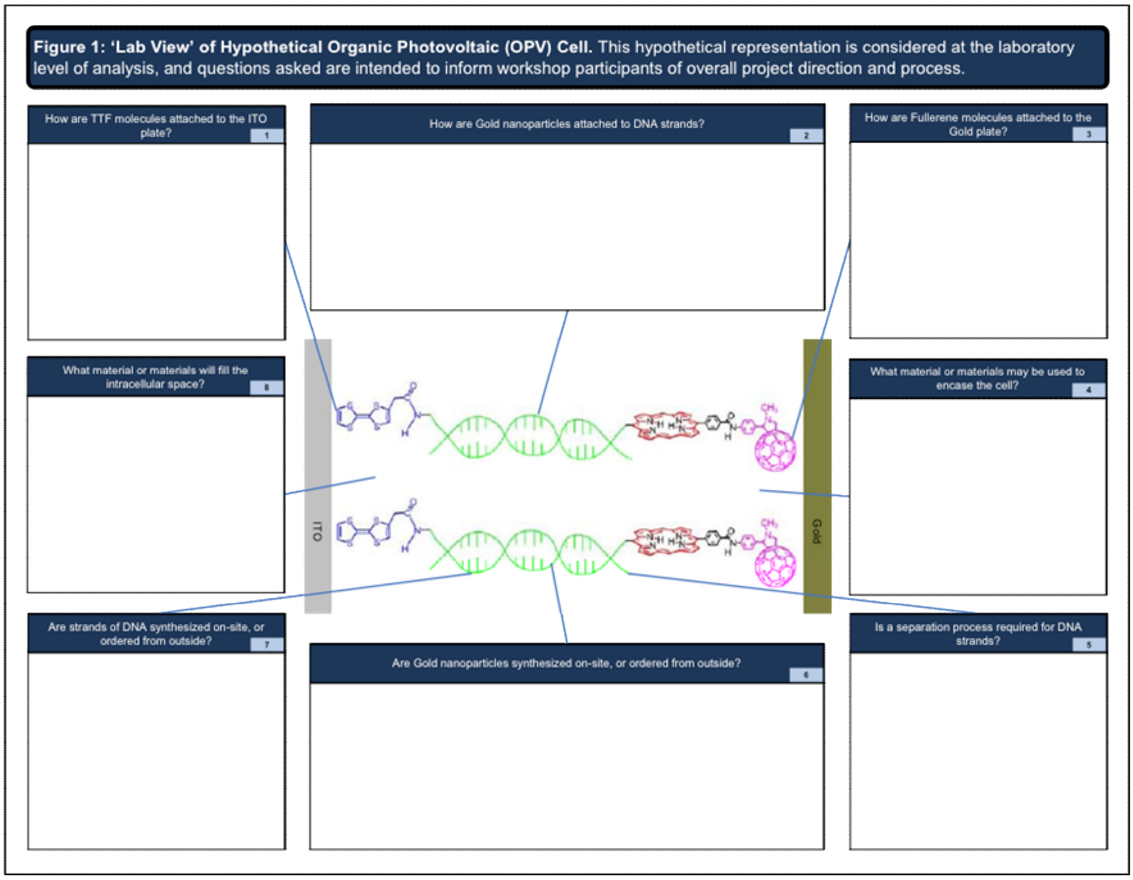

Figure 4: Lab View of Envisioned Device

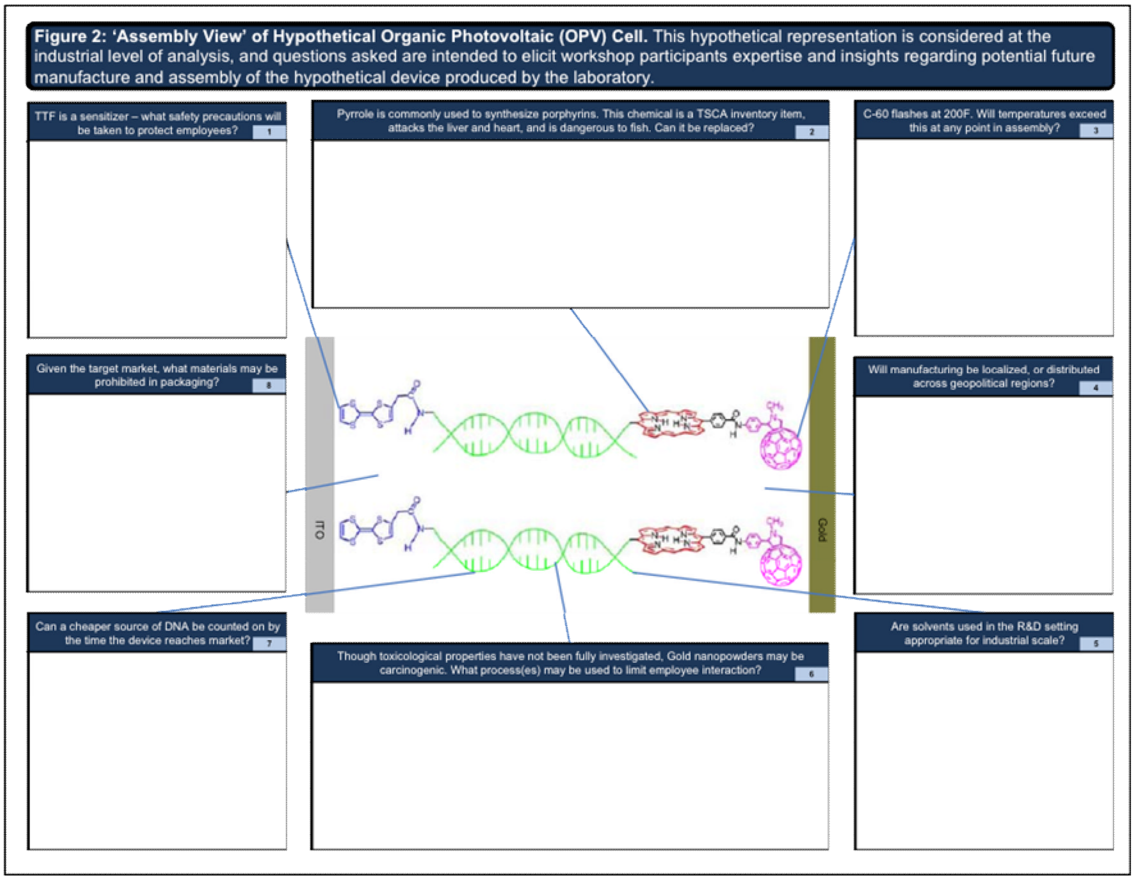

Figure 5: Assembly View of Envisioned Device

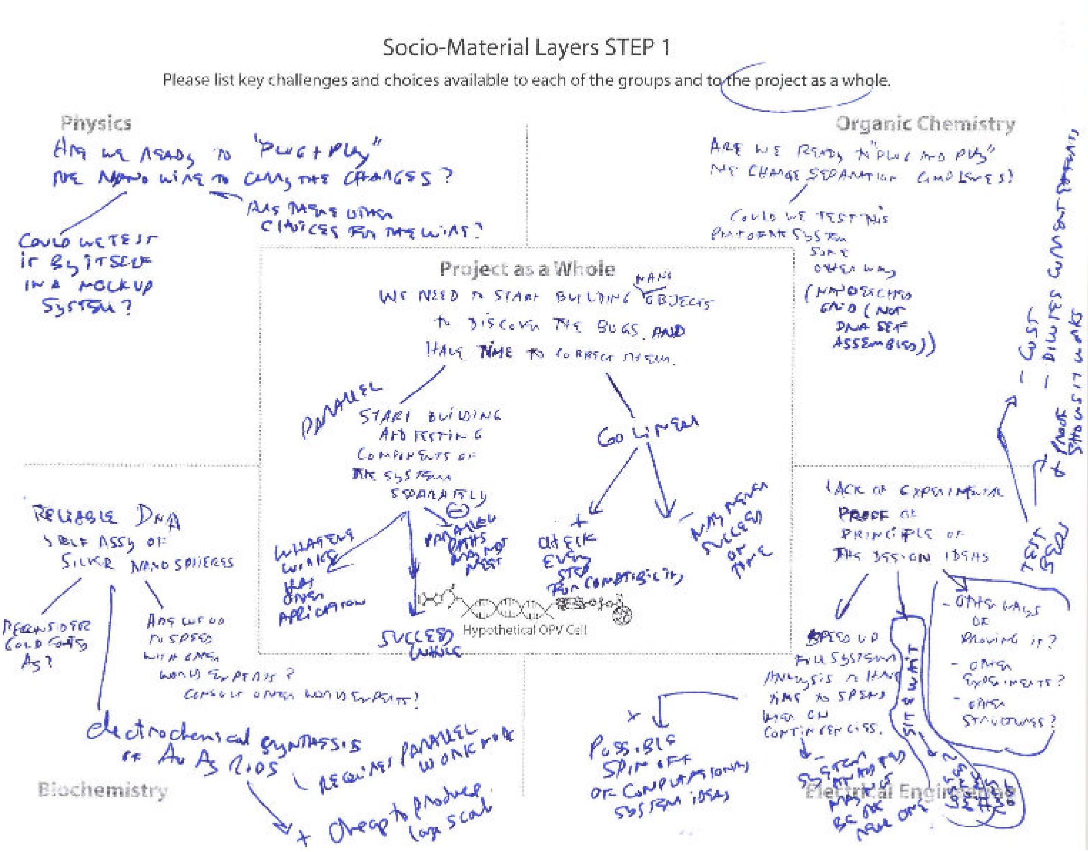

Figure 7: Public Value Challenge