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MIDSTREAM MODULATION OF NANOTECHNOLOGY RESEARCH IN AN ACADEMIC LABORATORY

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ABSTRACT

No clear implementation methods exist for US legislation on integrating societal considerations into nanotechnology research and development. An empirical study was thus undertaken to investigate the possibility and utility of "socio-technical integration" during nanoscale engineering research in an academic setting. For twelve weeks, an "embedded humanist" interacted with three graduate engineering researchers to identify and assess opportunities for influencing research decisions in accordance with societal concerns. The study focused not on the nature of societal concerns, but on the nature of engineering decisions, and on the potential capacity of researchers to perform integration by "modulating" their decisions. Engineering research decisions were found to be subject to societal influences, and researchers were found to become aware of the possibility of modulating their decisions accordingly. The interactions were not found to hamper research and were found to add value to research. No attempt was made to alter research decisions, only to stimulate awareness of the possibility of doing so. Still, one researcher did alter several decisions as a result of the study. Midstream modulation represents a promising approach for implementing US nanotechnology policy.

Ethics, midstream modulation, nanotechnology, policy, reflection, reflexivity, socio-technical integration.

BACKGROUND

US federal legislation mandates a challenging new approach to addressing societal concerns about nanotechnology. Rather than addressing them exclusively by traditional mechanisms such as product testing, product regulation, market performance, and public education, it requires broadening research and development (R&D) itself.

Nanotechnology Legislation

The *21st Century Nanotechnology Research and Development Act of 2003* requires "societal concerns…[to be] considered during the development of nanotechnology" by "insofar as possible, integrating research on societal, ethical, and environmental concerns with nanotechnology research and development" [1]. The House Science Committee report accompanying the Act stresses that such integration of societal and technological research is intended to "[influence] the direction of ongoing nanotechnology research and development of commercial applications" [2].

Policy Context

Policymakers worldwide are concerned that public perceptions of nanotechnology and lack of trust in regulatory regimes may undercut its projected economic benefits, as occurred with prior emerging technologies. Societal concerns about nanotechnology are not necessarily unique [3], and in many cases may come to nothing [4], but failure to consider them early may be unwise. A National Academy of Sciences review of the US National Nanotechnology Initiative (NNI) implied that "ignoring" societal concerns about nanotechnology could risk repeating nuclear and agricultural biotechnology public relations failures [5]. The report "recommended that the research on the societal implications of nanotechnology be integrated into nanotechnology research and development programs in general," according to a Congressional hearing charter on "Societal Implications of Nanotechnology" [6]. Public opinion surveys conducted after the Act's passage found a correlation between lack of trust and heightened perception of risk [7, 8]. Similarly, two UK bodies—the Royal Society and the Royal Academy of Engineering—recommended the early consideration of societal concerns about nanotechnology [9].

The NNI includes "responsible development of nanotechnology" among its four goals. It reports that activities that "incorporate research on societal implications" are underway "at some university-based nanotechnology centers" and that "such activities ensure that development takes place with an awareness of the societal impact of new technology" [10]. In 2005, the NSF established two Centers for

Nanotechnology in Society, one of which employs "Real-Time Technology Assessment" [11]. Given the potential weight of societal concerns about nanotechnology and the continuing attention being devoted to them, continued implementation of the Act's integration provisions is likely. Due to a lack of understanding of "how technical and social systems affect one another" [5], the eventual form of implementation remains largely uncertain.

Policy Precedents and Literature Review

The prescribed socio-technical integration is largely unprecedented and goes beyond traditional policy models [12-14]. Policies that bring societal considerations to bear on technological trajectories tend to occur either before ("upstream") or after ("downstream") R&D activities. The best known precedent for "self-critical federal science" is the Human Genome Project's Ethical, Legal, and Societal Implications (ELSI) program [15]. ELSI, however, failed to influence genomic R&D [16]. Institutional Review Boards for Human Subjects Research and the NSF's "broader relevance" criterion for proposals come closer to being "midstream" policy interventions. Neither, however, seeks to influence the direction of research once research has been authorized [17, 18].

Several bodies of literature study societal and ethical dimensions of science, engineering, and technology but provide no clear guidance for implementing the Act's integration provisions. Studies of normative influences on engineering processes [19-24] do not provide methods for engaging these influences at the level of research. One study documents the process of selecting an academic research project in accordance with explicit societal considerations [25]. Two approaches are known to exist for influencing technical projects in an ongoing manner: Constructive Technology Assessment (CTA) and Real-Time Technology Assessment (RTTA). CTA theorists use the term "modulation" to emphasize the importance of calibrating societal interventions to technology dynamics [26]. Developed in the Netherlands and currently being applied to nanotechnology [27], it inputs societal feedback into "the actual construction of technology" [28]. It is not known to have been applied at the level of engineering research. RTTA is being developed at the Center for Nanotechnology in Society at Arizona State University and seeks to "inform and support natural science and engineering research, and…provide an explicit mechanism for…influencing social values as they become embedded in innovations" [11].

PROJECT OVERVIEW

To investigate the feasibility of socio-technical integration during university based nanoscale engineering research, a decision protocol was regularly applied at different intervals to three research projects over a twelve-week period during the Spring of 2006. The study was intended to document and advance understanding about the capacity of engineering research to accommodate, and the role of engineering researchers to participate in integration activities. This understanding is meant as a foundation for developing and disseminating self-governance practices that might be further supplemented by societal research and eventually adopted as policies.

Rationale

Advancing understanding of socio-technical integration during engineering research is important for at least three reasons: effectiveness, value, and responsibility. Depending on the form taken, implementation of the Act's provisions could affect research funding, research conduct, and national policy goals. This study represents a proactive attempt on the part of the engineering community to develop internal methods for self-governance. Such methods are more likely to be in accordance with existing practices and conditions, and less likely to hamper research activities unnecessarily, than similar methods that are externally conceived and imposed. Additionally, socio-technical integration could add value to the societal aspects of engineering research—both inside and outside the lab—from issues of worker safety to sustainability. Finally, considering and addressing the broader implications of engineering activities can be considered an extension of engineering education responsibilities, at both undergraduate and graduate levels, and of professional responsibility.

Objectives

The general objectives of the study were (1) to investigate the empirical possibility for integrating societal considerations into nanotechnology research decisions; and (2) to ascertain the utility of doing so. Possibility was determined by verifying that, during the course of day-to-day research decisions, there exist *de facto* decision modulators including norms, values, expectations, and assumptions; and by attempting to stimulate *reflexive* awareness of such modulation during this same period. Utility was determined by researchers' views of the impacts of the study on their research activities.

Scope

We do not here consider the role of ethicists, social scientists, policymakers, or the general public in identifying, assessing, or promoting specific societal concerns. Similarly, we do not attempt to identify, assess, or promote any specific societal concerns.[1] While the study sought to stimulate *reflexive* modulation, we made no conscious attempt to alter research decision outcomes themselves.

THEORY

Ideally, integration will be seamless to maximize socially robust outcomes. Seamless integration would introduce broader considerations at every stage of a research project and make more explicit the extent to which such considerations are already implicitly present. It would require a tendency to remain open to questions and concerns and a willingness to revisit them at later stages. Due to practical constraints of engineering research, however, integration will usually be limited to opportunities for subtle modulation of ongoing processes.

[1] We assume that parallel or future societal research will identify the selection criteria by which societal concerns should be admitted for potential integration.

Midstream Modulation

To clarify the practical form that socio-technical integration would take, the framework of "midstream modulation" was developed as a policy instrument in line with CTA and RTTA. Modulation is an alternative to "top down" or external directives that seek to specifically control technological outcomes. Such directives can be ineffective since they fail to take into account actual dynamics of the contexts they seek to control [26]. Rather, modulation operates within the existing constrains of specific contexts [29]. As a policy instrument, midstream modulation (MM) is a means of incrementally influencing a technology during the "midstream" of its development trajectories. It thus asks *how* research is to be carried out, which is within the purview of engineering research, rather than *whether* a research project or product should be authorized, approved, or adopted, which is largely beyond the purview of engineering research. As an integral part of R&D activities, MM is a means by which research decisions might be monitored and broadened to take advantage of otherwise overlooked opportunities to weave societal factors into engineering decisions.

MM is theorized to occur in three main stages, which build upon one another: *de facto* modulation, in which research projects are shaped by a variety of both internal (cognitive) and external (social and physical) factors; *reflexive* modulation, in which researchers become aware of the role played by these factors, especially the cognitive and social ones, including their own position within larger interacting systems; and *goal-directed* modulation, by which researchers consciously alter their decisions in light of one or more specific societal goals or values that are identified by separate processes or agents.

Reflexive modulation, the awareness of internal and external influences upon one's decisions—including the fact that decisions are made in the first place—may or may not by itself lead to any particular form of *goal-directed* modulation. It was, however, posited to be a necessary and instrumental condition for *goal-directed* modulation. Thus, its presence (or absence) can be taken as one indicator of the possibility (or lack thereof) of socio-technical integration and of the normative influencing of engineering research.

METHODS

During a twelve-week period, three graduate researchers in the Department of Mechanical Engineering's Thermal and Nanotechnology Lab (TNL) at the University of Colorado were interacted with. Regular meetings consisting of semi-structured interviews were guided by an in-house decision protocol.

Research Participants

Three graduate engineering research members of the TNL collaborated in the study as volunteer research participants. Each was engaged with at least one major doctoral research project:

- Researcher 1 (R1): biomedical thermal probe
- Researcher 2 (R2): biomedical carbon nanotube device
- Researcher 3 (R3): carbon nanotube thermal application

The principal investigator was an "embedded humanist" with both humanities and policy research expertise, and who had been a member of the TNL research group for just over two years.

Decision Protocol

In order to characterize ongoing engineering research activities and measure the feasibly of influencing them by socio-technical integration, decisions were used as the units of analysis. Decisions were treated as ongoing processes that occur over time, often involve more than one decision maker, exist in various stages of completion or revision, and could be analyzed into discreet stages. Each engineering project was thus characterized as a series of iterative and evolving decisions, which could be further analyzed into decision components.

The Policy Sciences provides a framework for mapping and evaluating social contexts that are subject to policy intervention [30, 31]. Included in this framework is a model for decision processes that consists of seven interrelated and overlapping stages. This model had previously been employed to analyze engineering research projects in the TNL [32]. With the feedback of TNL researchers and social scientists, the seven stage process was adapted into a simpler four stage process meant to quickly and easily capture essential components of any research decision. This collaboratively developed model of engineering research decisions was applied both retrospectively and in real-time to track the evolution of engineering projects to investigate the extent to which socio-technical integration might be feasible.

The model took the form of a decision protocol that was used to as a basis for semi-structured interviews. The results were used to analyze ongoing decisions that researchers made or were considering on a regular basis over time. The protocol consisted of four decision components described here as follows:

- Opportunity: A state of affairs that requires or characterizes the need for a decision. Opportunity catalysts can be cognitive, social, or physical. Opportunities could take the form of a problem that requires a solution, an occasion to take advantage of, or any situation that warrants a response.

- Selectors: Potential internal (cognitive) or external (social or physical) influences that may act as drivers or constraints in determining the decision to be made. Cognitive and social selectors could include stated or implicit goals, values, concerns, expectations, or interpretations. Physical selectors could include equipment and resources; material properties and behaviors; and research data and results.

- Alternatives: Possible options for courses of action that are perceived and can be selected in order to respond to the opportunity.

- Outcome: The response to the opportunity, by means of choosing one or more of the alternatives, in light of one or more selectors. The outcome may be an initial, revised, or final response to the opportunity. Outcomes can be in various states of completion or anticipation and can occur in a distributed manner, over time and among various agents.

Meetings

The primary form of interactions between the "embedded humanist" (EH) and the research participants consisted of observing, discussing, and documenting the progress of research projects through regular meetings. Meetings lasted approximately 20-50 minutes. They consisted primarily of questions formulated to elicit the basic features of decisions made or about to be made by researchers, as outlined by the protocol, and the researchers' responses. Questions were meant to probe the potential flexibility of decision components.

For the duration of the study, the EH had different levels of regular meetings with the three researchers, as follows:

- R1: no meetings (no interaction)
- R2: monthly meetings (low interaction)
- R3: weekly and bi-weekly meetings (high interaction)

Additional Stimuli

As a member of the TNL research group, the EH also interacted informally with the researchers through being present in the TNL and the connected Nanoscale Fabrication and Characterization Laboratory. The EH's presence in these areas varied from two and a half to five hours per week, primarily in conversation with researchers and in attendance of weekly group meetings lasting two hours each.

To investigate the extent to which engineering research can feasibly respond to the prospect of socio-technical integration, it was deemed necessary to introduce sample potential concerns and questions about the societal implications of the engineering research being carried out. These samples were gathered from then current popular media accounts and policy developments, or were suggested by the research participants or members of the larger research group. They were viewed as hypothetical examples and potential opportunities to broaden research decisions. The samples ranged from environmental, health and safety (EHS) concerns to broader issues of privacy, access, and distribution.

Analysis

De facto modulation was measured by internal or external modulators that influenced research conduct, objectives, or outcomes. *Reflexive* modulation was measured by researcher awareness of *de facto* modulators and of decisions that they made or participated in. Such awareness is termed *reflexive*.

Pre- and post-program interviews were conducted to identify changes in *reflexive* awareness. Interview responses were analyzed by comparing references to potential internal (cognitive) modulators, potential external (social) modulators, and to the idea that choices are made during research. *Reflexive* awareness was taken to increase if awareness in any of these three areas increased.

Possibility was determined by gauging whether key decision components could be expanded via reflecting on engineering decisions in light of societal concerns. If decision selectors and/or decision alternatives could be broadened in this way, it was possible for research decision outcomes to be altered. Utility was determined by gauging the impacts of this study on research activities and outcomes, and by gauging the potential for such activities to influence research direction and outcomes.

Hypotheses

It was hypothesized that (1) research decisions would be found to admit of *de facto* modulation, in the form of either cognitive or social modulators, and thus to potentially admit of explicit influencing by means socio-technical integration. It was further hypothesized that (2) there would be a measurable increase in R3's *reflexive* awareness of the *de facto* modulators in which he played some role, including the decisions he made. Finally, it was conservatively hypothesized that (3) neither R2 nor R1 would show any increase in reflexivity.

- R1: No increase in reflexivity
- R2: No increase in reflexivity
- R3: Increase in reflexivity

RESULTS

All three forms of MM were found to have occurred.

De Facto Modulation

As hypothesized, *de facto* modulators were found to exist in various forms, including:

- Anticipated and unanticipated experimental results, and their interpretation
- Interactions with, and expectations of collaborators
- Unanticipated opportunities (proximity of otherwise unrelated research projects; productive delays; surreptitious observations; "random ideas")
- Timing
- Individual and institutional values and assumptions

Reflexive Modulation

Contrary to hypothesis, both R1 and R2 showed evidence of increased awareness in at least one of the three areas measured. In accordance with the hypothesis, R3 showed evidence of increased awareness, and did so in all three areas.

Researcher 1 In the pre-program interview, R1 had made no references to possible negative societal implications of his project. He also had made no references to any interactions that he might directly or indirectly have with wider social systems or agents. In the post-program interview, however, he stated, "[The device] may cause side effects, but [I] don't know. [I] will just research what [my collaborators] say has worked." Thus, he demonstrated an increase in awareness of both the possible relevance of societal concerns and the possible influence of collaborators on his research.

- Awareness of internal modulators: No change
- Awareness of external modulators: Increase

- Awareness of decisions: No change

Researcher 2 Contrary to hypothesis, R2 showed an increase in awareness, and did so in all three areas. For instance, with respect to internal modulators he stated, "I give a thought to it always now, earlier I did not." With respect to external modulators he stated, "[we] don't want to do anything bad to society in any manner." Finally, with respect to decisions and their components, he stated, "we should think before we make any decision"; he suggested that reflection "makes us aware of…any better options available"; and he noted the possibility of a "change the direction of our project."

- Awareness of internal modulators: Increase
- Awareness of external modulators: Increase
- Awareness of decisions: Increase

Researcher 3 In keeping with hypothesis, R3 showed an increase in awareness, and did so in all three areas. For instance, with respect to internal modulators he stated, "[I] don't have [a safer setup] now but [I] would like to have [one] in the future"; and "a little more care should be taken [in how carbon nanotubes are handled]. We have to change that." With respect to external modulators he stated that he "became more aware of…[the influence] interactions with others [can have upon research]." Finally, with respect to decisions and their components he stated that safety testing "needn't be done at the end [of a project]," and that it could be integrated earlier in the process so as to "make and test" in a more seamless manner. Additionally, he stated that the meetings and reflection they occasioned had an influence on research decisions during the project, stating, "otherwise, [carbon nanotubes would have been] just thrown in the trash," and that the research project "could have been a whole different thing."

- Awareness of internal modulators: Increase
- Awareness of external modulators: Increase
- Awareness of decisions: Increase

Goal-oriented Modulation

As R3's last responses indicate, the collaborations between the EH and himself seem to have influenced the direction of his research, even though such *goal-oriented* modulation was beyond the objectives of this study. Altered decision outcomes included:

- Developing a new disposal method for carbon nanotubes (there had existed no unique method for their disposal)
- Making a change in catalyst used for carbon nanotube synthesis (ferrofluid versus Ferrocene)
- Making a change in the experimental setup that was deemed safer than the previously established method (inserting a three way valve)
- Developing safety strategies for working with carbon nanotubes (there had existed none before)

These altered outcomes were presumably stimulated by the activities of the study. They are attributed to the *reflexive* modulation that was documented, since otherwise they would not (in the views of R3, the EH, and the TNL director) have occurred.

Possibility and Utility

Opportunities for expanding research decision selectors and alternatives were observed. Although attempts to act on these opportunities would have in most cases been beset by challenges, socio-technical integration was nevertheless deemed to be possible. Both R2 and R3 indicated that engineering research decision outcomes could be different as a result of applying the protocol to engineering research.

No discernable negative effects upon research conduct or outcomes as a result of the activities of this study were observed. Researcher participants were explicitly asked about the impacts of the activities of the study on their research. Their responses did not reveal any undesirable impacts, and suggested that the study added value to the research. The primary reason cited was that socio-technical integration enhanced the social value of research. Additionally, R3 noted on several occasions that discussing his research with the EH helped to clarify his own thinking about the research.

CONCLUSIONS

This study provides evidence of both the possibility and the utility of integrating societal considerations into and during nanoscale engineering research to influence research outcomes in accordance with public policy goals. A decision protocol, applied in the form of semi-structured interviews, stimulated graduate engineering researchers' awareness of cognitive and social research modulators. This awareness in turn led to specific cases where decisions were altered in accordance with societal concerns. The interactive methods of the study were not disruptive to research conduct and did not compromise its outputs.

Routine engineering research decisions allowed varying degrees of flexibility in expanding both decision selectors and decision alternatives. Due to the experimental and trial and error nature of research, however, decisions are in a continuous state of revision and transition, as is the thinking that goes into them. They occur in distributed, provisional, and parallel manners; are subject to multiple factors and uncertainties (participants, values, anticipated results and outputs, experimental results, timing, etc); and are often made in retrospect. Attempts to modulate research decisions with respect to societal concerns are thus themselves subject to revision and, to stay current with research evolution, would need to be continually updated and reconsidered.

A major challenge for socio-technical integration is that applications and consequences of research are extremely unclear. Much engineering research is aimed at producing enabling technologies that can be generically employed. Research can also be subject to lack of clarity about the immediate future. Accordingly, it is easier to address societal concerns that involve research processes, such as experimental procedures, rather than those that involve applications and end-user considerations. While opportunities for midstream modulation should probably be sought on an ongoing basis, it would often make sense to treat them provisionally until the trial and error of research runs its course and a clear set of alternatives emerges based on results, consultation, and objectives.

That said, midstream modulation of research processes can address immediate concerns of worker safety and exposure, and can identify and take advantage of opportunities to impact longer term outcomes. Further, it can instill the habit of reflecting on how decisions might be otherwise with respect to broader societal considerations. Pedagogically, while opportunities for *goal-directed* modulation may be infrequent, opportunities for building *reflexive* capacity abound.

In the early stages of the study, researchers were often unaware of internal and external modulators and also unaware of the very decisions they were making. The decision protocol and embedded collaborations, which were primarily aimed at asking questions, had "spin-off" value to the cognition of at least one researcher. *Reflexive* awareness may help researcher be more efficient and more effective insofar as it helps identify alternatives earlier and teases out additional alternatives that advance technical objectives. Implementation efforts should seek to maximize the "dual value" of socio-technical integration for both science and society.

The results of this study demonstrate that socio-technical integration during engineering research can occur in meaningful albeit incremental degrees. This opens the possibility that more aggressive or systematic collaborations or protocol employment can lead to more immediate and frequent results. The fact that *reflexive* awareness was enhanced largely by the simple yet sustained task of "holding out in the questionable" [33], and that these reflective activities led to different and possibly more desirable decision outcomes, speaks volumes for the capacity of engineering researchers to participate in socio-technical integration. Such activities can be employed for the sake of enhancing public trust in nanotechnology. Assuming socio-technical integration is both diligent and effective, such trust would be indeed warranted.

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APPENDIX: SAMPLE APPLICATION OF PROTOCOL

At the first meeting with R3, the protocol was retrospectively applied to a decision R3 made previously. His project involves carbon nanotube (CNT) synthesis in a Chemical Vapor Deposition reactor. Before beginning an experiment, the reactor must be tested for proper air pressure and for leaks. During his first dummy run, R3 discovered a leak in the reactor.

Opportunity: The reactor could not achieve the desired air pressure for an experiment; this problem was traced to a crack in the crystal tube used to encase catalyst and substrate samples.

Selectors: The need for a sealed chamber to maintain air pressure and contain chemical vapors.

Alternatives: Replace tube with a similar or identical one.

Outcome: Order a new crystal tube.

As indicated, the decision did not involve any conscious consideration of societal concerns, since none explicitly show up as “selectors.” Also, only one alternative was perceived at the time the decision was made. This was generally found to be the case for research decisions that were analyzed, although there were exceptions. What is of note, however, is that a leak in the system could easily lead to an explosion or to contamination of the atmosphere with CNTs and other potentially toxic material (EHS concerns). Thus, although societal concerns were not explicitly recognized at the time the decision was made, such considerations may nonetheless be present implicitly. Moreover, R3 later realized that at least one other alternative was available. Thus, as seen elsewhere, the protocol can potentially stimulate awareness of additional alternatives at an earlier stage.