Accurately Describing A Technology That Does Not Yet Exist

Mike Treder and Chris Phoenix

Introduction: The mission of the Center for Responsible Nanotechnology (CRN) is to raise awareness of the issues presented by advanced nanotechnology: the benefits and dangers, and the possibilities for responsible use. We explore the ethical, legal, and social implications (ELSI) of nanotechnology, and its potentially disruptive consequence, exponential general-purpose molecular manufacturing. The purpose of CRN is to educate those who will influence the use of nanotechnology, or be affected by it.

An important aspect of this educational process is to create 'theoretical, pictorial and textual representations' of what may become possible through nanoscale science and engineering (NSE), especially though molecular manufacturing. CRN studies, clarifies, and researches the issues involved—political, economic, military, humanitarian, and technological—and presents the results for both technical and popular audiences, working to supply the information as effectively as possible.

Our intention is to provide well-grounded and complete information, clear explanation, and workable proposals that support our vision of a world in which nanotechnology is widely used for productive and beneficial purposes, and where malicious uses are limited by effective administration of the technology.

This effort confronts numerous problems. Highly technical concepts must be explained to a non-technical audience, often in a text-only format. Our chosen topic of molecular manufacturing suffers from premature hype, premature debunking, and linguistic confusion resulting from the various meanings of the word ‘nanotechnology’. We struggle to maintain not only accuracy and simplicity, but also credibility and clarity. Meanwhile, we deal with uncertainty in scientific theory as well as in predictions of future actions and choices. Yet when the stakes may be so high, the effort is not only worthwhile, it is essential.

This paper reviews the process CRN follows in choosing how and what to describe as the likely results of our research into molecular manufacturing (CRN 2004). How do we select language that will be accurate, informative, and compelling, while promoting sensible and reasoned discussion? Is our strongest motivation to perform technical work and present unbiased results, or is it to develop and advocate for policy positions that support our mission? Can it be both?

As the lines between basic research, ethical responsibility, and advocacy are blurred and debated, it is important for anyone involved with NSE to ask themselves these questions. By examining and describing our own experience, we hope to shed some light on the subject.

Perspective: The first thing we, and perhaps anyone in a position similar to ours, must do is determine the perspective from which we will study a given field and report on our findings. Are we to be dispassionate observers, or concerned activists? The question is simple to pose but complicated to answer. It runs to the very nature of study and observation.

To begin with, can any observer stand fully outside of a subject field, or does the act of observation constitute an unavoidable involvement? We know that on the level of quantum physics, observation not only gathers information but also imparts it to the observed subject. Does this fundamental fact apply on a metaphorical basis to observers at the macro level?

But beyond these phenomenological questions, we must ask: What motivates us to engage in our analysis of nanotechnology and its societal implications? What preconceptions about these issues do we bring with us to the act of observation? What principles will guide us in analyzing and reporting our findings?

As we at CRN examine our motivations and practices (which is something we do on a regular basis), frequently we find that our preferred position is to be in the middle between opposing extremes. In this case, that means we do not view or present ourselves as completely dispassionate observers (if such a thing is even possible), nor do we desire to behave as or to be perceived as zealous activists. Rather, we hope to act and be accepted as informed, principled, interested analysts and, ultimately, effective advocates.

We approach the analysis of advanced nanotechnology armed with knowledge acquired through years of both specific and broad studies, of both a technical and general nature. Our current understanding has led us to certain conclusions that serve as motivation, but our principles also demand that we examine and consider arguments that may contradict our current understanding.

The major motivation behind our work at CRN is the conclusion that molecular manufacturing almost certainly will become a reality (through one of several technological avenues) within the next twenty years, and perhaps much sooner. Our studies suggest that this new general-purpose technology will have a significant impact across nearly all segments of society. It likely will be transformative, and could be highly disruptive.

If the technology does prove to be as powerful as we expect, it's easy to see that effective use of molecular manufacturing could be widely beneficial, and that unwise use could be highly dangerous. The extreme degree of the technology's potential will tempt extreme reactions and already is resulting in extreme proposed solutions. We are motivated, therefore, to research, propose, and advocate for policy positions that will allow for safe use of the technology while avoiding the societal damage—the human cost—of reactionary solutions. This approach often finds us pitted between those opposed to regulation in any form and those arguing for what we would consider to be unsupportably onerous restrictions.

Our conclusions about the potentially transformative and disruptive nature of molecular manufacturing are by no means widely accepted. It is far easier to find disagreement—sometimes vehement—from influential persons in government, business, and academia, than to find sympathy with our positions. Does this mean that we are wrong? Obviously, it does not, although of course it also does not mean that our conclusions are necessarily correct. The annals of history are replete with figures who struggled against the establishment until their iconoclastic ideas were finally proved correct, often posthumously. But there are doubtless many more persons lost to history whose unpopular ideas proved to be fallacious. So the unpopularity of our ideas does not signify anything about their correctness.

However, the fact that so many learned people are convinced we are wrong should lead us to carefully consider our positions and examine them for error.

Principles: Three particular principles are required for an effective examination of our positions. They are: 1) a dedication to the free exchange of information; 2) a desire for constructive dialogue with critics; and 3) a willingness to be wrong.

Of the three major types of organizations, Guardian, Commercial, and Information (Phoenix and Treder, 2003), CRN definitely is an Information-ethic organization. Our function is to produce information and publish it widely. Unlike Guardian institutions, we will attempt to be open about everything—hence a self-examining and revealing paper such as this one—unless there is an overwhelming reason to keep something secret. Unlike Commercial institutions, Information organizations are not focused on money; we view money as simply a means to an end. Our motivating principles include building a solid reputation, being known according to our work, and being distinguished by our unique contributions.

CRN operates on the belief that an understanding of future technical possibilities will be vital in order to prepare for smooth adoption and responsible use of new technologies, and to allocate research attention and funding appropriately. Estimates of nanotechnology's ultimate potential, and the timeline and cost for development, vary widely, to say the least. But information is power; only through intensive studies can we ensure that the developers and the future administrators of this powerful capability have the tools they need to make the right decisions. A detailed understanding of molecular manufacturing technology is necessary to prepare for its eventual development.

So we are dedicated to open exchange of information, we are motivated by the need for solid research to assist in the decision-making process, and we seek to understand opinions that differ from ours. We will admit when we are wrong and gladly will change our positions to something more clearly correct when that is indicated.

Presentation: With all this as background, we can address the specific issues of terminology and descriptive language chosen for use by the Center for Responsible Nanotechnology. In a recent email, CRN co-founder Chris Phoenix lamented:

> Perhaps we need to work on our communication skills. Whenever we propose anything, it seems like people hear it as suggesting the extreme, although that's usually not what we mean. A major meta-strategy of CRN is to be middle-of-the-road on almost everything, recognizing that extremes are very likely to be a bad idea for one reason or another. But somehow that message does not always come through clearly.

The challenge of selecting language involves not just technical accuracy but also effectiveness in communicating underlying ideas and intent. As noted above in the section on *Perspective*, CRN aims to be something between dispassionate observers and zealous activists. Similarly, we're trying to carve out a position between being "boosters" for nanotechnology, pushing for progress at all costs, and being "sentinels", raising awareness of potential dangers. We recognize the great promise of the technology to relieve human suffering and create unprecedented abundance, and we'll do whatever we can to bring that about. At the same time, it would be irresponsible of us not to study the inherent risks, report our findings, and suggest solutions.

Our internal debate over how to describe the field in which we work is instructive. We are called the Center for Responsible Nanotechnology—not molecular nanotechnology, or advanced nanotechnology, but simply nanotechnology. Is this an appropriate name, or is it misleading?

The word ‘nanotechnology’ has not yet acquired a common meaning. Widely disparate definitions can be found in dictionaries, organizational glossaries, and published documents on the Internet and in print. Usage of the term in science fiction, both credible and fantastic, along with the sometimes questionable adoption of the word by research facilities and companies seeking funding or investment contributes to this semantic dilution.

Because the main focus of CRN is on the results of a type of nanotechnology that may not exist for another decade or two, there could be some confusion if people think we are working to promote responsible use of present-day nanoscale sciences and products, such as paints, fabrics, coatings, or rocket fuels. Should we therefore have called ourselves the Center for Responsible Future Nanotechnology, Advanced Nanotechnology, or Molecular Nanotechnology?

A short name obviously is preferable over a long one. It also seems clear that to the large majority of people, ‘nanotechnology’ means something more exciting and futuristic than stain-resistant pants. It means—it is synonymous with—what we might more precisely call advanced nanotechnology or molecular nanotechnology.

In CRN’s early writings, during the first half of 2003, we made frequent use of the term ‘molecular nanotechnology’, and the abbreviation ‘MNT’. This was intended to distinguish our longer-term expectations for the field from the broader application of ‘nanotechnology’ that had become current as government funding was made available and applicants started labeling even mundane types of research as nanotechnology.

But around the middle of 2003, it became apparent to us that ‘MNT’ and ‘molecular nanotechnology’ possessed a negative connotation with many serious researchers. The terms were associated almost invariably with fantastic notions like bloodstream nanobots, true universal assemblers ("meat machines"), and theoretically ubiquitous "utility fog". Such concepts admittedly are fascinating to consider and someday may become reality, but they seem to be further in the future than are the middle-period developments that concern CRN.

Much of this connotative difficulty can be traced to the order in which Eric Drexler (who properly can be called the father of nanotechnology) introduced his concepts to the scientific community and the world at large. His first published book was *Engines of Creation* (Drexler 1986), in which he laid out the spectacular possibilities of this anticipated future technology, including "universal assemblers" that would "let us build almost anything that the laws of nature allow to exist". This promised the end of hunger, fine control of nature, mastery over space, and even glimpses of human immortality. *Engines* was a popular success and can be credited with inspiring many of today's nanoscale scientists, including Richard Smalley, to enter the field.

It wasn't until six years later that Drexler published *Nanosystems: Molecular Machinery, Manufacturing, and Computation* (Drexler 1992), a far more rigorous and detailed analysis of the science and technology that would be required to turn some of these far-out concepts into near-term reality. In *Nanosystems*, the focus was on the early stages of nanotechnology manufacturing and the tone was more sober and scholarly. Nevertheless, the die had already been cast, and Drexler hereafter was labeled by many in the scientific establishment as a visionary dreamer, and not someone to be taken seriously.

There are numerous critics of Drexler's ideas who only have read (or read about) *Engines of Creation* and never have studied *Nanosystems.* One wonders how things might be different today if the books had been published in the opposite order.

The words and phrases we use clearly will communicate more than just their particular meaning. Context and connotation also must be considered. As an example, every time we use the name 'Drexler' in a document, it has an effect on readers beyond simply being the name of a person. Depending on their awareness of the man and his work, and their opinion about it, inclusion of this name can in itself communicate significant meaning. The reader instantly may become favorably or unfavorably disposed toward CRN just by seeing the name, especially if it is used in context of which the reader strongly approves or disapproves.

Definitions: CRN's research is concentrated on what might be called the middle period of nanotechnology development, the point between today's non-manufacturing NSE technologies and the "sci-fi" visions of *Engines of Creation* (note again the recurring theme of being in the middle).

In response to the negative associations of 'molecular nanotechnology' and 'MNT' with visionary universal assemblers, we made an attempt in the latter half of 2003 to distinguish this middle period as dealing with a limited version of molecular nanotechnology, or LMNT. This was characterized as implementing just a tiny fraction of possible chemistry, aimed at achieving a limited molecular manufacturing capability based only on carbon lattice configurations—diamond, graphite, and fullerenes—known collectively as "diamondoid". We found, however, that although this is a useful and important distinction for technical writing, the meaning is too arcane and derivative for general usage.

Near the end of 2003, CRN decided to replace most usages of 'molecular nanotechnology' in our writing with 'molecular manufacturing'. This was thought wise not only to avoid the baggage associated with MNT but also to more specifically identify the period when large-scale manufacturing of products at the molecular level has become possible. To be more precise and descriptive, we sometimes will use the fuller phrase ‘exponential general-purpose molecular manufacturing’. Exponential refers to the capability of the technology to reproduce its own means of manufacturing (self-copying). General-purpose suggests that the technology has application across a broad spectrum of industries and hence will affect many segments of society.

Recently announced developments in nucleic acid engineering make it clear that our choice of the term ‘molecular manufacturing’ is a good one. CRN now defines molecular manufacturing as “any technology that implements digital operations, nanoscale construction, self-manufacture, programmable properties, and low error rates”, and this definition can apply to any technology—diamondoid or not—that meets all five criteria (Phoenix 2004).

Digital operations means that each manufacturing process has a well-defined discontinuity between success and error. If a certain design is constructed multiple times, the products that do not contain definite errors will be identical. This implies high reliability and predictability for the error-free copies.

Nanoscale construction means that the chemical building blocks can form, either singly or in combination, features in the 1-100 nanometer size range. Since no molecule is perfectly stiff, the physical arrangement of the features will not be perfectly precise. The permissible degree of uncertainty will depend on the application, but at least some physical coherence will be necessary for self-manufacture.

Self-manufacture means that the chemical system's range of designs must include devices that can contribute to the manufacture of other designs in the range. The functionality may range from flexible templating to nano-robotics doing pick-and-place operations. Self-manufacture may significantly lower the cost and increase the complexity of products, especially if it can be automated—which is made easier by digital operations and low error rates.

Programmable properties means that low-level designs can be specified or computed by describing higher-level features. Within a certain range, the design space will accommodate any specified feature without additional research. Essentially, this means that design rules and levels of abstraction can be used in the design process. A wide variety of features can be successfully specified without chemical research.

Low error rates means that the manufacturing process, and the subsequent operation of the products, has a usefully high success rate. Error rates may vary by many orders of magnitude. For example, a rate of 10^{-12} would be very poor for digital transistor logic, but a rate of 10^{-3} would be excellent for organic chemical synthesis. In general, an error rate per operation (e.g. per atom added to a product) of 10^{-9} to 10^{-12} may be adequate, though better rates may be achievable (Merkle 1997).

This new definition of molecular manufacturing is important and timely because nucleic acid engineering appears to be moving rapidly toward satisfying the five specified criteria (Shih et al 2004). It probably will be a few orders of magnitude less powerful than diamondoid, but still many orders ahead of today's manufacturing technologies. Until now, we have only had one technology—original Drexler-style MNT—to evaluate. But with two possible molecular manufacturing systems to compare, it's easier to talk about the performance tradeoffs of each technology.

Although no technology today qualifies as molecular manufacturing, each of the specified requirements is implemented in some currently existing technology, and at least two NSE technologies are developing rapidly toward a convergence of all five criteria. We now have a definitional framework with which to judge these and other new approaches that may be developed.

Conclusion: This paper has explained CRN's ongoing process of defining and describing our work. By carefully and repeatedly examining our terminology, we hope to succeed in walking the narrow middle line between dispassionate observation and zealous activism; between being boosters for nanotechnology and being sentinels. We aim to avoid being marginalized as irrelevant fanatics, and instead fulfill our chosen function as informed, principled, interested analysts and effective advocates for responsible use of nanotechnology.

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