Since Feynman’s 1959 lecture, “There’s Plenty of Room at the Bottom,” and particularly in the last 15 years, advances in instrumentation have permitted us to observe and characterize materials at atomic scale. New and even more powerful capabilities are rapidly becoming available. At the same time, our theoretical understanding and ability to model complex systems have matured to a level that enables us to begin making useful predictions in many areas, with the promise of further progress as we approach petascale computing. Progress in making and structuring nanoscale materials in commercially useful quantities is also being made, albeit more selectively. Exploiting chemistry and biochemistry to mimic nature’s accomplishments in living systems is a promising approach that is opening new possibilities. The remarkable progress of the last few years is already producing technological advances, and more can be expected as investments in nanoscience and nanotechnology increase. Just as advances in information technology during the second half of the 20th century produced dramatic technological, economic, and societal changes, so the coming nanoscale revolution will affect virtually every aspect of life in the 21st century.
I. INTRODUCTION

THROUGHOUT history, many of the improvements in the human condition have been enabled by advances in materials science and engineering. One notable recent example is our ability to make useful devices out of semiconducting materials at smaller and smaller scale. This ability underpins the information technology revolution that has transformed the world since the invention of the transistor in 1947.

This article deals with the remarkable progress of the last few years and the extraordinary potential of what is commonly described as nanoscience and nanotechnology. It addresses both the technological advances that I think are likely to follow and the societal impacts associated with these advances. I am firmly convinced that the impacts of nanotech will be fully on a scale with the impacts we have seen from information technology, or with what we expect from modern biology in the postgenome era.

In making these projections, I am cautioned by the fact that one of the best ways to look foolish in a decade or two is to make predictions about science and technology. Because of my own involvement in nuclear energy, I like to recall the prediction by Lewis Strauss, who as chair of the Atomic Energy Commission in 1954 offered that now famous quote that nuclear power would provide electricity that was “too cheap to meter.” As we all know, it hasn’t exactly turned out that way.

It’s also no accident that this is the second time in three years that nanotechnology has been the subject of the Distinguished Lecture in Materials and Society. In 2003, my friend Al Romig from Sandia National Laboratories gave an outstanding talk on this subject, in which he noted that “we are much closer to the beginning than the end of [the nanotechnology] journey.”[1] Although much has happened in the last two years, this is, of course, still true today.

I will begin with a review of Richard Feynman’s now famous lecture, “There’s Plenty of Room at the Bottom,” given at Cal Tech in 1959.[2] Starting with what is broadly viewed as the founding event for the field is not exactly novel—a GOOGLE* search on the words “Feynman” and nanotechnology produces tens of thousands of “hits.” However, I am focusing on the materials science elements of Feynman’s vision.

From my perspective, Feynman’s lecture lays out two very broad themes. The first theme has to do with the possibility of creating small machines that can do a variety of useful things, such as surgery inside small blood vessels. Feynman also proposed a notional method of building these devices by creating a machine capable of replicating itself at smaller scale. By coupling together a series of these machines so that each would replicate the actions of its next larger cousin, very small devices could be made. This part of the vision has captured the imagination of science fiction writers, with self-replicating nanomachines having been featured in the “Star Trek” television series, for example. It also shows up in some of the livelier public debate over the promise and perils of nanotechnology, as illustrated by the “gray goo” phrase popularized by Bill Joy while he was at Sun Microsystems.[3] Feynman recog-

nized the myriad of interesting technological challenges in the design and fabrication of machines on the scale of a human cell. And while there is a lot of work going on in this area, what can actually be achieved in practice is an active area of debate. Even though this is a fascinating topic, it is not one that I’ll dwell on today.

Rather, I will focus on the second of Feynman’s themes, which deals with the creation of new materials with remarkable new properties and transforming societal impacts. Feynman foresaw the ability to create novel materials through two strategies: (1) precise structuring of bulk materials, with atoms arranged as we want them; and (2) exploitation of quantum effects to make useful structures with small numbers of atoms. He presciently argued three points: (1) that we would be able to do these things as a result of advances in our ability to image and manipulate materials at the atomic scale; (2) that we would thus be able to create materials with a broad range of desirable and heretofore unobserved properties; and (3) that these materials would in turn enable dramatic technological, economic, and societal advances.

This is exactly the scenario that is playing out today. The potential of nano that Feynman predicted affords today’s materials scientists and engineers the ability to continue their longstanding tradition of advancing the human condition. However, this time we will be doing it one atom at a time.

II. NANO IS TRULY DIFFERENT!

Working at the nanoscale is truly different from traditional materials science. From a theoretical point of view, there are several reasons for this. Quantum effects do indeed become important at this scale. The electronic structure and chemical behavior of materials change as dimensions become comparable to length scales characteristic of electronic wave functions or of transport phenomena. The fraction of atoms at or near the surface becomes much larger as we move to smaller structure, so surface atoms begin to define bulk properties. Table I indicates the surface fractions for nanoscale clusters compared to roughly a microgram of material.

In practice, there is a more useful way of looking at this question of why working at the nanoscale is really different. Simply put, materials properties emerge at the nanoscale. The nanoscale structure begins to define bulk materials properties. Therefore, the ability to determine structure at the nanoscale allows us to create, control, and tune material properties in a way not previously possible. Three examples from three different materials domains show that working at the nanoscale makes as big a difference as I’ve suggested.

The first example may strike many readers as “old hat”—improving the properties of steel alloys. In fact, we’ve all seen a lot of relabeling going on just to cash in on interest in nanoscience. We have been using the “nano” prefix for a couple of decades because we know that is where much of the action is—both in funding agencies and in the marketplace. Nonetheless, we are actually seeing significant improvements in areas such as alloy development that draw on our knowledge of nanosize particles. Materials scientists have been working on improving steels for high-temperature applications for a very long time.

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