The Problem of a Common Understanding of Nanotechnology

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Reading Feynman Into Nanotechnology: A Text for a New Science

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Abstract
As histories of nanotechnology are created, one question arises repeatedly: how influential ‹ Richard Feynman's 1959 talk, "There's Plenty of Room at the Bottom"? It is often said knowledgeable people that this talk was the origin of nanotech. It *preceded* events like invention of the scanning tunneling microscope, but did it inspire scientists to do things t would not have done otherwise? Did Feynman's paper directly influence important scient developments in nanotechnology? Or is his paper being retroactively read into the history nanotechnology? To explore those questions, I trace the history of "Plenty of Room," includ its publication and republication, its record of citations in scientific literature, and the comm of eight luminaries of nanotechnology. This biography of a text and its life among other t enables us to articulate Feynman's paper with the history of nanotechnology in new ways a explores how Feynman's paper is read.

Keywords: Feynman; nanotechnology; history of technology

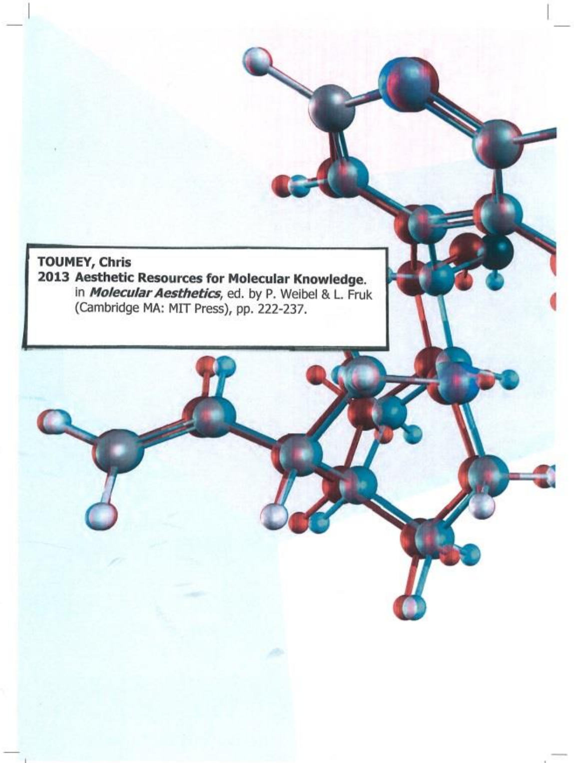
Introduction

I imagine that humanists must often look with envy at those who emend or expose a w established historical fact. Think of those who have shown that a fact is not really fact Lorenzo Valla, for example, debunking the "Donation of Constantine" in the fifteenth century using textual analysis.

Much more rare is the opportunity to emend the facts of the recent history of science. Beca these facts have been written not long ago, they lack the hoary status of myths to be exposed such. In addition, we expect the recent history of science to be well grounded empirically history, and well grounded empirically in science. So the potential for mischief with the rec history of science is slimmer than for other kinds of history, isn't it?

Take, for example, one well-established point about the origin of nanotechnology. Richard Feynman's 1959 talk to the American Physical Society, "There's Plenty of Room at the Botto (Feynman 1960a), preceded numerous crucial events that made nanotechnology possi including the invention of the scanning tunneling microscope, the atomic force microscope, the Eigler-Schweizer experiment of precisely manipulating thirty-five xenon atoms. Th inventions and other events led to nanolithography, computers with nanoscale components, precise control of individual atoms, and other developments that Feynman called for in Decem 1959. It is easy to see why people say that "Plenty of Room" was the ur-text that sta nanotech:

- Eric Drexler says that "The revolutionary Feynman vision … launched the glo nanotechnology race" (Drexler 2004:21).



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Nanotechnology Controversies

Chris Toumey

Nanotechnology is an arena for multiple scientific and social controversies. I will give reasons for this, including some reasons generated by social forces and cultural values, and some that reflect the scientific character of nanotechnology. First, however, we should begin with a working definition of this field.

Everything is made of molecules, and molecules are assemblages of atoms. This has been known for well over a century, but the behavior of individual atoms and molecules was extraordinarily difficult to observe for many decades. One can predict with great confidence how they behave in large quantities—in bulk, so to speak—and then draw inferences about how an individual atom or molecule will behave. But matter at that scale could seldom be observed at the level of individual atoms or molecules. Electron microscopes, originally invented in the 1930s, gradually became more powerful, enabling scientists to sometimes see images of units of matter like viruses, molecules, and occasionally even individual atoms. But the instrument that gave scientists a consistently good view of an atomic surface, and the objects on it, was the scanning tunneling microscope, invented in 1981. This and a related instrument, the atomic force microscope, produced detailed images of atomic surfaces, including individual atoms, and larger objects like molecules and viruses.

All of these objects are measured by the nanometer, that is, one billionth of a meter. The hydrogen atom, for example, is 0.1 nanometer thesis

Elegance and empiricism

C_{60} was discovered in 1985 but it took five years to confirm that this famous molecule was spherical. **Chris Toumey** revisits a debate that highlighted different approaches to science.

The best scientific explanations satisfy two standards at the same time: they are elegant and they are empirically substantiated. When a theory or a model explains a phenomenon clearly, directly and economically, we say it is elegant: one idea, easy to understand, can account for a large amount of data and answer many questions. The empirical qualities of an explanation are complementary but different, with multiple lines of evidence leading to a hypothesis that can be independently tested by other scientists.

Now, on the twenty-fifth anniversary of the discovery of the C_{60} molecule, we can revisit a case in which those two standards were separated. In the beginning this discovery had all the elegance that one could ask for, but not nearly enough empirical substantiation. Regarding the structure of the molecule, the five-person team that discovered C_{60} made a strong argument based on a logic that was as elegant as any in science. A different team challenged that explanation, not by offering an equally elegant alternative explanation, but rather by building a series of empirical arguments. And so, for a five-year period between 1985 and 1990, elegance and empiricism were pitted against each other in a contest to explain the structure of the newly discovered molecule. Let us revisit this story as a play in four acts.

Act I: Early days In 1966, David Jones speculated about "a closed spherical shell" of carbon hexagons, 100 nm in diameter, "resilient like little footballs"[1]. Four years later, Eiji Osawa theorized a truncated icosahedron of 60 carbon atoms that would be extremely stable. This was C_{60} as we now know it, but Osawa declined to pursue this possibility beyond presenting his initial vision. At the same time, he says, several Russian scientists imagined the same thing[2]. And in 1984 Andrew Kaldor and co-workers at the Exxon Corporate Research Lab created a series of carbon clusters of different masses by turning graphite to plasma and then cooling the plasma. Their mass spectrometry results included distinct peaks that corresponded to clusters containing up to about 100 carbon atoms, including clusters containing 60 and 70 atoms[3]. (Above about 30 atoms there were only peaks for clusters containing an even number of carbon atoms.)

Act II: September 1985 At the University of Sussex, Harold Kroto was investigating linear carbon molecules in interstellar space. He had a theory that these structures assembled themselves inside red stars and then stabilized in the coldness of space, and he hoped to model this process in a laboratory procedure. Richard Smalley at Rice University had an instrument called AP2 that could create a carbon plasma, cool it, and then detect the molecular structures that were produced. Smalley and Kroto, along with three other Rice researchers — Robert Curl, James Heath and Sean O'Brien — were recreating the work done previously by the Exxon group, although for different reasons. (Smalley and Kaldor had collaborated on other projects in the past, and the AP3 instrument used in the carbon-cluster experiments at Exxon[3] had actually been built at Rice[4,5].)

Smalley and co-workers also noticed sharp peaks of clusters of 60 and 70 carbon atoms. However, unlike the Exxon group, they concentrated on these two forms, and refined their procedure to create a large quantity of the 60-atom clusters, a lesser quantity of 70-atom clusters, and only negligible amounts of other clusters. If the 60-atom structure was as plentiful and stable as it seemed to be, what could be its shape? Inspired by the geodesic domes designed by the architect Buckminster Fuller, Smalley and Kroto

The paper reporting the discovery of C_{60} — complete with a photograph of "a football (in the United States, a soccerball) on Texas grass" — was received by *Nature* on 13 September 1985 and published on 14 November 1985 (ref. 6).

asked themselves whether it might be a closed sp… and pent… paper m… cardboar… that the… be an ico… hexagon… on a foo… some im… chemistr… Their… the disco… of scient… "equilibr… species", shape wa… symmetr… which is… bonded t… leaving n… made se… conditio… peak tha… the year… perform… new disc… lanthanu…

Act III: I… elegant, t… the icosa… be strong… an image… scanning…

thesis

Why do we see history so differently?

Chris Toumey illustrates how different groups of people involved with nanotechnology have different views on the history of the field and feel differently about its importance.

How important is it to know the history of nanotechnology? In the humanities and social sciences, the answer is simple: it is always good to know one's history. Always good to know what was done right and what was done wrong, and why, so that we can make good choices today. Sometimes we have superb work in the history of science and technology. Other times we do not. Regardless, the desideratum remains. We benefit by knowing how we got to where we are.

If so, then the next question is how does one know the history of nanotech? Do the people who examine this story disseminate their findings to the scientists and engineers who make nanotech happen?

In 2015–2016, I had a grant from the US National Science Foundation to examine whether research on certain topics in nanotechnology by persons in the humanities and social sciences actually reached the scientists, engineers and others who work in the field. One of those topics was the history of nanotechnology. My graduate research assistant Meagan Conway and I interviewed 60 people in four populations who work in nanotech.

The first group consisted of academic scientists and engineers who conducted research in nanotechnology. Of those with an interest in the history of nanotech, most were tightly focused on history related to their own research, for example, the discovery of the C_{60} molecule for some, or the story of quantum dots for others, or carbon nanotubes, or the origin of Moore's law, for those in microelectronics. Another focus was the development of nanotech policy within the US government, leading to the National Nanotechnology Initiative.

When some of these interviewees possessed a broader sense of the history of nanotech, they usually said that nanotechnology was anchored in Richard Feynman's 1959 talk, 'There's plenty of room at the bottom'[1]. And then a few added the influence of Eric Drexler's 1986 book, *Engines of Creation*[2], to this history.

Then again, one person said this: "I don't see how it will be useable for me. We are doing basic research. The aspects of how that research affects society, is not that it is not important, but it's not really our concern."

Similarly, another said that, "I don't think you are going to find very many research scientists who are going to be seeking out the literature, the scholarly literature, in the areas you are asking about."

One noted that it would be desirable to have "a cogent history of nanotechnology, which doesn't exist. If you come to me, I'll give you one story. If you go to somebody else, they will give you another story. And it will be heavily dependent on personal experience."

Our second group comprised persons in US government science policy, for example, programme directors who served as liaisons from their agencies to the National Nanotechnology Initiative. All had solid credentials in science or engineering.

We found that this population is more informed than the others about the history and development of nanotechnology. There are two reasons. First, these officials often have a responsibility to explain nanotechnology to others. Their superiors and colleagues in their agencies make up one audience; another consists of interest groups that want to know what their agency was doing, and why.

In both situations, they have an instinct to include a history of nanotechnology in their explanations. "It's helpful to have a broader understanding of what you're talking about when you go into a meeting," said one of the government scientists, and another added that, "I tend to work history into most of my briefings. I like to note that control at the nanoscale has a long history." I especially like the idea that, in the words of one person we interviewed, "you don't know the field if you don't know that stuff."

A second reason is that agencies affiliated with the National Nanotechnology Initiative need to measure progress and report it from year to year. "We know what we have accomplished in the past ten years. And we use that as landmarks," said one of the interviewees in the government.

Their knowledge of the history of nanotech centres largely on the origin and development of the National Nanotechnology Initiative. For this they speak of the work of Mike Roco, the engineer who is more responsible than anyone else for bringing the importance

of nanotechnology t… government agencie… multiple times to Ri… talk. Some also note… historical work fron… social sciences, for e… account of the inver… tunnelling microsco… force microscope[3].

Our next group … scientists and engin… ups, that is, the peo… knowledge from aca… applications. Some … others are recent Ph… their sense of the hi… similar to that of th… and engineers: most… development of the… they worked, such a… quantum dots that … light-emitting diod…

Furthermore, th… more general histor… had little or no valu… not actively seeking… philosophical quest… It's hard for me to se… impact what we do,' … interviewees. And a… "making it pertinen… will come across it I… my business."

Another perspec… the persons in start-… nanotechnology is t… for anyone to know… detail. "There is no … nanotechnology tha… words of one entrep… tends to drift towar… buckyballs and qua… the industry is goin… good point, I thoug…

There was also a… some interviewees t… scientific research a… have a very long his… decades, but that or… histories been subsu… nanotechnology. Ar…

I hope this does… people in nanotech…

thesis

Denominational interpretations of nanotech

Religious people tend to have a different view of nanotechnology than non-religious people. **Chris Toumey** explores whether there are also different views between different religious groups.

In 2009, two studies from the University of Wisconsin indicated that when religious people turn their attention to passing judgement on nanotechnology — if they ever do so — they rely upon their beliefs rather than the scientific content of nanotech[1,2]. They may have previously used those beliefs to judge the genetic modification of organisms or other topics, in which case they have ready-made templates for judging nanotech. These studies also indicated that the more religious a population was, the more uncomfortable it was with nanotech.

My sense of this conclusion is that nanotechnology constitutes an immensely dense scientific topic for non-scientists to master. Nanotechnology includes atomic physics and subatomic physics, organic and inorganic chemistry, molecular biology, microelectronics, plus materials science and other scientific disciplines and subdisciplines, not to mention technologies such as scanning probe microscopy and electron beam microscopy.

Other topics of science and technology are less dense and thus more accessible. One can craft an informed understanding of how a nuclear power plant works when a reactor is going to be built upwind of one's community, or whether local farmers should have the prerogative to grow genetically engineered crops. But it is more problematic to pass judgment on nanotechnology because the scientific knowledge is so rich.

Some nations are more religious than others. The United States, for example, is consistently more religious than most other industrialized countries. The more secular nations, especially Germany, the Netherlands and Scandinavian countries, are less likely to employ religious belief to shape their judgments of science, including nanotechnology.

On the assumption that religious templates are going to shape some non-scientists' perceptions of nanotech, and that different faith traditions have different values for judging science and technology, I collected a series of thoughtful and informed religious statements about nanotechnology. These statements included Lutheran, Catholic, Muslim, Buddhist and other religious views[3,4]. Jameson Wetmore also contributed much to the study of religious reactions to nanotech[5,6].

And yet there is still a question of whether religious believers know the texts about science and technology that are written by the leaders of their faith, like the ones we collected for nanotech, and whether those texts guide their judgments.

With these questions in mind, I received a grant from the US National Science Foundation to conduct a modest pilot study of denominational interpretations of nanotechnology. My graduate research assistant, Colin Townsend, and I recruited four Lutheran and three Baptist congregations based in Columbia, South Carolina, to explore religious reactions to nanotech.

We had a reason for this combination. The Evangelical Lutheran Church in America (ELCA) is the largest Lutheran denomination in the US. It devotes much attention to issues of faith and society, and it produces a series of documents on science and technology. We chose three Baptist congregations to discern whether African-American Baptists might differ from European-American Baptists when the members learned more about nanotech and then judged it in terms of their Baptist beliefs. (On this topic, there were no significant differences between the beliefs of African-American and European-American Baptists.)

For each of the seven congregations, we asked a contact person to form a group of 12 to 15 members. We provided each participant with a package of readable articles on three topics: an introduction to nanotechnology, applications for nanomedicine, and environmental issues in nanotech. We then met three times with each group, with each session dedicated to one of the three topics. The moderator had a light touch, asking questions such as: What do you think of the topic? What do you think are the ethical issues for this facet of nanotechnology? And, do your views reflect your denominational affiliation, that is, Baptist or Lutheran?

In other words, we hoped to discover whether there were denominational variations within religious reactions to nanotechnology. It was not enough for us to say that all religious people feel one way and secular people feel another way. On the contrary, religion is interesting because one faith community has a sense of what is real and what is good, and another faith community might see those topics differently. Not all religious people see reality the same way. Below is a brief report of what we learned from that work.

First, we found that the Baptist and Lutheran groups shared two particular concerns about nanotechnology. One was whether nanotech would cause environmental harm. Consider these two comments:

"To me, nanotechnology seems like a deeper manipulation of controlling the environment."

"I never thought about how toxic nanomaterials could be. The end product is what you do with it and how to clean it up. Too small to measure and detect, you could be creating something even more dangerous."

The second concern that Baptists and Lutherans had in common was control of nanotechnology:

"I think the biggest issue is who is going to be in control. Government isn't dependable and shouldn't be because it's run by humans. Would it be a group with a diverse background or just people in power?"

"Who has control over all this? Is there a governing body that controls it, or is everybody out there doing their own thing?"

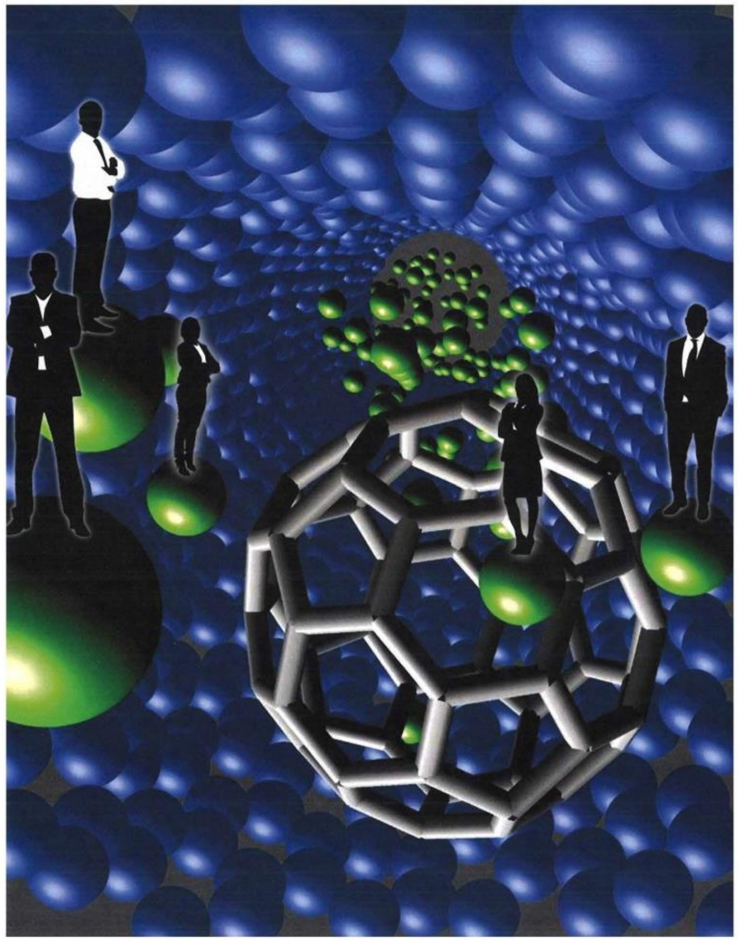
"Who has control — government or business?"

The most interesting result of this research was a difference between Lutheran and Baptist judgments about nanotechnology in general. The Lutherans were cautiously favourable to the development of nanotech, even with their concerns about control and environmental harm. Repeatedly, they said that science and technology are generally good, for example, "I think the ELCA is friendly to science in general" and "In the Lutheran faith we tend to embrace technology as being God-directed, so we are more accepting of it in that way."

This makes sense in light of a core principle of Lutheran belief, namely,

NANOTECH AND THE HUMANITIES

AN ANTHROPOLOGIST OBSERVES THE SCIENCE OF ATOMS AND MOLECULES



CHRIS TOUMEY


Dylan Connell


EVOLUTION ONE

Bielefeld DE, May 2005:

Graduate student in Philosophy tells us "There is no stable definition of nanotechnology!"

Uh-oh

Next speaker: eminent physicist said that the philosopher’s remark was nonsense:

scientists working in nanotech

know what nanotech is.

A question:

Do we have a common understanding of nanotechnology; and if not, why not?

If not, I have four reasons why not.

But we can use these four reasons to better understand nanotechnology.

First reason:

Nanotech is not a single technology or process.

Instead, it is a large group of scientific and engineering disciplines and subdisciplines,

Plus several technologies.

Atomic physics; subatomic [quantum] physics;
organic chemistry; inorganic chemistry;
molecular biology;
microelectronics;
materials science;
scanning probe microscopy;
electron beam microscopy;
etc., etc., etc.

Second reason:

There are some applications from nanotech that are available now, but most of its applications are in the future.

Near future? Microelectronics; perhaps targeted cancer therapies.

Far future? Molecular assemblers? Billions of self-replicating nanobots?

Realistic? Fantastic?

Lesson: different people can project different expectations onto nanotechnology.

Third reason:

Nanotech is not a single technology or a single process. Instead, it is a generalized, multi-purpose technology platform, like the assembly line.

Lesson: nanotech means different things to different people.

Fourth reason:

What we mean by "nanotechnology" may depend on how we tell the story of the origin and history of nanotechnology.

Not a technical reason, but an historical reason.

First account of the origin and development of nanotech:

Nanotech begins with Richard Feynman’s 1959 talk, “There’s Plenty of Room at the Bottom”.

Implications: nanotech centered on quantum physics.

Problem: Feynman’s talk largely invisible between 1959 and 1979.

Second account: Nanotech begins in 1974 when Norio Tanaguchi introduces the term “nano-technology”

Question: did other scientists make contributions to nanotech because of Tanaguchi’s paper?

Maybe, maybe not.

Third account:

Nanotech begins with Eric Drexler's 1986 book, *Engines of Creation*.

Problem: based on far-future fantasies like nanobots out of control ["gray goo"] and molecular assemblers.

Problem: very few scientists working in nanotech embrace this vision.

Fourth account:

Nanotech begins with the 1981 invention of the Scanning Tunneling Microscope and the 1986 invention of the Atomic Force Microscope.

Note that this means that nanotech began at IBM.

And, nanotech is driven by the invention of certain instruments, rather than by visionary statements.

Fifth Account: nanotech takes off with the Eigler-Schweizer experiment

Not exactly the origin of nanotech, but a demonstration that individual atoms can be controlled and moved.

Again, gives credit to IBM and reinforces the idea that IBM is the engine that drives nanotech.

November 1989: STM chamber at 4 degrees K at IBM Almaden in San Jose CA;

Xenon atoms on a nickel surface;

Over 22 hours, 35 atoms moved into a new pattern.

Published in *Nature*, 5 April 1990.

Positioning single atoms with a scanning tunnelling microscope

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SINCE its invention in the early 1980s by Binnig and Rohrer[1,2], the scanning tunnelling microscope (STM) has provided images of surfaces and adsorbed atoms and molecules with unprecedented resolution. The STM has also been used to modify surfaces, for example by locally pinning molecules to a surface[3] and by transfer of an atom from the STM tip to the surface[4]. Here we report the use of the STM at low temperatures (4 K) to position individual xenon atoms on a single-crystal nickel surface with atomic precision. This capacity has allowed us to fabricate rudimentary structures of our own design, atom by atom. The processes we describe are in principle applicable to molecules also. In view of the device-like characteristics reported for single atoms on surfaces[5,6], the possibilities for perhaps the ultimate in device miniaturization are evident.

The tip of an STM always exerts a finite force on an adsorbate atom. This force contains both Van der Waals and electrostatic contributions. By adjusting the position and the voltage of the tip we may tune both the magnitude and direction of this force. This, taken together with the fact that it generally requires less force to move an atom along a surface than to pull it away from the surface, makes it possible to set these parameters such that the STM tip can pull an atom across a surface while the atom remains bound to the surface. Our decision to study xenon on nickel (110) was dictated by the requirement that the corrugations in the surface potential be sufficiently large for the xenon atoms to be imaged without inadvertently moving them, yet sufficiently small that, when desired, enough lateral force could be exerted to move xenon atoms across the surface.

The experiments were performed using an STM contained in an ultra-high-vacuum system and cooled to 4 K. The entire

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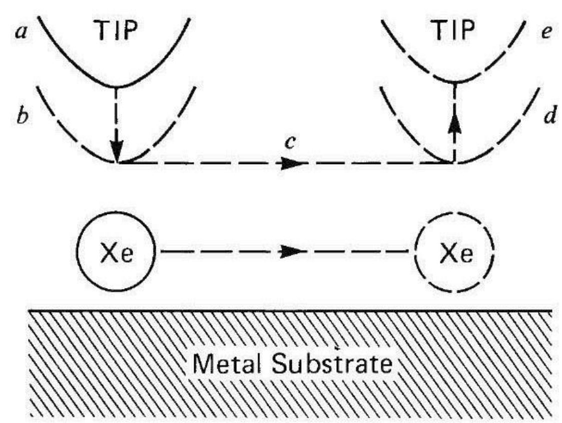

FIG. 2 A schematic illustration of the process for sliding an atom across a surface. The atom is located and the tip is placed directly over it (*a*). The tip is lowered to position (*b*), where the atom–tip attractive force is sufficient to keep the atom located beneath the tip when the tip is subsequently moved across the surface (*c*) to the desired destination (*d*). Finally, the tip is withdrawn to a position (*e*) where the atom–tip interaction is negligible, leaving the atom bound to the surface at a new location.

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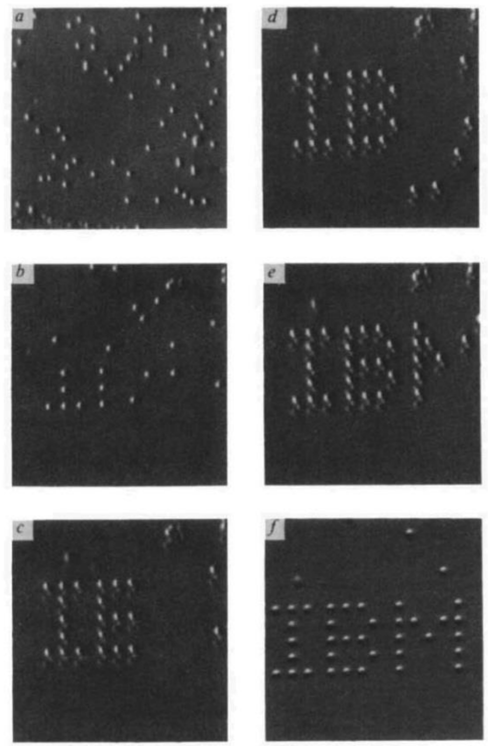
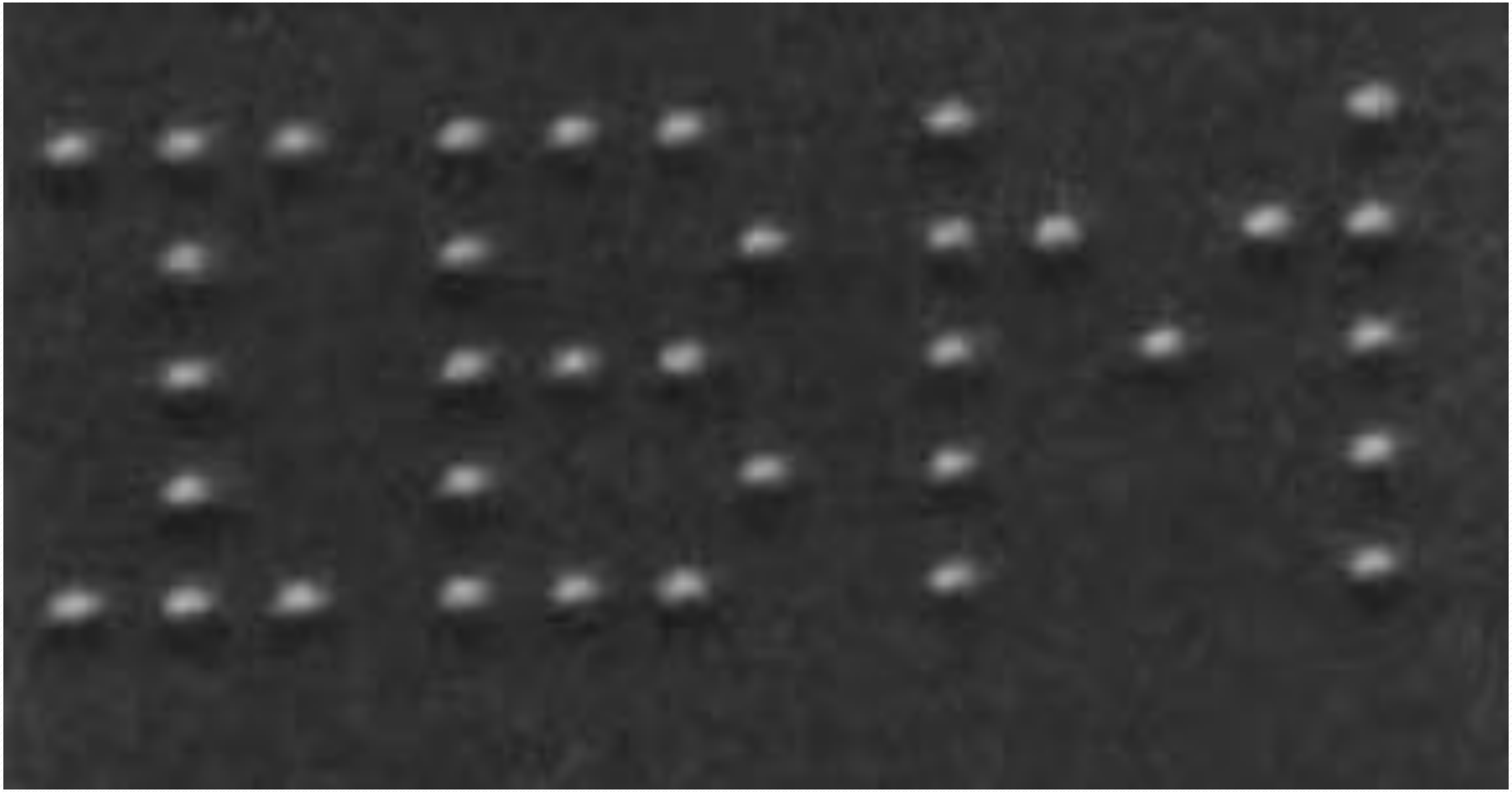


FIG. 1 A sequence of STM images taken during the construction of a patterned array of xenon atoms on a nickel (110) surface. Grey scale is assigned according to the slope of the surface. The atomic structure of the nickel surface is not resolved. The $\langle 1\bar{1}0 \rangle$ direction runs vertically. *a*, The surface after xenon dosing. *b*–*f*, Various stages during the construction. Each letter is 50 Å from top to bottom.


IBM

Lesson: with multiple ways to tell the story of its origin and development, nanotech means different things to different people.

A serious condition regarding our knowledge of nanotechnology:

But this does **not** mean that we know **nothing** about nanotech.

Let us build our knowledge of nanotech from the ground up, starting with a definition of nanotech:

Chris Toumey's four-part definition of nanotech, based on the wisdom of many knowledgeable people:

Part one:

Nanotech includes many scientific and engineering disciplines, plus several technologies which primarily serve nanotech;

Part Two:

For controlling matter.

Not merely understanding nature at the nanoscale, but using knowledge to change and improve things.

Medical therapeutics; microelectronics; environmental remediation, materials science, etc.

In other words, the *technology* in nanotechnology.

Part Three:

Matter which is measured by the nanometer, that is, a billionth of a meter.

Atoms; molecules; atomic surfaces; engineered nanoparticles; small viruses; etc.

Part Four:

Largely by taking advantage of properties, forces, and relationships that are unique to the nanoscale.

Catalysis; semi-conductivity; molecular recognition; etc.

So then,

Nanotechnology is a large group of scientific and engineering disciplines, subdisciplines, and technologies

For controlling matter

Which is measured by the nanometer

Largely by taking advantage of properties, forces and relationships that are unique to the nanoscale.

And so,

We cannot have a common understanding of
nanotech if we do not know certain technical
and historical conditions which
shape our knowledge of nanotech;

But if we can take those conditions into account,
then we can craft a definition of nanotech
which embraces them and all of the science,
engineering and technology which contributes to nanotech.

Thank you [English]
Danke schön [German]
Merci [French]
Go raibh maith agat [Irish Gaelic]
Thank-ya-vera-much [Elvis]

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