Nanotech and the Humanities

Nanotech and the Humanities:

An Anthropologist Observes the Science of Atoms and Molecules

By

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To Kathy, for many more reasons than I can list here

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FOREWORD

BRIGITTE NERLICH

In around 2003 I became interested in nanotechnology because my son, who was then in his early teens, told me about it. He had gleaned his knowledge from children's books and video games and I started to gather more knowledge from academic literature and colleagues both here at the University of Nottingham and abroad. I became interested in particular in the way nanoscience and nanotechnology interact with culture and society; how did it get into children's literature and games, for example, and how might it change their understanding of science, technology and themselves?

When trying to find out whether any research into such issues had been carried out by others, I came across only one publication, Chris Toumey's 2004 article titled 'Narratives for nanotech: Anticipating public reactions to nanotechnology', published in the journal *Techné*. I could not get access to the article, so I emailed the author, he sent it to me, and we have been in close contact ever since. We first met in person in 2007 and since then our paths have crossed several times across continents.

Since 2006 I have been following Chris's contributions to *Nature Nanotechnology*. These rather unique 'commentaries' are themselves hybrid objects situated between science and culture. As those interested in nanoscience and nanotechnology will know, countless articles and books have been written since 2003 about nanoscience and society, with a particular focus on public perceptions of nanotechnology, public engagement with nanotechnology, ethics and nanotechnology, and much more. However, my guess is that only a very small fraction of these publications have been read by both natural and social scientists, and even fewer by interested members of the public.

The commentaries gathered for this collection are different because they are written to be read rather than cited in other academic articles. They are also written in a style that makes reading them enjoyable for a wide range of readers. They are not 'science communication' in the sense of science popularisation. They are also not mere exercises in academic or scholarly critique. Instead, they enable readers to gain novel insights into a strange, fantastic and intriguing world by making them see this world through the eyes of those who probe it with complex and fascinating instruments. This is not all however, as readers also learn to appreciate that this is not just a world of science but a world of culture, history and human affairs.

At a time when we hear more and more about ‘responsible research and innovation’, I think it is time to reflect on what one may call responsible academic writing and responsible language use. Here I echo Chris Toumey’s words: those of us, especially in what is called Science & Technology Studies, where we use the humanities and social sciences to better understand nanoscience and nanotechnology, have a responsibility to share our work with the very scientists and engineers that make nanotechnology happen, as well as with as large an audience as possible of non-specialists who care very much about science, technology and their societal issues. This means writing in order to be understood rather than writing to show off how clever we are. The chapters for this book accomplish these tasks brilliantly. They are readable, understandable, enjoyable, but nonetheless profound. They are great examples of responsible research and writing.

The twenty-five commentaries of this book, plus the four longer pieces, lead the reader through the history of nanotechnology which began in the 1950s, engage with its reception and discussion in the public sphere at the end of the 20th and beginning of the 21st century, and then home in on one of the main ways in which nano became public, indeed an object of visual consumption: nano images. In Part Seven of the book some more recent and more problematic incidents and debates around nanotechnology are discussed.

If I had to choose my favourite commentary, I would have great difficulty in accomplishing this task. But I might choose “Thirty-five atoms that changed the nanoworld”. This commentary exudes enthusiasm, a type of enthusiasm that I have come across myself when interacting with those dealing with the nanoworld – they are unstoppable (and I am thinking in particular about my colleague at the University of Nottingham, Philip Moriarty, whom Chris knows well). This commentary tells the story of what one might call particles, pictures and persons. The iconic picture is that of 35 xenon atoms pushed around in such a way as to form the IBM logo on a nickel surface (and if you want to know what ‘pushed around’ means here, you’ll have to read the commentary). The persons are Don Eigler and Erhard Schweizer (and more, for which I again recommend reading the commentary!). Of course I liked the image of the IBM logo that illustrates the original commentary. But I really loved the image of a page of Eigler's lab book, also in the original, at the bottom of which he had scribbled "I'm Really having Fun!!" This fun comes through in many interviews that Eigler has given after this feat of atom shuffling. In these interviews he made clear that delving into the nanoworld made him see the 'real' world differently, something that I have experience myself. Some years ago, standing on the balcony of a newly-built hotel overlooking Monument Valley, I pointed to a mountain or butte and said to the consternation of my family: "Look, Eigler's Copper Perspective", an image of an atomic surface well known in scanning probe microscopy which looks like a desert canyon. You can find it on the website of Eigler's STM Image Gallery at IBM Almaden.

But let's end this foreword with a quote from Don Eigler himself: "Yeah. I see atoms everywhere. Having the 'hands on' experience of working with individual atoms has changed the way I see myself and the world around me. In the past, I used to see myself as a whole and separate entity from the rest of the universe. Now, when I look at the world around me I have a sense of affinity for everything. 'That rock you see there… yep… Atoms! You see that star in the sky? Yep… Atoms! And just look at yourself. Yep… Atoms!' When you see yourself this way, you cannot help but take on a different perspective. And, Oh Yes… you are never alone" (Interview for *Nanooze*, 2005).

The commentaries collected here express a similar enthusiasm, and I hope they will change the way readers see the world and themselves.

INTRODUCTION

THE AUTHOR INVITES YOU INTO THE WORLD OF NANOTECHNOLOGY

Yeah, yeah, I know. You the reader have two good questions about the book in your hand. First, what does nanotechnology have to do with the humanities? Is not nanotech dense enough already without involving philosophy, art, and other humanities disciplines?

And your second question: how can it be that a cultural anthropologist is my guide to exploring nanotechnology? Are not these guys supposed to explore indigenous people who live pre-modern lives, and do so in lands that are thousands of miles away from Research Triangle Park, Silicon Valley, and other epicenters of high tech?

Good questions both.

For the first: the humanities and their cousins in the social sciences have examined science and technology since before you or I were born. History of science, for example, is now so well established that some people consider it downright stodgy. About twenty years ago I was at a meeting of the Society for Social Studies of Science in Charlottesville, Virginia. There I had a conversation with a young scholar in the history of technology. He explained this to me: those in the history of science wear three-piece suits and silk ties when they come to academic conferences. The ones in history of technology wear suit jackets too, but they also wear jeans, and they own few ties.

So then, history of technology can have a vibe which is different from that of history of science. A generation gap, so it seems, between the two kinds of history. When we put the two together, along with philosophy of science, philosophy of technology and a lot of other subdisciplines, we see that the study of science and technology from the perspectives of the humanities and social sciences is rich, diverse, and worth appreciating.

Is it worth doing? If so, why?

When the U.S. government launched the Human Genome Project, it mandated a generous amount of dollars for "ethical, legal and societal implications" (known as ELSI). There is a feeling that ELSI ended up being not what the humanities and social sciences had in mind. Not a critical examination of the Human Genome Project which challenged intellectual assumptions and societal implications of the project, but rather a public relations exercise which minimized the friction between the project and its critics. Even so, ELSI nurtured an impressive generation of researchers in the humanities and social sciences just before nanotechnology caught the attention of some of them.

ELSI made an important point. If the U.S. government is going to invest large numbers of dollars in a new science or technology, then it makes sense to include considerations of ethical, legal and societal consequences.

That principle was the basis of SEIN, i.e., "Societal and Ethical Implications of Nanotechnology". Even before the "Twenty-first Century Nanotechnology Research & Development Act" became law in 2003, the U.S. National Science Foundation began sponsoring research on nanotech from the perspectives of the humanities and social sciences.

The European Union, the United Kingdom, Germany, Norway, Canada, and others joined this enterprise. Thus there was a golden age of about fifteen years when Western Europe and North America nurtured a community of scholars in the humanities and social sciences who used their concepts and methods to ask good questions about nanotech.

The funding for these studies of nanotech is now in the past, but it was generous for many years, and because of it, it might be that nanotech has received more attention from the humanities and social sciences than any scientific topic except the creation-evolution controversies.

I hope this answers your first question. Nanotechnology embodies consequences for society, culture, economy, power, and other realities. Good it is that the humanities have had the resources to ask hard questions of this technology.

The alternative is technological determinism. We can accept that a new technology is inevitable, and that we will have no voice in how it changes our lives. The humanities may not be a great engine of shaping technology policy and its consequences, but they look a lot better than the despair of determinism.

For your second question – why an anthropologist to lead me through an exploration of nanotechnology? – I have a story about how I became neck-deep in studying nanotech.

I work in the subdiscipline of the anthropology of science. I established a modest reputation there before I ever heard about nanotechnology, and I also realized that I could learn a lot from people in history of science, sociology of science, and many other subdisciplines that are linked together by their common purpose of examining science and technology. After I arrived at the University of South Carolina in 2000, I met a group that had begun to examine nanotech with the benefit of those subdisciplines. At first I declined to join them in that work because I was trying to get a different research project off the ground, and also because I saw that studying nanotechnology would be a very steep learning curve for me. But slowly I saw that I might have a modest place in studies of nanotech. I attended a meeting in Darmstadt, Germany, in October 2003, where I realized that everyone there knew more about nanotech than me. I wondered what I was doing there, and I feared that I would make a fool of myself.

Everyone else had good powerpoint presentations. I was behind the curve of communications technology, as usual. My visual material was a series of overhead transparencies. How sad is that?

But the powerpoint projector was two meters to the left of the speakers' podium, and there were several cables between the two places. This was before speakers had hand-held devices to advance their slides. So I saw three days of middle-aged academics climbing over the cables to show their next slides.

There was also an overhead projector for people like myself who were stuck in a pre-powerpoint mind-set. That might have been good for me, except that when I packed my bag for the trip to Darmstadt, I forgot to include my transparencies. So I had only my speaking notes.

Two good things resulted: I did not have to climb over the cables to get to the powerpoint projector, and I made a lot more eye contact with the audience than most of the other speakers.

My talk was a very simple account of how a certain anthropological theory could help one understand how people might react to nanotech. In my opinion, then and now, it was distinctly more modest than the presentations of dozens of people there who knew nanotech much better I did. But it went well anyway, probably because it was so simple.

As a result, I was asked to do that presentation eleven times over a period of six months at various venues. This opened my eyes. If my middling presentation was that much appreciated, then there might really be a place for me in the growing world of studying nanotechnology if I could do better than my talk in Darmstadt.

And then something else happened to me. In 2003, when I first became interested in nanotechnology, I heard that Richard Feynman's 1959 talk, "There's Plenty of Room at the Bottom", was the origin of nanotech. The next year I decided to map the history of nanotech, from Feynman to the present, via an exercise in citation tracing. This is an esoteric pursuit in which one finds the first generation of citations to the original text – in this case, "Plenty of Room", first published in 1960 – and then the second generation of citations that referenced the first generation, and so on. That way one could show the scientific pathways by which nanotechnology arose from the Ur-text, i.e., Feynman's vision.

My colleague Cyrus Mody convened a conference on the history of nanotechnology for March 2005 in Philadelphia. I timed my research on "Plenty of Room" so I could do a presentation at the Philadelphia meeting (which I believe was the first meeting on the history of nanotech). During that time I benefitted greatly from the assistance of reference librarians and others who helped me with my research.

As the Philadelphia conference approached, my findings surprised me. Feynman's paper was published six times in three years (1960-62), which was very impressive indeed. But it was cited only seven times through 1979, mostly in the field of microelectronics. (Later, Cyrus Mody found several more citations from around 1979.) Eight leading scientists in nanotech, including two Nobel Laureates, told me that Richard Feynman's paper had influenced them not at all.

So much for the standard belief about the origin of nanotech. But this lesson reinforced one of the instincts that we acquire in cultural anthropology: if everybody in a community believes the same account of the origin and history of something important to them, we need to ask whether that account is an origin myth. In that spirit I proceeded.

Shortly after the March 2005 meeting I wrote a text of my presentation and sent it as a courtesy to those who had helped me. One of them was

Doug Smith, an editor at *Engineering & Science*, the Caltech magazine that had first published Feynman's "Plenty of Room" forty-five years earlier. Mr. Smith surprised me by saying that *Engineering & Science* wanted to publish my paper on "Plenty of Room" and its role – or non-role – in the history of nanotech. The late Richard Feynman was a demi-god at Caltech, and rightly so, in which case it seemed peculiar that the editors of the Caltech magazine would publish a paper that challenged the importance of Feynman's 1959 vision.

But they did. My paper, "Apostolic Succession", appeared in *Engineering & Science* in May 2005. Later I learned that UCLA Chemistry professor J. Fraser Stoddart (actually *Sir* Fraser Stoddart, a Scot knighted for his impressive contributions to Chemistry, and later a Nobel Laureate in Chemistry) had seen my piece in the Caltech magazine. Professor Stoddart passed it on to Stuart Cantrill, who had earned his PhD in Chemistry at UCLA, and who was working at Nature Publishing Group (NPG) in London shortly after "Apostolic Succession" was published.

NPG publishes the journal *Nature* on a weekly basis. It also publishes a lot of important science that cannot fit into the weekly publication. To this end it has a group of about thirty specialized monthly journals: *Nature Genetics*, *Nature Photonics*, *Nature Biotechnology*, and so on.

When Nature Publishing Group was planning to launch the next member of the family, *Nature Nanotechnology*, in 2006, Stuart Cantrill showed my "Apostolic Succession" paper to Peter Rodgers, who was about to become the editor of *Nature Nanotechnology*. Rodgers wrote to me in the summer of 2006 to say that the nanotech journal was in the works, and that he had read "Apostolic Succession". He told me that he hoped to have a short commentary, called a "Thesis" in NPG's vocabulary, in each month's issue, and would I be interested in writing four of them each year?

I agreed. My first "Thesis" appeared in the first issue of the first volume, in October 2006. Ever since then, I have greatly enjoyed having this platform in a leading nanotech journal to show scientists and engineers how the humanities and social sciences can contribute to our understanding of nanotechnology.

After about six happy years of working with Peter Rodgers, a new editor came on board when Peter moved on to a different editing project. Now I send my commentaries to Fabio Pulizzi, the new chief at *Nature*

Nanotechnology. Peter and Fabio have different editing styles, but I have been entirely happy with both.

My citizenship in the SEIN community has been a great pleasure for me, but I also accept two responsibilities that come with the pleasure and the funding. If it is true that we know nanotechnology better with the benefit of the humanities and social sciences, then we should not limit our insights to our own little academic communities: philosophers speaking only to other philosophers, for example. On the contrary, the audiences for our research and writing should include the scientists and engineers who change the world by creating nanotech and its applications. This is my prime motivation for writing commentaries for *Nature Nanotechnology*.

Furthermore, there are many thoughtful and informed nonscientists and nonacademics who have a legitimate interest in knowing what an emerging science is doing and how it might affect us socially, culturally, politically, and economically. These people constitute another important audience for our work. And so I try to write about nanotechnology in a way which is accessible to multiple different audiences: not only to my colleagues in SEIN, and not only to scientists and engineers, but also to the kinds of readers who enjoy *Scientific American*, or the "Science" section that appears in the *New York Times* every Tuesday, or the articles and blogs on science in *The Guardian*.

I have had more than fifty of those pieces in *Nature Nanotechnology* . This book contains the better ones. And as an academic I also write peer-reviewed papers for journals, edited volumes, and encyclopedias. Four such papers are in this book.

* * * * *

Before we go further, it would be a good idea to nail down a definition of nanotechnology. Mine has four parts.

Nanotechnology is:

[A] a large group of scientific and engineering disciplines, subdisciplines, and technologies;

[B] for controlling matter;

[C] at the nanoscale, that is, matter measured by the nanometer (which is one billionth of a meter);

[D] and it does so largely by taking advantage of forces and processes that are unique to the nanoscale.

Each of these components deserve a bit of elaboration. For **[A]**, we can say that nanotech is not a single product like a better smart phone, or a better process like polymerase chain reaction. Instead it is a multifaceted body of work that includes atomic physics, subatomic physics, inorganic chemistry, organic chemistry, molecular biology, material science, microelectronics, electron beam microscopy, scanning probe microscopy, and many other kinds of scientific work.

Regarding **[B]**, we should note that nanotech is not limited to understanding matter. It is meant to control matter for the better, that is, to change our material culture for microelectronics, medical diagnostics, medical therapeutics, environmental remediation, and other desirable results.

Nanotech gets its name from the nanometer. This is the scale at which one measures atoms, molecules, atomic surfaces, proteins, and small viruses. The water molecule, for example – H_2O – is approximately 0.28 nanometers in diameter at room temperature. The DNA molecule has a diameter of about 2.0 nanometers. This gives you an idea of the nanoscale **[C]**.

Nanotech works mostly by taking advantages of forces and processes that happen at the nanoscale, and not elsewhere. This is item **[D]**. Reactivity, catalysis, semi-conductivity and other phenomena are different at the nanoscale. Nanotech is not merely a matter of making large things very small. It is more of a way to make very small things useful by virtue of the fact that their very small scale embodies advantages that are not found at larger scales. This is my sense of what nanotech is.

* * * * *

I have gathered twenty-five of my commentaries from *Nature Nanotechnology* into five themes. The first is "Moments in the Story of Nanotechnology". Here we have an account of the invention of the scanning tunneling microscope, the Eigler-Schweizer experiment of 1989, and three more events that stand out in the story of nanotechnology.

Next is "Interactions with Religion". There is good reason to believe that public attitudes about nanotech will be strongly influenced by religious beliefs, and not by public knowledge of the science of nanotech. Also, I have a long-term interest in the question of relations between science and religion. I know enough about science and enough about religion, that both deserve to be understood and appreciated on their terms, without reducing either to a foil for the other. I strongly dislike simplistic formulas about science-and-religion because they usually do violence to science or to religion or to both. If ever there was a mandate for nuance and particulars, it is here. My hope is that you will see my views on nanotech-and-religion as a worthy antidote to simplistic formulas.

"Public Engagement with Nanotechnology" is the third theme. Here is a good question: can nonscientists have active and constructive roles in science policy discussions? If so, we call this "democratizing science". This too is rich and deep, and in fact nanotechnology came to the attention of science policy experts at about the same time (circa 2000 – 2003) that a series of experiences and theories coalesced into a vision of democratizing science. Nanotech was expected to be the case study that made "democratizing science" credible.

I still believe in "democratizing science" as a general principle, but I have also learned that some forms of science serve this principle better than others. Here you see how nanotech fits into the idea of democratizing science.

After that I give you Part Four: "Life in the Culture of Science". Here I try to get into the heads of the scientists and engineers who make nanotech happen so we can see how they think.

Part Five consists of "Some More Observations". These are commentaries that do not fit neatly into the first four themes, but have merit enough to be in this collection. Here we have nanobots, gender, violence, and a handful of other topics.

It may please you to know that I declined to include more of my commentaries because others are not as good as these. I am not cleaning out a dusty old attic and dumping everything into the lap of you the dear reader.

For Part Six, "Diving Deeper into Nanotech", I gather four of my longer papers. One is my best-known piece about nanotechnology, "Reading Feynman into Nanotech". The premier origin myth of this science says that nanotech began with Richard Feynman's 1959 talk, "There's Plenty of Room at the Bottom". I disagree, and here I take you on my expedition to challenge that story. As you will see, this has displeased some people. If you like, you can think of this as a long addendum to the short pieces in Part One, "Moments in the Story of Nanotech".

"Seven Religious Reactions to Nanotechnology" embodies a paradox. There is good reason to believe that when nonscientists form attitudes about nanotech, they will rely not on the science itself, but rather on well-established religious beliefs. If so, this paper presents a spectrum of religious beliefs, and it identifies some common concerns in that spectrum.

Next there is a question about the pictures of atoms and molecules that come from scanning probe microscopy: does an atom or a molecule really look like a picture of the object? If not, what is the problem that comes between the object and the picture of the object?

The question is not merely technical and not only aesthetic. Instead it represents an intersection of the two. "Aesthetic Resources for Molecular Knowledge" presents this problem and then suggests some constructive ways to think about it. For readers who are curious about how a scientific instrument uses technology and aesthetics to generate an image of atoms or molecules, this paper will feed that curiosity.

Lastly in Part Six there is "Nanotechnology Controversies". Science would be monotonous if there were no controversies; but then again, science does not amount to total endless disagreement, as if all its controversies are impossible to resolve. In this paper I argue that certain features of nanotechnology instigate controversies. I do not need to tell you who is right and who is wrong. Instead, I point to certain conditions so that we can see patterns in the origins of the controversies that help make nanotechnology interesting.

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If this collection pleases you, then it pleases me that we have something in common: a serious curiosity about science, plus a confidence that the humanities and social sciences have some things worth saying about science.

* * * * *

I have too many to thank by name for nurturing my interest in nanotechnology, and appreciating what I have written, and becoming wonderful friends to me.

My best friend in studies of nanotech is Brigitte Nerlich at the University of Nottingham. We have met face-to-face only five times – in Montreal, Paris, Nottingham, Darmstadt, and Norrkoping. But it has been great to share ideas with Brigitte. We are not intellectual clones of each other, but instead we complement each other nicely, and my work is better because of our friendship.

If I recognized another dozen people by name, that would be too few. If I recognized two or three dozen, that would still be too few, but it would also cause you the reader to roll your eyes because you would want me to move quickly to the substance of this book. So I have a standard for saying “thank you”. If you ever had a pint or two with me at a conference or any other gathering about nanotechnology, then you should know that I appreciate your knowledge and your friendship.

There are also some who I have not met face to face, but who have still helped to make my nanotechnology years some of the happiest years of my academic life. Every scholar should have as many friendships, face-to-face or keyboard-to-keyboard, as I have had in this time because of our shared interest in nanotechnology.

In addition, I have benefitted from multiple sources of funding. The team at the University of South Carolina had two large awards from the U.S. National Science Foundation, and I am grateful that I was able to join that team. Later I had three of my own grants from NSF, and these enabled me to do a lot more of my own research on nanotech. Here I must add that my views are my own: while I deeply appreciate support from NSF, my views are not necessarily those of that foundation. In addition, I received help from some other sources that enabled me to travel to high-quality conferences and workshops. The Norwegian government, the European Science Foundation, the Gulbenkian Institute in Lisbon, Portugal, and the ZKM (Center for Art and Media in Karlsruhe, Germany), have been most generous to me this way. And I had a Coolidge Scholarship for the 2010 research colloquium of CrossCurrents (The Association for Religion and Intellectual Life) to study denominational positions on nanotechnology in July 2010. There is no danger that I will fail to appreciate the support I have received from these sources.

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I have said that the first twenty-five chapters appeared originally in *Nature Nanotechnology*. At the head of each one I indicate the month and year when it was published.

Chapter 6.1, “Reading Feynman into Nanotechnology”, appeared in *Techné* in 2008 (Volume 13, pages 133-168). Chapter 6.2, “Seven

Religious Reactions to Nanotechnology", was published in *NanoEthics* in 2011 (Volume 5, pages 251-267). "Aesthetic Resources for Molecular Knowledge", Chapter 6.3, comes from the 2013 volume *Molecular Aesthetics*, edited by Peter Weibel and Ljiljana Fruk, MIT Press, Cambridge MA, pages 222-237. Finally, Chapter 6.4,

"Nanotechnologgy Controversies", is from *Controversies in Science & Technology*, edited by Daniel Lee Kleinman, Jason A. Delborne, Karen A. Cloud-Hansen, and Jo Handelsman, published by Mary Ann Liebert Inc., New Rochelle NY, 2010, pages 231-242.

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I usually write my *Nature Nanotechnology* commentaries in American English, after which they are converted to British English because they are copy-edited according to the standards of Nature Publishing Group in London. *Center* becomes *centre, while* is changed to *whilst*, and so on. I thought about tweaking them back to American English for this collection, but then I felt that these pieces ought to retain the eccentricities of English on the other side of the Atlantic (where American English is the variant that makes editors scratch their heads). In my experience, the humanities accommodate eccentricities of language very nicely, so this collection of observations about nanotech benefits from a modest dose of linguistic eccentricity. Sometimes British, sometimes American. One more reason to enjoy the humanities, don't you think?

PART ONE:

MOMENTS IN THE STORY OF NANOTECHNOLOGY

THIRTY-FIVE ATOMS THAT CHANGED THE NANOWORLD

APRIL 2010

If the scientific community ever needed to be convinced that nanotechnology was real, Don Eigler and Erhard Schweizer provided the evidence in the 5 April 1990 issue of *Nature*. Working at IBM's Almaden Research Center in San Jose, California, Eigler and Schweizer used a scanning tunnelling microscope to position individual atoms on a metal surface. In possibly the most famous image in the history of nanotechnology, they wrote the letters IBM with 35 xenon atoms on a nickel surface[1].

Scientists had studied atoms and the subatomic particles inside them for decades, but to see individual atoms so clearly — and to move them around one by one — was something else. The paper in *Nature* showed that the tools of nanotechnology could control matter at the nanoscale, atom by atom. And if we describe Eigler and Schweizer as the scientific heroes of April 1990, then we should add a third hero: the scanning tunnelling microscope itself.

The scientific adventure that led to the breakthrough by Eigler and Schweizer started at least 35 years beforehand. On 11 October 1955, at Pennsylvania State University, Erwin Müller used a field ion microscope, cooled to liquid-nitrogen temperatures, to record an image of a tungsten lattice in which the individual tungsten atoms were visible[2,3].

Another character in this adventure is Russell Young, who developed an instrument called the 'topografiner' while working at the US National Bureau of Standards (now called the National Institute of Standards and Technology). This device contained a tungsten field emitter mounted on a piezoelectric platform. When the emitter was placed about 3.0 nm from the surface of a sample, an electrical current flowed, causing electrons and photons to be released from the surface. A pair of detectors was used to measure these electrons and photons as the emitter was moved across the surface, while keeping the emitter–surface separation fixed, which allowed the measurements to be transformed into a three-dimensional picture of the surface. A vertical resolution of 3.0 nm was common, although, on occasions, the topografiner achieved a vertical resolution of 0.3 nm (which is good enough to detect 'steps' just one atom high on a surface)[4,5]. However, the topografiner had two limitations: it was not able to image individual atoms, and the high voltages required sometimes damaged the samples.

Looking at single atoms

The first scanning tunnelling microscope (STM) was built in 1981 by Gerd Binnig and Heinrich Rohrer, who wanted to study atomic surfaces in greater detail than was possible at the time. Binnig and Rohrer, who were based at IBM's Zurich Research Laboratory, mounted an ultrafine probe on a piezoelectric platform, brought the tip of the probe to within a nanometre of the surface, and then applied a voltage, causing electrons to tunnel from the tip to the sample. The tunnelling current depended very sensitively on the distance between the tip and the surface, so measuring how this current changed as the tip was scanned over a sample allowed objects as small as atoms to be imaged[6].

The development of the topografiner came to an end in the 1970s. The field ion microscope and the electron microscope (in many different guises) still have important roles in microscopy, but the STM and its younger cousin, the atomic force microscope, now do most of the heavy lifting for nanoscale imaging.

As late as their article in the August 1985 issue of *Scientific American*[7], Binnig and Rohrer were describing their invention only as an imaging device, not as an instrument for moving individual atoms. Meanwhile, an engineer from Tucson, Arizona — Conrad Schneiker — began writing a series of papers in 1985 that argued that the STM could also move matter at the nanoscale. He called the STM a 'Feynman machine' because he believed that it could fulfil Richard Feynman's vision of precisely controlling individual molecules and atoms[8–10]. In December 1986 — in their Nobel Prize lecture — Binning and Rohrer included a brief comment about the possibility of using the STM as a 'Feynman machine'[11].

It was not long until the ability of the STM to control the positions of atoms was demonstrated. In January 1987, the month after Binnig and Rohrer had collected the Nobel Prize in Stockholm, Russell Becker and colleagues at Bell Labs reported that they had used the tip of an STM to make an atomic-scale modification to the surface of a germanium crystal[12].

This "surface bit" was, they wrote, "the smallest spatial rearrangement of surface atoms we have observed to date," although the precise nature of the "surface bit" remained unclear.

Then, in 1988, John Foster and colleagues at IBM Almaden announced that they had used an STM to "pin" individual organic molecules onto a graphite surface, and had also removed other molecules from the same kind of surface[13]. The manipulation of nanoscale matter was now well on its way.

Moving single atoms

On 28 September 1989, Eigler moved a xenon atom back and forth between two defect sites on a platinum surface. In his lab notebook of that date, under the heading of "first atom to be manipulated under control", Eigler wrote "Did it," "Did it" and "Did it again! 3 in a row."[1] Although a single atom had been manipulated, the platinum surface was problematic for imaging the before and after locations: Eigler needed an image that would demonstrate clearly that he had achieved reproducible atomic-resolution positioning capability.

The surface of a nickel (110) crystal, obtained from Eigler's colleague Jo Stohr, solved the problems of demonstrating both atomic precision and reproducibility. On 9 and 10 November 1989, Eigler and Schweizer, a visiting scientist from the Fritz Haber Institute in Berlin, cooled an STM chamber to 4 K, and then dosed the nickel substrate with xenon atoms. After mapping the randomly adsorbed xenon atoms, they lowered the STM tip closer to the surface than is customary for imaging. This enabled them to make a xenon atom adhere to the tip, so that they could drag the atom across the substrate, place it exactly where they wanted, and then release it at a new location. After doing this with 35 xenon atoms, one at a time over a period of 22 hours, they had spelt 'IBM' in atoms (Fig. 1). It was, they wrote, "our first construction of a patterned array of atoms."

On 14 February 1990, Eigler used a different method to manipulate single atoms: instead of dragging the xenon atoms across the substrate, he lifted them up off the nickel surface and then put them back down in their new locations. The lab notebook for that day records "success at pick up" and "success at put down" six times each — no doubt about reproducibility here — followed by "I'm really having fun!!" in big bold writing (Fig. 2).

Subsequently Eigler and co-workers built a variety of structures, atom by atom, and explored a range of previously unknown physical phenomena in these structures. The STM Image Gallery offers a delightful record of this work, along with some clever puns about visual art[14]. And after April 1990, it became common for researchers to create institutional logos and other images using STMs.

Eigler and Schweizer wrote that “This capacity has allowed us to fabricate rudimentary structures of our own design, atom by atom.” But they tempered their optimism with caution when they added, “We anticipate that there will be a limiting class of adsorbed atoms and molecules that may be positioned by this method.”

In this spirit, we should keep in mind that the value of this kind of work is not in applications for manufacturing. It is entirely impractical to position individual atoms on a large scale. As Eigler puts it, atom manipulation with an STM is a “laboratory tool” not a “manufacturing tool,” and its value lies in allowing us to learn more about how atoms behave. What’s more, adds Eigler, atom manipulation is “as exciting today as it was” 20 years ago (D. Eigler, personal communication).

A postscript

A video shot at the Museum of Science in Boston on 30 March 2008 shows a scientist demonstrating the scanning tunnelling microscope to an audience of museum visitors[15]. As he manoeuvres the mouse of his laptop in Boston, the screen shows a metal surface that is being imaged in real time by an STM in San Jose, on the other side of the continent. The cross-hairs that represent the tip of the STM are moved until they are centred over a single copper atom. The tip is lowered, and we hear the atom adhering to the tip. The tip is raised, and then moved to a different location, where it releases the atom in a new location. A new scan confirms that the atom has been moved. Is there any doubt that this is just as exciting as the original Eigler–Schweizer experiment?

As his presentation comes to an end, the scientist says: “If you want to come up and move an atom, come up here and we’ll give it a try.” As the credits roll, we see the scientist telling a delighted child, “You have moved an atom.” The scientist is Don Eigler.

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PROBING THE HISTORY OF NANOTECHNOLOGY

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The scanning tunnelling microscope (STM) and its offspring, the atomic force microscope (AFM), are synonymous with nanotechnology, and one might assume that it was inevitable that nanotechnology became possible because of these two instruments. But as Cyrus Mody makes clear in his new book, *Instrumental Community: Probe Microscopy and the Path to Nanotechnology*, the history of these two instruments and the scientific communities that coalesced around them could have turned out differently. The STM, for example, came close to being rejected as a technical failure: if that had happened, the AFM would not have been invented and nanotechnology as we know it today might not have happened. Let us look at four series of events that Mody, a historian of science at Rice University, covers in his book[1].

First, in 1972, Russell Young developed the ‘Topografiner’ at the US National Bureau of Standards (now the National Institute of Standards and Technologies). This instrument possessed certain crucial features that appeared later in the STM: a piezoelectric platform was used to manoeuvre a scanning probe, and images of surfaces were generated by measuring how the electric current between the probe and the surface changed as the probe was scanned over the surface. Unfortunately, Young experienced both technical and political problems. Uncontrolled vibrations made atomic-scale resolution impossible at the time, and the NBS started to focus more on ‘applied’ research — and the Topografiner was not applied enough for Young’s bosses at the NBS.

The demise of the Topografiner also caused problems for the STM, which was invented at the IBM-Zurich Research Laboratory in 1981. First, early patent applications for the STM were rejected on the grounds that the Topografiner had got there first. Second, Gerd Binnig and Heinrich Rohrer — who shared the 1986 Nobel Prize for Physics for their design of the scanning tunnelling microscope — needed to demonstrate that the STM was better than the Topografiner. It was not until they produced an image of the 7 × 7 reconstruction on silicon with atomic resolution that the STM was able to escape the shadow of the Topografiner.

The second crucial development reported by Mody was the STM being embraced by a community of researchers. Looking back one might think that the electron microscopy community would have welcomed the STM with open arms, but it did not. The infant STM was too unreliable for scientists used to working with transmission electron microscopes and scanning electron microscopes. However, surface scientists quickly saw the potential of the STM for studying very clean samples and were prepared to wait for its performance to improve. It also helped that IBM employed a large number of surface scientists who could introduce the instrument to other researchers in the field.

The third development was generational. Whereas senior scientists were reluctant to embrace the STM because it reminded them too much of the Topografiner, and because the first STM images were of poor quality, younger scientists viewed things differently. And because companies like IBM and the owners of Bell Labs wanted their young scientists to enjoy intellectual freedom, the STM flourished. One of the pleasures of reading *Instrumental Community* is to watch some of the giants of nanotechnology — such as Donald Eigler[3], Christoph Gerber, James Gimzewski, Clayton Teague and Mark Welland — enter the field as young researchers, mostly at an IBM lab or at Bell Labs.

The fourth (and final) critical development happened at various IBM labs and two universities in California. By 1986, surface scientists were very satisfied with the performance of the STM, especially as it was so well suited to the ultrahigh vacuums and ultralow temperatures often used for surface-science experiments. However, a small number of scientists — Paul Hansma of the University of California at Santa Barbara, Calvin Quate of Stanford University, and Rohrer — wanted to move beyond the extreme conditions favoured by surface scientists and study biological samples under ambient conditions. The thought of performing an experiment ‘in air’ at room temperature, and all the impurities that this would involve, horrified many surface scientists. However, because Hansma, Quate and Rohrer were willing to take risks and to make mistakes to make progress, the benefits of the STM and the AFM (invented by Binnig, Quate and Gerber in 1986[4]) were soon experienced in areas other than surface science.

Reading Mody’s book, it is very clear that the fates of the STM and the AFM could have been very different. It is easy to understand how