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Notes toward a Nanotech Timeline

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Nano science and technology has been growing rapidly for nearly two decades. One indication of this growth comes from the rise of scientific and engineering articles on the topic. As a first approximation, this article pool can be measured by searching for "nano*" in the titles, abstracts, and keywords of all articles in the ISI Web of Science database. This collection of nano articles shows two distinct periods of growth. Between 1983-1990, the number of nano articles grew exponentially, doubling roughly every 7.3 years. Between 1991 and 2005, however, the rate of new nano articles increased considerably, doubling every 3.3 years.[1] (See fig. 1.)

Researchers at UCLA have developed a more sophisticated search algorithm to build up the pool of nano scientific and engineering articles (adding a list of 475 keywords to the "nano*" search string, still based on the ISI Web of Science database). Even with this more advanced technique, their data still show a distinct break in rates of growth in the take-off of nano articles before and after 1990-91 (Zucker and Darby 2005). (See fig. 2.) The phenomenon thus seems to be robust—and hence the question: what might account for the sharp inflection point ca. 1990-91?

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[1] Growth rates in figure 1 are shown in terms of e, the base of the natural logarithms. Doubling times are simply related as follows: $e^{t/\tau} = 2^{t/d}$, or $d = \tau \ln(2)$.

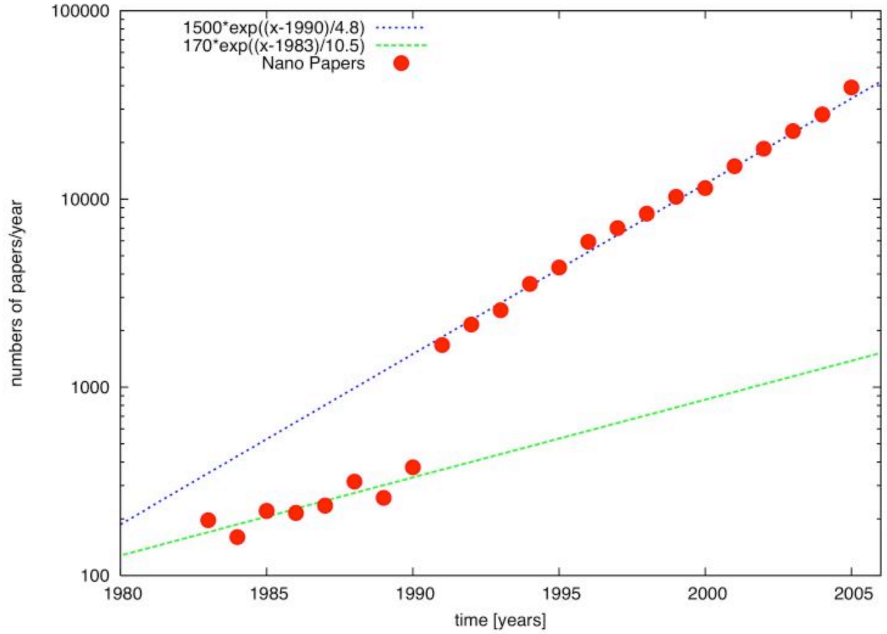

Fig. 1. Number of articles on nano science and engineering, based on the presence of the string "nano*" in article titles, abstracts, and keywords in the ISI Web of Science database. Data provided by David Wojick; figure prepared by Luis Bettencourt.

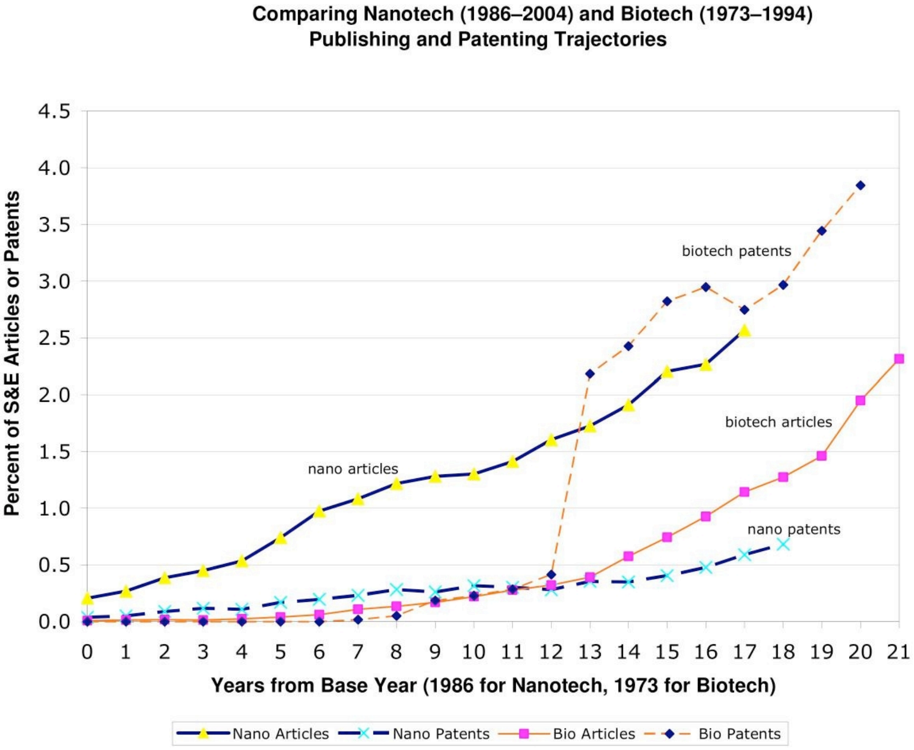

Fig. 2. Number of articles and patents in nanotech (1986-2004) and biotech (1973-1994), from Zucker and Darby 2005, p. 26. Note that Zucker and Darby used a more complicated search algorithm to identify nano

articles in the ISI Web of Science database, *and* that their plot is in terms of percentage of (time-varying) total science and engineering publications per year, rather than raw numbers of articles per year. Even so, their data clearly show an upturn in rates of nano publication between 1990 (year 4 in their scheme) and 1991 (year 5). Figure © 2005 by Lynne G. Zucker and Michael R. Darby.

The swift change in rates of growth is rather different from other examples of the diffusion of scientific ideas and techniques, such as Feynman diagrams within theoretical physics during the late 1940s and 1950s (Bettencourt et al., 2006). Indeed, using the simplest mean-field approach to modeling the diffusion of scientific techniques, built in analogy to epidemiological studies—the SIR model, involving only susceptible, infected, and recovered populations, with one constant contact rate and one constant recovery rate—this type of sharp break seems difficult to account for.

Several hypotheses might explain the sharp break in growth rates:

1. *New recruits*: Perhaps the population of susceptibles grew suddenly ca. 1990. As Bettencourt notes, "an exponential increase in the number of authors is expected in a large population without finite size constraints. The rate 1/tau is (naively) proportional to the contact rate *times* the relative size of the susceptible population. The jump in 1990-91 could be explained by a sudden jump in the susceptible (and total) population." (Bettencourt email, 31 May 2006).

2. *New discoveries*: Perhaps the jump in nano articles comes from one or more important discoveries that garnered unusual amounts of attention. These could have turned large numbers of people 'on' to the field (ibid.).

3. *New instruments*: Perhaps the sudden availability of new scientific instruments immediately prior to 1990-91 could help account for the sudden take-off in publications.

4. *New label*: Perhaps the sharp break comes not from an underlying discontinuity in actual scientific practice, size of susceptible population, or contact rates, but from sudden changes in *labeling* for work that had previously passed under various,

non-unified names (Kaiser email, 27 January 2006). After all, our article pool was found by searching for the term "nano*" in article titles, abstracts, and keywords; if for some reason this *label* began to stick with special force after 1990, that's all our search would currently allow us to see (without detailed information about authors, institutions, specific lines of contact and influence, previous lines of research, etc.). This could certainly help account for the less dramatic break in growth rates found in Zucker and Darby 2005 (cf. fig. 2), who built their article pool from more than just the "nano*" string.

Naturally these four hypotheses are hardly orthogonal. It is conceivable that the sudden availability of new (easier-to-use) instrumentation, combined with a few high-profile discoveries, led to a coalescence around the term "nanotechnology," which in turn solidified the new term's use while also inspiring practitioners from neighboring areas to begin working on "nano" topics. That is, hypotheses 2-4 could all contribute to a sudden increase in the population of susceptibles, as in hypothesis 1. To begin the process of evaluating these hypotheses (and their various admixtures), it is important to establish a basic timeline for the development of nano science and technology, with special attention paid to the period immediately prior to 1991.

1975: NSF solicited proposals for a university-based National Research and Resource Facility for Sub-micron Structures. MIT, Berkeley, Cornell and others competed. In an effort to strengthen their proposals and better their chances, each institution also began building up their existing facilities (clean rooms, microfabrication facilities, etc.). This in turn led to an intensification in their training of more students to work at the "sub-micron" scale. Cornell won the "National" center, while the others continued to operate, too (Mody 2006).

1981: The scanning tunneling microscope (STM) was invented by IBM research scientists (Binnig, Rohrer), offering atomic-scale (that is, nanometer) resolution. The STM required an ultrahigh vacuum environment, however, and proved unwieldy to use; it spread relatively slowly to other industrial and academic labs. Moreover, it could only be used for imaging conducting materials; hence it was primarily picked up for use by surface scientists (Mody 2005).

1986: The atomic force microscope (AFM) was invented (Binnig, Quate, Gerber) by people who tinkered with STMs. Unlike the STM, the AFM operated in open air (no need for ultrahigh vacuum), *and* could be used to image any type of material: conducting, non-conducting, organic, inorganic, etc. It was much easier to use and more flexible, and was picked up more quickly by industrial and academic groups (Mody 2005; Zucker and Darby 2005).

1986: Eric Drexler (early nano enthusiast) published the popular book, *Engines of Creation: The Coming Era of Nanotech* (New York: Anchor, 1986). The book was widely seen as having introduced the term "nanotechnology," although it was later pointed out that a Japanese researcher had used the term in the mid-1970s. In any case, Drexler's widely discussed book certainly helped put the term "nanotechnology" into common use (Mody 2004).

1987: Cornell renamed its NSF-funded national center the "National Nanofabrication Facility" (Mody 2006).

1987: Digital Instruments—a spin-off company of Paul Hansma's STM/AFM group at UC Santa Barbara—was founded and shipped its first commercial STM (Darby and Zucker 2003; Mody 2004, 2005).

1989: Digital Instruments shipped its first commercial AFM (Darby and Zucker 2003; Mody 2004, 2005).

1989: Former graduate students and postdocs from Calvin Quate's Stanford STM/AFM lab founded Park Scientific Instruments (for a time, the main rival to Digital Instruments for supplying commercial probe microscopes) (Mody 2004).

1989: Eric Drexler founded the "Foresight Institute" and hosted the first annual Foresight Conference on nanotech (27-29 Oct 1989), "the first comprehensive conference" on the subject (according to Foresight Institute's website, www.foresight.org). The meeting was cosponsored by the "Global Business Network" and Stanford University's computer science department (Mody email to Kaiser, 14 February 2006).

1989: Ari Aviram (a theoretical chemist at IBM, specialist on "molecular electronics") organized an annual conference series bringing together experts on microfabrication, probe microscopy, and molecular electronics (Mody 2006).

1990: Don Eigler produced the first "IBM" logo made out of individual atoms. The widely reproduced image first appeared on the cover of *Nature*, vol 344 (5 Apr 1990): 524-26; it quickly became a major icon for nanotech (Mody 2006).

1990: Report of AFM atomic-scale resolution of DNA; this likewise garnered the influential cover of *Nature* (Baldeschwieler et al, *Nature*, vol 356 [19 July 1990], 294-96). The article created an immediate, large stir—if true, it held out the promise of being able to use AFMs to sequence DNA, just as the massive Human Genome Project was getting underway—but equally quickly the claim was disputed. An active controversy ensued and the original claim was eventually discredited, although Baldeschwieler never formally retracted the claim (Mody 2004, 2005).

1990: Jim Murday (surface scientist at the Office of Naval Research, and the primary federal grant officer for the field) renamed the annual STM conference of the American Vacuum Society the "STM/NANO" conference.

1991: Japanese researcher Sumio Iijima produced carbon nanotubes, based on the 1985 discovery of buckminsterfullerine (C60), combined with improvements from 1990 on means of manipulating the supermolecule using ordinary laboratory techniques (Bettencourt email, 31 May 2006; http://www.personal.rdg.ac.uk/~scsharip/tubes.htm).

1991: AFM used on living cells (Haberle, Horber, Binnig): "observed the effects of antibody attachment and changes in salinity on living red blood cells" (Zucker and Darby 2005).

1992: Murday (now president of AVS) founded its "Nanometer-scale Science and Technology" division.

We immediately see some points of interest. For starters, many of the threads that would become known as "nanotechnology" long pre-dated the use of the term, giving some credence to hypothesis 4 ("new labels"). Second, there was indeed a major increase in the availability—and usability—of nano instrumentation immediately prior to the take-off in nano publications. Moreover, once AFMs became commercially available, researchers from a variety of fields (not just surface science) could begin to make atomic-scale images of practically anything. Mody shows in detail that the resulting images were far from obvious to interpret (either for those who made them or for those who had to evaluate and use them), but the images themselves became tremendously easier to produce, and their range of uses seemed to expand overnight (Mody 2004, 2005)—all consistent with hypothesis 3 ("new instruments"). Third, some major discoveries did receive unusual amounts of attention ca. 1990-91, including several prominent covers of *Nature* and *Science* (hypothesis 2, "new discoveries")—and these discoveries came from a variety of host disciplines, far beyond surface science, which could well have contributed to the excitement (and even notoriety) of nanotech (hypothesis 4, "new labels"). Fourth, some of the most enthusiastic proponents/propagandizers for nanotech (Drexler, Murday) became especially active between 1986 and 1992, helping to introduce the term "nano" to large groups of researchers, funders, university officials, and the public (again, hypothesis 4). Thus we do see signs for a convergence ca. 1990-91, each element of which is likely to have contributed to a sudden increase in the susceptible population (hypothesis 1).

A more careful content analysis of individual nano articles from the period 1989-91 would be required to evaluate hypothesis 2 ("new discoveries") more conclusively. At this point, however, it seems unlikely that the "new discoveries" hypothesis can really account for the sudden change in rates of growth. Zucker and Darby note that throughout the entire the period 1980-2001, the largest number of "high impact" nano papers (that is, articles that have received 250 or more citations) have consistently come from work on semiconductors and integrated circuits—that is, the surface science work that first spawned the STM—rather than from buckyballs, nanotubes, or biological applications. High-impact nano papers on biological and chemical applications did begin to rise around 1988 and have continued to grow steadily, but they show no sharp break around 1990 or 1991, and they have consistently numbered less than half the number of high-impact nano papers on semiconductors and integrated circuts (Zucker and Darby 2005). Presumably these high-impact articles trace larger trends within the full nano article pool.

Likewise, the weekly on-line journal, *Virtual Journal of Nanoscale Science and Technology*, which reprints significant new articles from all the specialist journals (as selected by an elite editorial board), has been in operation since 2000. The largest share of articles selected to be reprinted has consistently come from classic surface science areas: optical properties of materials (greater than 20% of all articles over the journal's lifetime) and electronic structure and transport (e.g., semiconductor properties, 15-20% of all articles). Articles on carbon nanotubes made up less than 5% of the articles through July 2001, and by June 2002 still only accounted for about 12%. Likewise, articles on "supramolecular and biochemical assembly" (which would presumably include topics like buckyballs) accounted for well under 5% of all articles since the journal was founded. So while the 'exotic' discoveries might well have helped create a "buzz," they do not appear to have significantly tipped the balance of nano publications. That is, the role of "new discoveries" seems most likely to have been an additional input to hypothesis 4 ("new labels") rather than a major contributing factor on its own.

Meanwhile, an additional facet of the ‘new instrumentation’ hypothesis comes from another of Zucker and Darby’s observations: the number of nano articles authored by private companies rather than by exclusively academic teams rose sharply during the period 1988-91, compared with the period 1984-87, and rose sharply again during 1992-95 (Zucker and Darby 2005). This is at least consistent with the influx of commercially available STMs and AFMs during this period, which could be operated more as “off the shelf” equipment than as finicky tools that required substantial experience and tacit knowledge.

Taken together, these observations suggest an important modeling consideration. In the Feynman diagram case (and in dozens of other examples studied qualitatively by historians and sociologists), considerable time spent in apprenticeship and training were required before members of the susceptible population actually became active users of new scientific ideas or techniques. (This is why our group explored the SEI and SEIZ models in addition to SIR, where the “E” denotes members of a population who have been “exposed” to the new idea but do not yet manifest it in their work; Bettencourt et al., 2006.) If nanotech were a well-defined research area, then one would also expect to see considerable delay times (measured in years, not weeks or months) before new recruits began to work actively in the field, publishing papers, etc. That is, neither a cache of exciting new discoveries nor even an effective buzz/re-labeling campaign would be expected to produce an avalanche of new nano articles within one calendar year.

If, instead, “nanotech” is much more of a multi-purpose label that can be applied with little “cost” (in training, in re-tooling, in conceptual re-thinking)—but with significant gains (in newly organized conferences, publicity, federal funding initiatives, institution-building opportunities)—then one or two off-scale, newsworthy developments could indeed inspire a rapid re-labeling across previously disparate areas. Combine the “buzz” factor with a well-timed infusion of new instrumentation (that could be treated as a “black box” rather than labored over for years) and some well-placed label-pushers—all processes that could occur on the time-scale of weeks and months rather than years—and one could indeed imagine seeing a sharply discontinuous expansion in the susceptible population.

It might be possible to capture this effect in the classic SIR model simply by fine-tuning the parameter Λ, the influx of new recruits to the susceptible population. We could either have it grow exponentially or even make it a step function, timed to 'go off' in 1990. Or we might want to play with entirely new models, beyond SIR and SEI/SEIZ, to take into account these non-apprenticeship, fast-paced re-labelings that can occur across previously uncorrelated research fields. Here we might make more contact with epidemiological models of rumors and fads (with which Carlos is no doubt most familiar).

Finally, note that all of the factors above were focused on the behavior of the susceptible population over time, $S(t)$. There might well have been a jolt in the average contact rate, β, at the exact same time: email came into widespread use (at least among academics) at *exactly* this moment. So whereas the period of interest (ca. 1989-91) falls *before* the rise of the internet—and hence web-based contact and transmission is irrelevant to the take-off period—we might nonetheless expect an abrupt break in average contact rates right around 1990. Before that time (ca. 1983-1990), we might expect contact and transmission rates akin to those we found for the Feynman diagram case, based on who trained with whom and what conferences people attended. After 1990, email might have come to dominate—*especially* if the nano spread owed more to re-labeling among people who were already up-and-running in their separate fields rather than to genuine apprenticeship in a well-defined area.

Given the unnerving regularity of the number of nano articles per year after 1991 (growing exponentially with virtually no fluctuations around the best-fit curve), moreover, it doesn't look like the web played a qualitatively new role once it did become available. That is, we seem to have a constant contact rate after 1990, perhaps affected by email but seemingly unaffected by the web. If the web *had* been a major factor in the way nanotech spread, one would expect to see another inflection point in the nano articles output after ca. 1995.

Thus it might be possible to model the diffusion of nanotech using an SIR model in which both Λ and β change discontinuously around 1990. Of course, as we have emphasized all along, exploring any of these modeling options in more detail will require some means of measuring or approximating the *author* pool for all the nano articles (in particular, the first-time authors per year), rather than the number of articles alone. Work along this front continues.

References

Bettencourt, Luís, Ariel Cintrón-Arias, David Kaiser, and Carlos Castillo-Chávez. 2006. "The power of a good idea: Quantitative modeling of the spread of ideas from epidemiological models." *Physica A* 364: 513-536.

Darby, Michael and Lynne Zucker. 2003. "Grilichesian breakthroughs: Inventions of methods of inventing and firm entry in nanotechnology." NBER Working Paper 9825, July 2003. (Available at http://www.nber.org/papers/w9825.)

Mody, Cyrus. 2004. "How probe microscopists became nanotechnologists." In *Discovering the Nanoscale*, ed. D. Baird, A. Nordmann, and J. Schummer, 119-133. Amsterdam: IOS Press.

Mody, Cyrus. 2005. "Instruments in training: The growth of American probe microscopy in the 1980s." In *Pedagogy and the Practice of Science: Historical and Contemporary Perspectives*, ed. David Kaiser, 185-216. Cambridge: MIT Press.

Mody, Cyrus. 2006. "Constituent communities and the creation of nanotechnology." Invited colloquium presented at MIT's Program on Science, Technology, and Society, 27 February 2006.

Zucker, Lynne and Michael Darby. 2005. "Socio-economic impact of nanoscale science: Initial results and NanoBank." NBER Working Paper 11181, March 2005. (Available at http://www.nber.org/papers/w11181.)