= Drexler ? Smalley debate on molecular nanotechnology =

The Drexler ? Smalley debate on molecular nanotechnology was a public dispute between K. Eric Drexler , the originator of the conceptual basis of molecular nanotechnology , and Richard Smalley , a recipient of the 1996 Nobel prize in Chemistry for the discovery of the nanomaterial buckminsterfullerene . The dispute was about the feasibility of constructing molecular assemblers , which are molecular machines which could robotically assemble molecular materials and devices by manipulating individual atoms or molecules . The concept of molecular assemblers was central to Drexler 's conception of molecular nanotechnology , but Smalley argued that fundamental physical principles would prevent them from ever being possible . The two also traded accusations that the other 's conception of nanotechnology was harmful to public perception of the field and threatened continued public support for nanotechnology research .

The debate was carried out from 2001 to 2003 through a series of published articles and open letters . It began with a 2001 article by Smalley in Scientific American , which was followed by a rebuttal published by Drexler and coworkers later that year , and two open letters by Drexler in early 2003 . The debate was concluded in late 2003 in a " Point ? Counterpoint " feature in Chemical & Engineering News in which both parties participated .

The debate has been often cited in the history of nanotechnology due to the fame of its participants and its commentary on both the technical and social aspects of nanotechnology . It has also been widely criticized for its adversarial tone , with Drexler accusing Smalley of publicly misrepresenting his work , and Smalley accusing Drexler of failing to understand basic science , causing commentators to go so far as to characterize the tone of the debate as similar to " a pissing match " and " reminiscent of [a] Saturday Night Live sketch " .

= = The participants = =

= = = K. Eric Drexler = = =

K. Eric Drexler is generally considered to have written the first scholarly paper on the topic of nanotechnology , and was a key figure in popularizing these concepts through several publications and advocacy work . Trained as an engineer , Drexler was inspired by a then @-@ obscure 1959 talk by physicist Richard Feynman called There 's Plenty of Room at the Bottom , which posited that it should be physically possible to manipulate individual atoms using top @-@ down engineering methodologies . Drexler was also inspired by recent advances in molecular biology such as recombinant DNA technology . In a 1981 publication in Proceedings of the National Academy of Sciences , considered to be the first journal article on nanotechnology , he argued that biological systems such as the ribosome were already capable of building molecules atom @-@ by @-@ atom , and that artificial machines with this capability could also be constructed . Drexler went on to publish two books on nanotechnology : Engines of Creation in 1986 , which was intended for the public , and the technical work Nanosystems in 1992 . He also co @-@ founded the Foresight Institute , a public interest group devoted to increasing public awareness and information about molecular nanotechnology .

Drexler 's vision of nanotechnology , now called molecular nanotechnology , is based on the concept of the molecular assembler , a molecular machine which would manufacture molecules and molecular devices atom @-@ by @-@ atom . Drexler drew a distinction between wet nanotechnology based on biological systems , and " second @-@ generation " dry nanotechnology which would be based on mechanosynthesis , positional control of molecules through principles more related to mechanical engineering . Drexler and his followers have focused almost exclusively on the latter form of molecular nanotechnology , but Drexler has stated that both are valid pathways to creating molecular machine systems .

= = = Richard Smalley = = =

Richard E. Smalley , a chemist at Rice University , was best known as a co @-@ discoverer of the C60 form of carbon known as buckminsterfullerine in 1985 , along with Harry Kroto , Robert Curl , James Heath , and Sean O 'Brien . Buckminsterfullerene was the first to be discovered of the class of molecules known as fullerenes , which also includes carbon nanotubes . The study and application of fullerenes forms a significant part of the fields of nanomaterials and nanoelectronics , and Smalley , Kroto , and Curl were awarded the 1996 Nobel Prize in Chemistry for their discovery .

Smalley had also taken a prominent public policy role in relation to nanotechnology , and was an outspoken advocate for using nanotechnology to develop solutions to the world 's energy and health problems , for example raising the possibility of using nanomaterials for efficient energy storage and transmission , and of developing nanomaterial @-@ based drugs for targeted drug delivery . Smalley was also active in commercializing his academic research into carbon nanotubes , having founded Carbon Nanotechnologies Inc . , and serving on the scientific advisory board of two other biotechnology and nanotechnology startups . Smalley died of leukemia in October 2005 , after the conclusion of his debate with Drexler .

= = The debate = =

= = = Smalley 's Scientific American article = = =

Smalley wrote an article , " Of Chemistry , Love , and Nanobots " , for the September 2001 issue of the popular science magazine Scientific American , which was a special issue on the topic of nanotechnology . Smalley opened by comparing a chemical reaction to an intricate dance of atoms :

When a boy and a girl fall in love , it is often said that the chemistry between them is good . This common use of the word " chemistry " in human relations comes close to the subtlety of what actually happens in the more mundane coupling of molecules . In a chemical reaction between two ' consenting ' molecules , bonds form between some of the atoms in what is usually a complex dance involving motion in multiple dimensions .... And if the chemistry is really , really good , the molecules that do react will all produce the exact product required .

He referenced the idea of a molecular assembler , a nanorobot capable of manipulating individual atoms to build a desired product , posing the question of how long it would take such an assembler to produce a meaningful amount of material . He estimated that one assembler working alone would take millions of years to produce one mole of material , but self @-@ replicating assemblers could within a minute produce a large enough ensemble of assemblers that would then be capable of producing a mole of product in a fraction of a millisecond . Smalley then discussed the fear that the nanorobots could mutate and reproduce indefinitely , causing a grey goo scenario , or , referring to Bill Joy 's previous article " Why the future doesn 't need us " , that the nanorobots could develop swarm intelligence and become alive in some sense .

Smalley then considered how realistic was the concept of a self @-@ replicating nanorobot . He noted that in a chemical reaction , the chemical bonds are all interconnected and that the placement of each atom is sensitive to the position of all the other atoms in the vicinity . He then asserted that a molecular assembler would thus have to control many atoms simultaneously in order to work , and would thus have to have many manipulator arms . This led him to raise two objections to the concept of molecular assembler , which he calls the " fat fingers problem " and the " sticky fingers problem " :

Because the fingers of a manipulator arm must themselves be made out of atoms , they have a certain irreducible size . There just isn 't enough room in the nanometer @-@ size reaction region to accommodate all the fingers of all the manipulators necessary to have complete control of the chemistry .... [Also ,] the atoms of the manipulator hands will adhere to the atom that is being moved . So it will often be impossible to release this minuscule building block in precisely the right spot . Both these problems are fundamental , and neither can be avoided . Self @-@ replicating ,

mechanical nanobots are simply not possible in our world .
Smalley closed the article by returning to the analogy of chemistry as a dance of love , remarking that " you don 't make a girl and a boy fall in love by pushing them together . "

= = = Drexler 's response = = =

Drexler responded by publishing a rebuttal later in 2001 through the Institute for Molecular Manufacturing , which was co @-@ authored with others including Robert Freitas , J. Storrs Hall , and Ralph Merkle . The authors first discussed the " fat fingers " argument by attacking Smalley 's notion that a chemical reaction must involve five to fifteen atoms , stating that many reactions involve only two reactants , one of which can be immobilized and the other attached to a single " finger " . They cited as evidence experimental and theoretical results indicating that using scanning tunneling microscope (STM) tips and related technologies could be used as a reactive structure for positional control and for interaction with surface @-@ bound molecules . They also noted that atomically precise final products do not require precise control of all aspects of the chemical reaction . The authors noted that the " sticky fingers " problem is valid in some reactions , but argue that it would be fallacious to conclude that all reactions have this problem .
The authors put forth the ribosome as an example of a natural molecular machine ; because the ribosome suffers from neither problem , they must not be fundamental , saying :
This ubiquitous biological molecular assembler suffers from neither the ? fat finger ? nor the ? sticky finger ? problem . If , as Smalley argues , both problems are ? fundamental , ? then why would they prevent the development of mechanical assemblers and not biological assemblers ? If the class of molecular structures known as proteins can be synthesized using positional techniques , then why would we expect there to be no other classes of molecular structures that can be synthesized using positional techniques ?
The authors also questioned Smalley 's figures for the replication time of nanomachines . Instead of Smalley 's figure of 1 GHz for the atomic placement frequency , they point out that Nanosystems suggested a frequency of 1 MHz , a thousand times slower , and that at Smalley 's higher frequency diamondoid nanomachines would overheat and decompose in milliseconds . The authors called this a straw man argument , writing that " in a serious scientific discussion , a discrepancy of three orders of magnitude between what has been proposed in the literature and what is criticized suggests at best an inadequate grasp of the proposal . " The authors closed by stating that the best way to find out whether molecular assemblers are feasible is through experimental and theoretical work , and that " there are many worthy molecular systems engineering challenges to overcome , but thus far , there has been no credible argument that these devices are infeasible . "
Drexler followed up with two open letters to Smalley in April and July 2003 . The April letter began , " I have written this open letter to correct your public misrepresentation of my work . " Drexler accused Smalley of continuing to dismiss his work by publicly describing molecular assemblers as requiring what Drexler now calls " Smalley fingers " , which he stated to be unlike the enzyme @-@ like systems he had actually proposed . He asserted :
The impossibility of " Smalley fingers " has raised no concern in the research community because these fingers solve no problems and thus appear in no proposals . Your reliance on this straw @-@ man attack might lead a thoughtful observer to suspect that no one has identified a valid criticism of my work . For this I should , perhaps , thank you .
Drexler compared the nanotechnology debate 's importance to that of discussions of spaceflight before Sputnik or to theoretical work on nuclear chemistry before the Manhattan Project . He disputed Smalley 's arguments that the fear of a grey goo scenario would hinder continued funding of nanotechnology research , arguing that the potential for long @-@ term risks made research even more important . His conclusion stated , " your misdirected arguments have needlessly confused public discussion of genuine long @-@ term security concerns . "
The July 2003 letter referenced a note from Smalley promising to respond , which had yet gone unfulfilled . Drexler mentions inconsistencies in Smalley 's previous public statements on atom @-@ by @-@ atom construction , and ended by stating " I would not ordinarily raise an issue so

persistently , but the question of what nanotechnology can ultimately achieve is perhaps the most fundamental issue in the field today ? it shapes basic objectives and expectations ? and your words have been remarkably effective in changing how this issue is perceived . "

= = = Exchange of letters in Chemical & Engineering News = = =

The debate was concluded in a " Point ? Counterpoint " feature that was the 1 December 2003 cover story of Chemical & Engineering News , the newsmagazine of the American Chemical Society . The feature first reproduced Drexler 's April 2003 open letter to Smalley . Smalley 's response began by apologizing for any offense his September 2001 article had caused , and stating that Drexler 's book Engines of Creation had triggered Smalley 's own interest in nanotechnology . He agreed that " Smalley fingers " could not work , and then asserted that the same reasons that would preclude atomic control of reactions would also preclude the manipulation of larger building blocks , since each molecule would have multiple atoms which would need to be controlled

He then agreed that something like an enzyme or ribosome would be capable of precise chemistry , but asked how the nanorobot would be able to obtain , control , and repair such an enzyme , and noted the incompatibility of many reactions with water @-@ based biological systems , stating that " biology is wonderous in the vast diversity of what it can build , but it can 't make a crystal of silicon , or steel , or copper , or aluminum , or titanium , or virtually any of the key materials on which modern technology is built . " Smalley asked what kind of " nonaqueous enzymelike chemistry " Drexler would envision for his molecular assemblers to operate upon , calling this " a vast area of chemistry that has eluded us for centuries . "

Drexler 's counterresponse began by returning to Feynman 's 1959 talk , stating that " although inspired by biology ... Feynman 's vision of nanotechnology is fundamentally mechanical , not biological . " He characterized the challenges as being that of systems engineering rather than solely chemistry , and referred Smalley to Nanosystems , with its vision of mechanical control of chemical reactions with no enzymes and no reliance on solvents or thermal motion . He stated :

Positional control naturally avoids most side reactions by preventing unwanted encounters between potential reactants . Transition @-@ state theory indicates that , for suitably chosen reactants , positional control will enable synthetic steps at megahertz frequencies with the reliability of digital switching operations in a computer . The supporting analysis for this conclusion appears in " Nanosystems " and has withstood a decade of scientific scrutiny .

Drexler reiterated that these molecular assemblers would require no impossible fingers , and would augment solution @-@ phase chemistry to produce macroscopic products with precise arrangements of chemical building blocks , using solution @-@ phase molecular assemblers to bootstrap the construction of more sophisticated assemblers . He concluded by writing :

U.S. progress in molecular manufacturing has been impeded by the dangerous illusion that it is infeasible . I hope you will agree that the actual physical principles of molecular manufacturing are sound and quite unlike the various notions , many widespread in the press , that you have correctly rejected . I invite you to join me and others in the call to augment today 's nanoscale research with a systems engineering effort aimed at achieving the grand vision articulated by Richard Feynman .

Smalley began his concluding letter :

I see you have now walked out of the room where I had led you to talk about real chemistry , and you are now back in your mechanical world . I am sorry we have ended up like this . For a moment I thought we were making progress . You still do not appear to understand the impact of my short piece in Scientific American . Much like you can 't make a boy and a girl fall in love with each other simply by pushing them together , you cannot make precise chemistry occur as desired between two molecular objects with simple mechanical motion along a few degrees of freedom in the assembler @-@ fixed frame of reference . Chemistry , like love , is more subtle than that .

Smalley stated his belief that most reactions using mechanosynthesis would simply give the wrong product , and that very few reactions and target molecules would likely be compatible with such an approach . He asserted that any robotic assembler arm would need an enzyme @-@ like tool at its end such would require a liquid medium , and as all known enzymes use water as that medium , the

range of products must be limited to the " meat and bone of biology . " He accused Drexler of creating " a pretend world where atoms go where you want because your computer program directs them to go there . "

Lastly , Smalley recounted his recent experience reading essays written by middle and high school students after an outreach visit , saying that nearly half of them thought that self @-@ replicating nanorobots were possible and that most were worried about the results of them spreading across the world . Smalley called this a deeply troubling bedside story that he did his best to allay . Smalley concluded his letter :

You and people around you have scared our children . I don 't expect you to stop , but I hope others in the chemical community will join with me in turning on the light , and showing our children that , while our future in the real world will be challenging and there are real risks , there will be no such monster as the self @-@ replicating mechanical nanobot of your dreams .

= = Critical response = =

= = = Tone = = =

The debate has been widely criticized for its adversarial tone . David Berube in Nano @-@ Hype : The Truth Behind the Nanotechnology Buzz characterized it as " two people talking over each other ... not conducive to reasonable rebuttal , " and quoted nanotechnology blogger and journalist Howard Lovy as saying " the tenor of the debate is about personal pride , reputation , and a place in the pantheon . " Zyvex founder James von Ehr remarked that " Eric [Drexler] didn 't do himself any favors by getting into a pissing match with a Nobel @-@ prize winner . " An article in The New York Times called the debate " reminiscent of that old Saturday Night Live sketch ... [with] Dan Aykroyd and Jane Curtin tossing insults at each other while ostensibly debating a serious political issue , " referring to a version of the long @-@ running Weekend Update segment .

= = = Technical commentary = = =

The debate has received technical criticism as well . Steven A. Edwards in The Nanotech Pioneers noted that the ambiguity of the specifications and even definition of a molecular assembler makes an evaluation of the argument difficult and minimizes its scientific implications . He remarked that " nowhere in it does Nanosystems contain a blueprint for a molecular assembler ... We are told , for instance , that a manipulator arm would involve 4 @,@ 000 @,@ 000 atoms , but we are not told which atoms , or how they would be put together . " He concludes that " the debate over mechanosynthesis so far is huge to the participants , but mainly an entertaining academic diversion to most nanotechnologists . "

On the other hand , futurist Ray Kurzweil in his book The Singularity Is Near declared Drexler as the winner of the debate , reiterating the view that Smalley distorted Drexler 's ideas and calling Smalley 's responses " short on specific citations and current research and long on imprecise metaphors " and asserting that " Smalley is ignoring the past decade of research on alternative means of positioning molecular fragments using precisely guided molecular reactions ... [which have] been extensively studied . " He quoted experimental results on enzyme function in nonaqueous solutions , and pointed out that modern non @-@ biological technology such as airplanes and computers have exceeded the capabilities of natural biological systems . He also noted that " earlier critics also expressed skepticism that either worldwide communication networks or software viruses that would spread across them were feasible ... [but today] we are obtaining far more gain than harm from this latest example of intertwined promise and peril . "

= = = Commentary on public perception of nanotechnology = = =

The debate 's focus on the public perception of nanotechnology has also received commentary .

Political blogger Glenn Reynolds stated that " the business community is afraid that advanced nanotechnology just seems too , well , spooky ? and worse , that discussions of potentially spooky implications will lead to public fears that might get into the way of bringing products to market . " Lawrence Lessig criticized the scientific establishment , represented by Smalley , for arguing that " if so @-@ called dangerous nanotech can be relegated to summer sci @-@ fi movies and forgotten after Labor Day , then serious work can continue , supported by billion @-@ dollar funding and uninhibited by the idiocy that buries , for example , stem cell research . " Kurzweil wrote that Smalley 's approach to reassuring the public would backfire because it denied both the benefits and risks of molecular nanotechnology .