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Interview with Damian Gregory Allis

Questions by Sander Olson. Answers by Damian Gregory Allis

Damian Allis obtained his doctorate from Syracuse University in Quantum Chemistry where his research interests included molecular electronics, neutron spectroscopy, solid-state molecular theory, crystal engineering, and molecular nanotechnology. Damian received the Foresight Institute's Feynman Distinguished Student Award in 2004 for his application of theoretical computer models to the design and study of molecules and nanostructures. He has received four patents in molecular design, written many articles and given numerous technical presentations at conferences and universities. His ongoing research includes solid-state vibrational theory in conjunction with the new VISION facility in development at Oak Ridge National Laboratory, computational drug design and modeling with Molecular Insight, Inc., and numerous independent research efforts. His personal web site is located at www.somewhereville.com.

Question 1: Tell us about yourself. What is your background, and what are your current affiliations?

Most of my youth was spent in front of Legos. I left high school a jazz drummer with no inclination towards science and finished college with no aptitude for anything else. There's a lesson in there for every student and a beacon of hope for every concerned parent. I did both my B.S. and Ph.D. at Syracuse University, which, in theory, was to keep me on a straight-and-narrow path through the research I started as an undergrad. Graduate students of my generation are the ones that got caught up in the explosion of academic interest in what started as "nanotechnology" and turned into "nanoscience" or, more accurately, "science at the nanometer scale." The change was pretty transparent to most of us, as advisors just began tacking "nano-" in front of their research and we all kept doing what we already were. My little research boat was caught in that sea change, and I even managed to snare a bit of cargo as nanotech was... mainstreamed.

Currently, I'm still living in Syracuse as a resident theorist of sorts working in neutron scattering spectroscopy, inorganic cluster theory, bits of main group chemistry, molecular electronics, and supramolecular chemistry. The department has been very good to me, as my apartment isn't wired for having 60 CPUs running full-time. My formal appointment at Syracuse is as a CIA post-doctoral research fellow working in the field of terahertz spectroscopy and molecular solid-state theory. Off campus, I consult as a theorist for a pharmaceutical company in Boston, am on the advisory board for Nanorex, Inc., do some outside collaborations in nanomaterials modeling with the help of computing resources at NCSA, and occasionally peddle my molecular graphics from my own site and The Nanotechnology Group. And I occasionally pick up the drum sticks for gigs.

Question 2: You are a research fellow with the Molecular Engineering Research Institute (MERI). What is that Institute? What research are you doing for that institution?

MERI is embryonic and I'm very much the new guy, so I unfortunately don't have specifics for you, as we're all still figuring out what it is we want it to be. I'll begin in a seemingly roundabout way by saying that, as an 8-year member, I'm glad to see that the Foresight Institute is settling into the important role of bridging near-term and long-term research in molecular nanotechnology. That's the most important thing any group not directly involved in pure research can do right now. Engineers at companies directly turn results from scientists at universities into products

MERI, I suspect, will be a very vocal proponent for the long-term end of the journey in molecular nanotechnology, advanced molecular manufacturing (AMM). I don't think anyone in this business doesn't recognize K. Eric Drexler and J. Storrs Hall, whose names adorn the content now place-holding the current site. They and the other members of MERI are very much in the AMM mindset and are performing research towards that end, some of which I suspect will be elaborated on in the questions. I realize that's a very long answer with very little information, but I've little more to add until everything goes live. I'm slowly putting together the official website, making it yet another long-term goal somewhere in molecular nanotechnology. Please stay tuned.

Question 3: You are also doing research for Molecular Insight Pharmaceuticals (MIP). What work are you doing for that company?

MIP is a company developing diagnostic and therapeutic radiopharmaceuticals, with a heavy emphasis on the diagnostic side. In the interest of acclimation, radiopharmaceuticals are just molecules that contain radioactive isotopes, or radioisotopes, of certain nuclei. The breakdown product of the radioactive decay of the isotope is then either used for imaging purposes, which is what my work has been geared towards, or for obliterating cells in the vicinity of the decayed nucleus, meaning a correctly placed radiopharmaceutical can, for instance, serve the role of a chemical scalpel.

In both cases, placement is key. If your goal is heart or lung imaging, you clearly want the radiolabeled drug localized in the heart or lung. The last thing a hospital technician wants to see is a six-foot glowing patient in a PET machine or gamma camera while trying to diagnose a finger-sized piece of tissue. That'd be as useful as looking for sunspots with your naked eye in the middle of summer. Localization comes through identifying molecules that bind specifically in certain kinds of cells or tissue. If you know a molecule will settle in a specific organ and not others, then imaging becomes a very straightforward process. Towards that end, one way to image an organ is to identify molecules (drugs) that we already know bind there and then piggy-back small molecular pieces that contain the radioisotope. You can, of course, run through the process of starting from absolute scratch to design a drug, but any amount of bet-hedging one can do in the field is *de rigueur*, given how little we still understand about the human body.

So, to spare gory details and keep the patent lawyers happy, what I do as a theoretician is diagnose drug candidates that the company's interested in and, as applicable, recommend changes. My typical screening process is to identify where a drug binds on a particular protein, modify the drug with a particular molecular subunit containing the radioactive nucleus, and run simulations to see if and how the radioactive subunit affects the binding of the drug. There are many assumptions made in such a study. Specifically, we assume the radiolabeled drug won't bind somewhere else that we can't predict. That's where the leg-work leading up to the clinical trials comes in. We also assume, for the most part, that the drug interaction with the protein is the same with or without the label, so we're only monitoring changes to the drug binding with a big bulky group on it. It won't tell you that a drug will bind once the pill is popped, but the theory provides a very good picture of if and how the drug would bind given the assumptions I mentioned above. Theory's very good at telling you if a tether connecting the drug and the radiolabel may be too short, if the choice of subunit holding the radioisotope is sub-optimal based on steric interactions in the binding pocket and if another subunit may be more appropriate, etc. The top brass at MIP also like my pictures, so I get occasional dual-use.

Question 4: Tell us about your work with the nanotechnology startup company Nanorex.

Well, just to make sure no one's out of the loop, Nanorex, Inc. is a Detroit company developing an open source nanomechanical CAD/simulator package called nanoENGINEER-1 (nE-1). Nanorex, Inc. is sponsoring the initial development and focusing the architecture so that future developers, of which we hope there will be many, have all the blueprints they need to make sure the package is as flexible but integrated as possible. We hope that the program, while geared at nanomechanical engineering, will also find favor among quantum chemists, molecular dynamics folks and materials scientists. Those are very well-defined disciplines where researchers walk into projects with very specific needs and expectations of software, which makes the task of integration a very significant and

had about as much interaction with one another to date as mail clerks would have with the CEO of a multi-national corporation. Developing molecular manufacturing correctly is going to require answering questions at every order of magnitude. The ultimate goal is to have nE-1 be a package that provides users with that kind of functionality.

My primary role is an advisory one. I'm not a mechanical engineer, but I've had more than my fair share of experience with quantum chemical and classical dynamics programs. My use to the company is as a typical end-user with some background in the tools of the trade and expectations of what the program should do to make lives easier. Another part of what I'm doing is showing where methods, specifically quantum chemical methods, are best applied and how to apply them in the context of nanoscale simulation. My other chemistry research is very applied, where I'm trying to answer very specific problems in the lab. I know when certain theoretical methods are applicable to a problem, when the theoretical methods break down for what I'm trying to study, and, after enough time in the field, when to say "when" on a particular project and not push the use of theory any further than it needs to go. That seems like a strange point, but computational chemistry is, if nothing else, processor-dependent. There's no need to wait a week for an excellent answer when a one-day calculation to get a good enough answer is warranted.

I'm also doing what I can in the developmental side, which has largely consisted of troubleshooting problem spots in the parameter generation for the simulator engine in the program, storyboarding instances where quantum chemical studies are required so that those doing the real development can see how a researcher might want to use the software to tackle specific problems, and getting my hands dirty running calculations to answer questions people have in the simulations while the code to automate the process is still being developed. I suppose I'm working hard to put myself out of a job, playing resident quantum mechanic in the meantime.

Question 5: Nanorex has managed to get both Eric Drexler and J Storrs Hall as employees. What is Nanorex doing that is so special?

Well, as it happens, Josh Hall was never brought on board. He owns part of the boat! Josh and Mark Sims happened to have the same notions of putting together a nanoCAD package at the same time and decided that two heads were better. Josh's expertise is in the simulation side, while Mark Sims has a tremendous CAD background and is graciously providing the infrastructure within which everyone is making the program happen. The world would be a much better place if we had more people like him.

Nanorex and nE-1 end up being very special, active at every rung on the nanotechnology excitement ladder. At the bottom end, it's a very feature-rich molecular/nanoscale design interface and molecular dynamics simulator that includes quantum chemical functionality through, at the moment, my favorite program GAMESS and Brian Helfrich's Nano-hive package, which uses MPQC. A phenomenal free interface to phenomenal free programs, because the computers are expensive enough. Further up the ladder, nE-1 is available for Windows, Linux, and OSX and runs identically in all OSs, meaning a user can sit in front of any computer and always get work done, even if that person's a Windows user who thinks that a "terminal window" is one that won't close. Windows may own 95% of the home and business market, but I know Syracuse's chemistry department is 40% Mac, and I imagine other departments run in similar numbers given the number of PowerBooks I see at academic conferences.

One large step above those rungs, it's a program with a CAD interface designed around the treatment of atoms and molecules as components in nanostructures. There's functionality for treating periodic solids, such as diamond, as bulk materials for nanoscale designs, and then similar functionality for treating molecules as building blocks in larger structures. The molecular treatments are, of course, standard at this point, as most programs have some kind of subunit manipulator for making peptides, DNA strands, dendrimers, or any other kind of polymer.

One large step up, it's a package that includes all of the necessary tools to begin thinking about nanostructures as mechanical components, including jigs for standard molecular dynamics features such as thermometers and thermostats, and introducing rotary and linear motion through motors in the simulations themselves, so that the mechanical properties of nanostructures can be examined within the framework of a classical dynamics simulation.

limitations of modern theoretical methods, people will be able to address design and operational issues in nanoscale devices through quantum chemical modeling and the mechanical properties of nanostructures through classical dynamics simulations. Personally, I foresee a broad user base for the program because it's turning into a very powerful computational chemistry package that's going to ignite engulfing flames under many a chemist's trousers. That said, much of the functionality in the program is being designed with "Drexlerian" nanotechnology in mind. Accordingly, everyone on the project would agree that having Eric as a guiding force is as valuable to us as having Richard Feynman teaching you physics or Linus Torvalds walking you through kernel development.

But stepping back for a moment, the program will be broadly applicable to any nanoscale researcher that sees a use for theory before experiment. Theory is at a point now where its ability to help researchers answer questions is limited only by the speed of the processor in the computer being used to hammer on the equations. At this point in the game, there's no need to go cold into any scientific endeavor involving anything chemical. Theory's as predictive as it is descriptive and everyone that can benefit from the insights calculations offer should take advantage of them.

Question 6: You have done research into molecular electronics. How sanguine are you about the future of molecular electronics? Do you believe that molecular electronics will eventually supplant conventional silicon CMOS?

I would love to see the world's supply of Twinkies and Spam put to better use. There are those, like James Tour or Mark Reed, who do molecular electronics with interest in using molecules for nanoscale electronics, then there are those who look at the properties of macroscopic materials made out of molecules, such as in liquid crystal devices or nonlinear optical materials, and optimize molecular properties to optimize macroscale properties. I'm the latter, because some Syracuse alum had to do it. Accordingly, as it's not my expertise, my opinion on the feasibility of molecular CMOS + $0.02 = $0.02.

So, to provide an opinion anyway, I see no reason why everything won't go molecular and, given all the fuss and high praise in my Scientific American issues from the mid-90's, I'm surprised we don't hear more about it than we do in even the general media, meaning I suspect the cruel reality of chemical synthesis caught up with people's optimism or the field's in that intermediate phase where successful work is being done quietly *en route* to applications. I don't know which, but I check digg and slashdot all the time just in case. I think the same hype hit carbon nanotubes around the same time when everyone was "thinking" nanotech while only a few were actually "doing" nanotech. I'm sure the chip companies will be just as resistant to retooling their production lines for anything molecular electronics as the automobile industry is to retooling for hydrogen, electric, or more efficient petrol combustion. It will be a humorous switch to go from worrying about quantum phenomena in current lithographic approaches to worrying about the statistical mechanics of polymer-based quantum computers.

I see images of current carbon nanotube transistors and can't help but picture the original 15 cm transistor in my head, but it's all been shown in the lab. I think Ellenbogen and Love's "pink book" is still a great read and, as it's free, everyone should check it out.

Question 7: The Foresight Institute has an animation of a desktop manufacturing system in operation. How technically accurate is this animation?

The revolution will be televised! Or, at the very least, bittorrented. I'm glad you asked. There are a lot of levels to the animation, and I'm not just talking about the levels of abstraction. I'll begin by saying that, at every step, either something is technically correct or is, for lack of a better term, allegorical, meant to highlight some very intricate process or event that can be made to be technically correct but that doesn't need to be for the sake of getting the point across. People wishing to knock holes in the merits of the animation will look at the "indicator" aspects and scream "implausible," which is regretful. After the Drexler/Smalley debate in Chem. and Eng. News, there was one letter to the editor entitled "Oh Dear, What Can The Matter Be" where, apparently, the writer's only criticism of content in the debate was a caption that showed a nanoscale depositor placing a feedstock into a workspace. He

There are certain parts to the movie that probably bug attentive chemists, including myself to some extent, but those parts are there to be scrutinized and "filled in" by research, which is the first thing I thought of when I saw them. I won't speak for Eric and John Burch, but I would imagine that one important part of having this walk-through of a mechanosynthetic process is to finally have specific steps in a fabrication process drawn out, on screen, for people to begin arguing about. Why argue about feasibility when you can knit-pick individual steps along one proposed path? Further, if someone doesn't like what's proposed in a step, they're more than welcome to propose a way around it.

I can speak to the three first steps in the fabrication process, those steps being (a) the sorting of the acetylene feedstock, (b) the binding of the acetylene to the tooltips, and (c) the deposition of the dimer onto the growing block workspace. Beyond the deposition and transfer of the blocks to the later assembler, the value of my opinion drops exponentially with increasing scale in the movie. I'm not an assembly linesman, although I assume we'll be able to accurately manipulate 50 nm blocks in the future if we can move single atoms now.

So, the sorting rotor. The movie shows a cylinder with a divot in it for binding the acetylene, then the passing of the acetylene from one chamber to another before finally getting deposited on a tooltip. Is this part of the movie rendered with atomic precision enough to shake the skeptics into submission. No. This is one of those "indicator" sections. To the typical viewer, they see a molecule being sorted and probably wouldn't think hard beyond it. To a supramolecular chemist or someone knowledgeable in guest-host chemistry, they'll look at the rendering of the acetylene binding pocket in the movie and scream in horror. That said, those chemists would be able to look at the movie and say "Ah. They want to sort acetylene. A binding pocket could probably be designed to preferentially bind acetylene or other small, non-polar, linear molecules that would bind those molecules tightly enough to allow for this mechanical transfer. Jot jot jot, thermochemistry, some quick calculations, a plausible binding pocket falls out. Now, the chemical approach to this piece of the movie might just be to synthesize a membrane that will only pass very small molecules, might bind some small molecules, like molecular oxygen, preferentially, or have a gamut of reaction vessels to get the acetylene as pure as possible beforehand. J. Storrs Hall presented a sorting rotor design at the 13th Foresight Conference that is far more mechanical and complicated than either the animation or this chemical approach are, the point being that we can design a way to sort acetylene and get it pure enough for the next step in the fabrication process.

The tooltip. I refer readers to the following paper from the Journal of Computational and Theoretical Nanotechnology that Eric Drexler and I wrote concerning the use of a molecular tooltip for dimer transfer in mechanosynthesis. I will, accordingly, skip a lot of detail and say that the dimer-transferring tooltip seems completely reasonable in a mechanosynthetic context. One of the biggest problems I've run in to with people arguing against specific aspects of mechanosynthesis is the reactivity of the tooltips being proposed for building these larger structures. If this were chemistry, I'd agree completely. My mechanosynthetic response is very simple. If you work with a system where all interactions NOT between tooltip and workspace are forbidden, then you only get what you want in the fabrication process. That requires, and will require, environmental control beyond what we can do now in the lab, but anyone today that doesn't see a possibility for improvement in their work aren't looking hard enough.

The designed tooltip, which we refer to as **DC10c**, contains, by design, considerable strain and high potential reactivity in the wrong environment. But if you put a stark-raving mad homicidal lunatic on a deserted island with no one to kill and only vegetables to eat, he's an OK guy. There's a big difference between chemical stability and chemical reactivity. The closest structural analogue to the DC10c tip as shown in the movie is the molecule cycloheptyne, which degrades or polymerizes rapidly in solution but which can be studied exhaustively in matrix isolation. This molecule is highly reactive, but I have the vibrational and electronic spectra for that molecule in pdf form on my laptop. A solution-based DC10c approach to deposition would be riotously unpredictable, given the same studies on the strained cycloalkyne rings and, therefore, useless in AMM. That difference between stability and reactivity is key to understanding mechanosynthesis as shown in the deposition process.

is that the surfaces being built up in atomic crystals are prone to reorganization as reactive sites planned for deposited atoms or fragments couple to neighboring reactive sites to form the most stable forms they can given their unusually strained, unbound geometry. When these processes happen faster than envisioned mechanosynthetic deposition, and they all would, the workspace you're expecting and the workspace your tooltip encounters may not be the same, which would be analogous to a carpenter trying to build a Styrofoam wall in a small tidal pool at high tide.

Which means what? To build a periodic solid or nanostructure from a common feedstock, you need to know the properties of the feedstock, the properties of the surface the feedstock is being deposited onto, the stability of the feedstock on the surface after deposition with respect to the positioning of another feedstock next to it, and the properties of the in-process workspace. An important, though not often mentioned aspect of that is picking the best feedstock for the job, which isn't addressed directly in the movie because there are plenty of potential feedstocks and plenty of other workspaces to deposit onto. The dimer and single atom tooltips are easy to consider now because they're small and can be run at very high levels of theory. The feedstock for a diamond block may have to be something bigger, but we won't know the best tools for the job until we've done the calculations. Chemists have found elegant ways to solve synthetic Chinese puzzles. Fortunately, computers are fast enough and software functional enough that we can begin to do those studies in much greater detail than have been, which will guide us through the end of the most quantum mechanical aspects of AMM. After that, it's mostly engineering.

Question 8: You have also done some animations and computer generated images of molecular components. How technically accurate are your animations? Could these animations serve as a template for actual molecular component design?

What few animations I've done have been purely chemical and are all the results of quantum chemical studies, such as animating molecular vibrations or plotting energies relative to some molecular motion. I've steered clear of animating nanostructures because they're too big to run quickly, most of the software I'd been using previously was not up to the task, and most every computer I use is perpetually bogged down with more important calculations. As far as the issue of technical accuracy, almost all of the nanostructures I've played with were calculated with NAMD using CHARMM parameters, both of which are very standard tools to people working in molecular simulations. When a CHARMM parameter isn't available for something I'm modeling, I'll tweak an available number or roll-my-own parameter. Within the classical mechanics equations being used to describe their interactions, there's nothing physically wrong with any of the designs, right down to the packing interactions in the bearing assemblies. I wouldn't sleep well at night just putting "some design" together.

As far as templates, all of my designs are aimed at putting theoretical meat onto a bone that's usually a very benign chemical concept. For instance, I might want to see how to use a dative bond in a self-directed assembly process for nanotubes, or structural designs for making rigid frameworks out of nanotubes, or what else can be done with diamond lattices to make structures, so I'll make lots of big structures to demonstrate how I want to use some simple chemical interaction. I think a long Lego history has hipped me most to the problems of structural quantization in structural designs. For instance, anything you do with diamond runs into restrictions due to the length of the carbon-carbon bonds. It is nice to know there's a lower limit to what we can design, of course. There just aren't enough hours in the day to have complete freedom down there like we do at the macroscale.

And as if I hadn't plugged nE-1 enough. Prior to nE-1, any one of my images involved 3 to 5 hours of sitting there and fiddling to thread together repeat units, figure out correct sizing to make sure things with surfaces were within van der Waals radii contacts, etc. I remember vividly the first nE-1 board meeting where Mark Sims, in a timeframe of 30 seconds, had generated a Drexler/Merkle bearing from two repeat units. After the sudden joy of seeing it done so quickly, I remember thinking about how many hours of my life I'd never get back that I spent doing the same thing by hand.

Well, the inherent feasibility question is the easier one for me to answer. We've all had more time to double check our numbers, and we see people doing more things that hint at atomic precision. From my own perspective, I think an important factor driving new optimism stems from the stagnation of the feasibility debates. We have a group of people who say it's possible, likely, and maybe even necessary given our drive towards the absolute control over matter, we have the group who say it's impossible, unlikely, or not practical for one of many reasons, and we have people just hanging out to see where this trip is going. It's abundantly clear that the "yay" group and the "nay" group are fairly well dug into their trenches and there's nothing to be gained from further debate until there's more research for one or the other side to claim as their own. That would change if someone were to compile the list of all of the grievances opponents of AMM have so that proponents could address them specifically instead of having people's opinions flood the pop. sci. with the same old feral metadata. It is my hope that the discussions on Howard Lovy's Nanobot are saved for future generations, because a lot of interesting, healthy debate went on there that probably looks, in form, very familiar to what similar public discussions concerning quantum theory, the heliocentric view of the solar system, representative democracy, and lots of other ludicrous ideas looked like. I get the feeling that the feasibility debate is over or, at least, it's no longer an issue, I think everyone knows who the major players are and where they stand.

I look at where science has come since Nanosystems, and especially since Feynman's "There's Plenty of Room at the Bottom," and I just think we're on a right track despite what the nay-sayers tell us. You've got single Si atom manipulation, Feringa's optical motors, Tour's got his nanocar. Those things aren't dimer deposition to build diamondoid gears, but they're far more "mechanical" than chemists were thinking 30 years ago, and they certainly hint at all the potential we have for fundamental control over matter that we still don't have today in ANY field. If he were alive today, maybe Feynman would have titled his presentation "There's Plenty Marooned at the Bottom."

Question 10: Chris Phoenix of the Center for Responsible Nanotechnology has stated that molecular manufacturing "might become a reality by 2010, likely will by 2015, and almost certainly will by 2020". Can you foresee any scenario for developing molecular manufacturing capabilities within 10 years?

I'd suspect you could use my knowledge base as a small wedge to straighten Chris's knowledge base on uneven floors. Dinners with him are a mental whirlwind, and I've followed his lead in a number of great discussions. All that said, I'll begin my answer with a taste of Niels Bohr.

"Prediction is very difficult, especially of the future."

Can I foresee a scenario? Sure. Can I foresee a scenario that will be gobbled up by the larger scientific community so that they drop everything and spend 10 hard years getting us to that point? Nope. Envisioned molecular manufacturing is a very straightforward concept coupling feedstock and workspaces to functional devices that's fundamentally different from how most chemists manipulate atoms and most engineers understand building materials. Even if there was full-blown interest in molecular manufacturing, there are still many technological gauntlets to run between what we can do and what we, some of us, want to do, that all are going to require considerable investments to even bootstrap. Now, as an academic, I've been on the receiving end of proposal rejections for projects that probably would have worked within the timeframe of the grant requirements. Even from a purely practical standpoint, there's a finite number of researchers working with finite resources to perform a finite number of experiments to add to our infinitesimal understanding of the world around us. Molecular manufacturing will not happen in theory, in notebooks, in debates. It'll happen in the lab, where everything else does. If experimentalists looking to help AMM proponents test theories and designs are willing to put up time and energy and funding agencies or really nice rich people are willing to put up money to help experimentalists test designs or help theorists convince experimentalists to test designs, then we'll have AMM. Meantime, AMM proponents are kids sitting on the back of a pickup truck in an apple field. We can't go and grab any apple we want to polish and show the world, but the truck is rushing through a very fertile field and we're getting glimpses of what's to come and, increasingly more often, having wonderful peer-reviewed fruit fall right in our laps while we wait.

current climate in the next decade, although I'd love to be proven wrong. AMM is about control and I think we're always pushing towards greater control. In the absence of AMM proponents, science would push so close to what's being envisioned that there probably wouldn't be a difference anyway. In that context, AMM proponents are just trying to make the driver of the apple truck turn in one direction or another to steer it in what we think is the right direction.

Question 11: The mainstream scientific community still treats the concept of advanced molecular manufacturing as an inherently flawed paradigm. Is this due primarily to ignorance, to political expediency, to legitimate technical issues, or a combination of all three?

Well, there are prominent members in the mainstream scientific community who see AMM as inherently flawed, probably lots of quiet ones that don't buy it, and many more that haven't committed much thought to it. I think many factors contributed to the marginalization of AMM. One, it was too new and way beyond what people were doing in the lab at the time of the NNI organization. Two, AMM was being proposed by a very small group of very smart, dedicated researchers who, had they been proposing work more underneath the US research umbrella, would have been shoe-ins for exploratory funding. Three, some very influential people decided it wouldn't work, and they did that based on their opinions. If there were an absolute smoking gun either way, the debate never would have taken place. The fact that we still have these arguments means there's work to be done. Four, those influential people owned very expensive soapboxes. Five, those soapboxes were all stored in Washington DC. Six, people deciding where to put money into nanotech wanted sure things in short order, and sure things are not possible when you have to hold the grass down yourself to start a path. Seven, venture capital came raining down on nanotech, realized that the promises being proposed in the media and popular culture were decades from being reality, and feverishly dried up. The differences between the 8th and 10th Foresight Conferences were remarkable in that respect. Eight, and I think this is the ONLY good reason for what happened with the NNI, there's a lot of good research going on in the US being done by professors at small schools with shoestring budgets. I think investing capital in a group of researchers to think about AMM would be a fine idea, but, at the beginning of the NNI, I don't think anyone believed there was going to be a fundamental retooling of US research interests given the gap between what was proposed and what was currently available. It's a sad state of affairs, but people doing very good work now get turned down for very small grants. You consider how much it cost to make any of the major Hollywood movies this summer, think about how many research groups that money could have funded for a decade, then realize that no one went to see those movies.

The AMM debate is not occurring between "academics" and "crack-pots," which is the tone of many of the short little news articles people can find all over the internet when they google nanotechnology. I consider myself cautiously optimistic. As a scientist, I want hard numbers either way. I'll stand by the research before I stand by my opinion, which is about all I'd ask of both the proponents and the opponents. Frankly, I don't get the whole debate thing. My God, shouldn't we all be in league against the bioinformaticists!? People like Whitesides, Ratner, and Smalley are all very familiar, respected researchers in their fields who have done considerable good for chemistry who all argue against AMM, each with more years of research experience under their belts than I've been alive. I'm amazed by the creativity in George Whitesides' lab, Richard Smalley will be remembered as a man who did a lot of good by pushing nanoscience into the mainstream, and everything I know about molecular nonlinear optical materials I learned from Mark Ratner's publications. Their technical criticisms are to be taken seriously and need to be respectfully addressed. That said, Eric Drexler is categorically the most knowledgeable and well-rounded scientist I have ever met, period. He's one of those few people in the history of science to do the most important thing any scientist can do. He's made many, many people, scientists AND non-scientists alike, THINK. He's brought into the scientific forum an idea that treats matter in a way no one had thought of before in a purely scientific context and those ideas have taken root in society, although it's a shame that a decade or more was lost as people explored "grey goo" scenarios instead of addressing all the beneficial possibilities to not scare people off. As my reading goes, he's the first to comprehensively bridge engineering and chemistry, which means he's also engaged very different fields at once and started a dialogue before all the interdisciplinary pushes we now find happening in academics. If it works out as is

AMM is a testable concept. It is my hope that feasibility and plausibility will be put to the test in a laboratory setting. Those of us thinking it will work will keep publishing until it's either shown in the lab or blows up in our faces. End of discussion.

Question 12: What specific goals do you hope to accomplish within the next decade? Do you have any predictions regarding the state of nanotechnology in 2015?

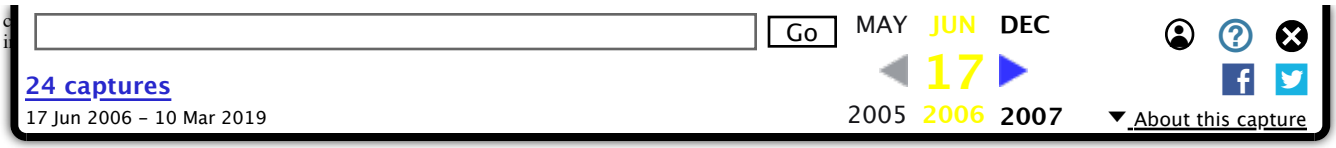
My primary goal is, as always, more computers.

I think, considering what's being proposed and the friction the ideas have caused in the scientific community, it's amazing that the blueprints for most of what we're looking to accomplish in molecular nanotech are only about 20 years old. There's clearly a big gap between what we want to do and what we can do, but that's a gap addressable both directly by working with researchers towards a specific end and indirectly by continuing with theoretical proof-of-principle work. What I would like to do in my work is help to bridge that gap. That's a tall order because we don't actually know what's on the other side yet. The ideas put forth in AMM are amazing ones. Even if we never get to that point, imagine how much further along we'd be if research in manufacturing or device design or molecular electronics were to take from the blueprints.

I think we're correct by expecting atomic precision in our future endeavors, and AMM, whether as envisioned or in some other form more akin to chemical manipulation under extremely new conditions, has to be our ultimate goal. Otherwise we're just dirtying flasks and sitting on a system of the world that involves fractional reaction yields. Chemical theory is all right at this point, we're just waiting on faster machines. To that end, theory is to experiment what architecture is to construction. My goal in nanotech is to help experimentalists look before they leap.

I think AMM is a living, breathing thing reacting to scientific progress. There's a very solid concept of "self" but it will ultimately be driven where science takes it. A big part of what Nanorex and nE-1 are about is testing the physically realizable parts of AMM originally put forth by Drexler. I made this point on nanodot recently. We AMM proponents need to be as scientifically accurate as possible. By putting forth bad designs or flawed concepts, we would do more harm than good, so we need to make sure that what we think will work really WILL work. In the absence of a wet lab to fabricate this stuff, we have to use theory to test things out which, despite the many shortcomings (that's why we call them the "approximate methods!"), manage to get the right answers when the right theory is applied to the right question. We're stubborn in our belief in the plausibility, but we're not THAT stubborn. If things aren't going to work, we want to know so we can address the problems and work around them. As a practicing researcher, I'd much rather have someone criticize a speed reducer gear than the feasibility of molecular manufacturing, because we two parties can sit down and address the gear directly because the design and all the atoms are sitting in front of us. Ideally, the critics would put some energy into constructive alternatives. There is no greater thrill to me than having an idea brainstormed in a room full of people that know their stuff that are interested in finding a way from A to Z. It is my expectation that what Nanorex is doing will change the tone of the discussion in that respect away from catalytic handwaving and towards critique of potentially realizable systems.

As for predictions, not a one. I'm not a futurist by any means. I'm having a hard enough time figuring out what it is I've already done.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