Molecular Nanotechnology – the Best Tech on Offer (if only we could find the assembly manual)

Version 2 ▪ Mark C Marson, 18th November 2024

Abstract

This paper attempts to solve a problem which is blocking the development of full molecular nanotechnology (MNT) – defined as the ability to exactly arrange the molecular structure of materials (in particular those made of crystalline carbon or silicon). I ask if technological progress has an end state and argue that this can only be the ability to synthesize any viable material. I give a very brief account of how this idea developed from the 1950s on and mention one notable debate which illustrates both the fundamental difference between MNT and regular technology and a potential obstacle to the development of MNT if we adhere to conventional approaches. **I then describe a novel synthetic technique that solves this problem – the directed evolution of nanomineral isomers – and detail its six main steps: nanomineral growth, antibody/nanomineral association, antibody differentiation, antibody/nanomineral separation, nanomineral characterization and selection, and iteration.** I discuss nanomineral catalysis and the augmentation of nanominerals with functional groups, some aspects of the design of nanomineral components, a few other obvious applications of MNT, the possibility of so-called smart materials, and the implications of MNT for robotics. In conclusion I argue that the development of MNT is essential if we are to fulfil our potential as a species, and that we needlessly limit ourselves if we do not do that.

Introduction – an overview of technology

The most distinctive feature of humanity is our use of technology, which can be defined as the extension of our abilities resulting from our control over matter. Indeed, the major historical epochs – the stone, copper, bronze, and iron ages – are named after the predominant technological material of the time (the era we currently live in could be called the carbon/silicon age). Our technology evolved for millennia, but progress sped up in the seventeenth century, due in part to the emergence of modern science. Our tools had allowed us to study natural and artificial phenomena more carefully, which led to theories explaining how the physical world works, which in turn often inspired and enabled the development of even better technology. This prompts an obvious question – how will the process end? Is there an ultimate technological capability which, if acquired, would enable us to do anything that is physically and economically possible? And if so – can we not just create it? Is there anything stopping us from improving today's technology up to the limits set by physical law? Since the capabilities of our current non-molecular technologies are determined only by the skill with which we can shape and blend matter the answer may *seem* to be No. Meanwhile, the capabilities of our molecular technologies (chemistry and biochemistry) are determined by how effectively we, or the micro-organisms we control, can synthesize organic molecules. But these *latter* disciplines leave an enormous range of potential molecular technologies unexplored and

undeveloped – those are technologies that could exist if we were able to specify the molecular structure of minerals and the shape of mineral particles at the nanometre scale.

This is the realm of inorganic chemistry and material science. Each type of mineral is defined by its 'unit cell' – an irreducible arrangement of atoms conceptually similar to a chemical compound – and these usually have distinct isomeric forms (a.k.a crystal polymorphs). When the geological preconditions necessary for a particular mineral are present, a lattice of its unit cells will grow resulting in crystal formation. (This can be contrasted with metal alloys where a species is defined by proportions of elements, but the particular elemental composition and arrangement of atoms in a given volume is only known statistically.) We can emulate geological processes in the laboratory with the right equipment, but beyond what this allows us to do we cannot synthesize arbitrary chemically stable mineral unit cells. This matters because it has become clear that we can apply the methodology of mechanical engineering to the design of nanominerals. As things stand then **a truly vast range of materials and molecular devices – which we know are viable – are physically unobtainable.** Speaking figuratively, half of the technological possibilities that molecular science promises (i.e. those based on minerals not organic chemicals) are simply unavailable.

Molecular Nanotechnology – the last and best technology

The field of molecular nanotechnology consists of the study of those technological possibilities and the development of techniques for the synthesis of atomically tailored minerals. MNT was inspired, to a certain extent, by the emergence of biochemistry in the first half of the twentieth century and the realization that certain classes of macromolecule within the cell *are* actual molecular machines (which perform chemical reactions) – a fact which almost guarantees that other implementations of molecular engineering are possible. The most famous exposition of this was Richard Feynman's speech **There's Plenty of Room at the Bottom**(1) given in 1959, quote:

The biological example of writing information on a small scale has inspired me to think of something that should be possible. Biology is not simply writing information; it is doing something about it...

Feynman then talks about practical ways to miniaturize contemporary technology, but goes on to talk about synthesizing tailored minerals (see **Ref 1**), and comes to this conclusion:

Ultimately, we can do chemical synthesis. A chemist comes to us and says, "Look, I want a molecule that has the atoms arranged thus and so; make me that molecule."... But it is interesting that it would be, in principle, possible (I think) for a physicist to

synthesize any chemical substance that the chemist writes down. Give the orders and the physicist synthesizes it.

Feynman gave a follow-up talk twenty five years later in 1984(2) and if we collate his thoughts on the matter, it has to be said that he came painfully close to stating explicitly that inorganic molecular machines could in theory perform chemical reactions (rather than build molecular structures just by placing atoms). This position was however stated much more explicitly two years later by K Eric Drexler in his book **Engines of Creation**(3), and computer simulations soon confirmed that nanominerals could be assembled to form such machines. A development such as this would complete the trend of miniaturization that has massively increased computing power since the 1950s. It would also, for the first time, offer the defining benefit of digital computing to engineers working in hard non-organic matter – the ability to make perfect copies of something without an extensive infrastructure.

However, as alluded to earlier, it is not clear that we can develop MNT simply by improving existing synthetic techniques – if we imagine where those could lead on their own we run into a wall far short of being able to build inorganic molecular devices. If we want to break through that wall we must first clarify some basic ideas, such as how we envisage MNT ultimately working. We also need to acknowledge a basic axiom – a technology can only be *first* developed with *pre-existing* tools. The best engineering tool we have ever possessed is the human hand, and it would be nice if we were able to manipulate atoms and molecules freely and bond them together exactly as we wished (within the rules of chemistry) as if playing with building blocks, but unfortunately it is not that simple. Everything at the molecular level is structured to the same atomic level of detail. Consequently, for any given molecular structure there is one and only one spatially complementary structure that can hold it perfectly and thus manipulate it with perfect control (enzymes are a good example of this – each is tailored to catalyze one particular reaction). MNT researchers would not therefore be able to make a *single* 'molecular assembler' that could make anything else, because that would entail the manipulator changing *its own* structure. This point was made (implicitly) by chemist Richard Smalley in a debate with Drexler from 2001-03(4).

There is however a very simple remedy for this problem – multitasking. A common design solution in engineering is for each tool in a set to be attached to the same type of grip. The appropriate machine can then pick up and use all of the tools with one gripping mechanism. This tactic is used in machine tool multitaskers, multi-bit screwdriver sets, and ribosomes – although ribosomes do not 'pick up' tRNA molecules, rather they select them from aqueous solution using complementary hydrogen bond patterns on mRNA strands, and the workpiece (i.e. the protein) folds into shape by itself so the ribosome does not have to move around it. Multitaskers will certainly play a large role in later

generations of MNT, but it is difficult to see how that prospect can help us create MNT in the first place, since the simplest way to build a molecular multitasker would be with the help of another molecular multitasker! (This 'chicken or egg' dilemma could be seen as Smalley's underlying criticism; see **Ref 4**.) Note too that anything that can be made with a multitasker – either macroscopic or molecular – could also be made using a single purpose method (most production lines are single purpose with a degree of flexibility). To state the obvious though, we do not have molecular scale nanomineral production lines either, so the problem persists. To solve it we need to stop thinking about final forms and instead think about what incremental steps we can take to eventually attain them.

Directed Evolution – a remedy for the intractable

An obvious parallel to this situation exists in nature where species evolve through small incremental changes in their anatomy and physiology. But is such a strategy applicable outside of biology? A nanomineral can be imagined as a single atom onto which other atoms have been added at the right places in a certain order so that a novel nanomineral isomer is formed – this is how we would construct a model of such a structure in computer simulation. (The word 'isomer' refers to the fact that two nanominerals could have the same chemical composition but *different* structures.) However, if we try to modify the 'chemistry by fiat' approach of molecular simulation in order to plan a synthesis that we could possibly carry out in the real world, we immediately find that (as mentioned above) we would need a variety of molecular tools to get the job done. Consequently, since those tools do not exist, we are currently obliged to *grow* nanominerals without regard to the isomeric forms they take(**5**); and therefore logically we should try to *select* the nanominerals we want from the inevitable isomeric mixtures and build on those chosen variants to obtain better structures. In other words, we should for now set aside direct methods and instead adopt an evolutionary approach comparable to that found in nature. Not evolution by natural selection but evolution by artificial selection, or in other words *directed evolution*.

This process would not suffer from the aimlessness of evolution in the natural world – it could be compared to retrosynthetic analysis in organic chemistry where researchers have a target molecule in mind and work backwards choosing plausible precursors until they arrive at easily available chemicals (and as in organic chemistry we would have to deal with the product being mixed with byproduct at each stage). It would also be much faster – in nature gene pools are usually stable for many generations before a new mutation is selected for as advantageous and spreads; in nanomineral evolution we would be selecting a variant from each successive generation (or 'iteration'). In essence then the initial synthetic strategy would be to incrementally enlarge nanominerals while repeatedly selecting those variants that are intermediates on a path to the final

desired nanomineral (the selection would be done using a technique called affinity chromatography which employs antibody proteins to latch on to specific molecular shapes). Here is how the procedure would work in more detail:

1. **Nanomineral growth:** A sample of identical seed nanominerals would be exposed to growth conditions for a short period of time – these would typically be high temperature, high pressure, or laser irradiation. A short duration growth period would ensure that the resulting nanomineral variants were only marginally larger than their precursors;
2. **Antibody/nanomineral association:** The mixture would be exposed to a range of antibodies in aqueous solution (as in normal affinity chromatography) – each antibody species would then weakly bond to an unspecified but *structurally* specific nanomineral variant. This 'random fitting' obviates the need to simulate or predict how a given antibody would bond to that iteration's desired variant;
3. **Antibody differentiation:** The antibody/nanomineral complexes would be separated from eachother by exploiting differences in *their* mass or charge e.g. using conventional chromatography. We thus avoid the problem of how to separate nanomineral variants with different structures but *the same* mass and charge (i.e. different isomers). This is why affinity chromatography is so well suited to this kind of work;
4. **Antibody/nanomineral separation:** Each fraction from Step 3 would have its antibodies separated from their nanomineral isomer molecules using conventional techniques. To get the best result for Steps 2-4 each antibody species would have to bond to one nanomineral isomer only and vice versa, but if this did not happen, different antibody combinations could be tried until that *was* the case;
5. **Nanomineral characterization and selection:** the structure of each nanomineral isomer would be determined using X-ray diffraction or micro-electron diffraction(**6**). At this step we could also find out if a fraction contained impurities (i.e. if the antibody was absolutely selective) and thus decide whether to redo the procedure with different antibodies. Assuming sample purity we would select the isomer which was the best intermediate for eventually obtaining the target nanomineral;
6. **Iteration:** The nanomineral isomer thus chosen would be put through the procedure again to obtain the next desired variant starting at Step 1. Note that we would soon know which antibody to use in each iteration in order to extract the correct intermediate, thus massively simplifying the following steps. The procedure would be repeated as many times as necessary to obtain the final desired nanomineral product.

Note that a variety of different synthetic pathways might be available for obtaining a given nanomineral, and obviously we would want to transition to catalysis as soon as possible so as to cut out the huge amount of byproduct that directed evolution would generate at each mineral growth stage.

Also note that before commencing such research we would have to choose the initial experimental material – basic considerations restrict this choice to silicon based minerals or the mineral form of carbon i.e. diamond (which is considered inorganic even though it is made of carbon). In version 1 of this paper (BTO1) I had doubted the wisdom of using nanodiamonds to get the project started – even though diamond is in general the ideal choice for MNT – but I now think that nanodiamond *would* be a better choice over silicon for the initial material. My opinion changed after looking into two topics: the difficulties of working with silicon(7) and advances in the synthesis of nanodiamonds(8). These studies also affirmed BTO1's take on the importance of the functionalization of nanodiamond isomers, indeed chemists have long been fascinated by this topic(9). Linking functionalized nanodiamonds to make molecular devices could easily be seen as a natural progression of current state-of-the-art research; and such devices could then perhaps provide a more efficient way to make nanodiamond components (i.e. by catalysis) compared to the technique set out in this paper.

To summarize then: directing evolution using artificial selection would enable the incremental improvement of a nanomineral's molecular structure (and it would be much more efficient and quicker than evolution in nature); nanodiamonds could be our working material from start to finish; and, we do not require positional control of molecules beforehand in order to work toward that as a goal.

Applications of Molecular Nanotechnology

The incentive for developing MNT is the wealth of practical applications it promises. To begin with, tailored nanomineral isomers could be used to catalyze reactions in organic chemistry; and this ability would be enhanced if, in addition to using the surfaces of nanominerals for immobilization, we assembled them into devices with moving parts which were able to 'grab' molecules and pull them apart or 'hold' reagents and push them together. This is how many enzymes work, although for them the reaction is often coupled with the burning of a fuel molecule (e.g. ATP). So how could a nanomineral be incorporated into a molecular device as a moving part? Normally in mechanical devices the parts hold eachother in place, but it would be difficult to assemble that kind of structure in the early stages of MNT. Instead, a nanomineral sample could be augmented with surface bonded functional groups and the resulting mixture could be separated into variant specific samples based on *where* exactly on the surfaces those groups had bonded. Different nanominerals functionalized in this way would react together in aqueous solution according to normal chemical rules – which would allow us to connect two nanominerals with a single covalent bond so that the final structure moved in a predictable way (perhaps in response to an electric charge similar to electroactive polymers). This strategy is conceptually similar to various biochemical processes e.g. how amino acids are

linked using peptide bonds during protein synthesis or the way proteins use disulfide bonds to stabilize their structures.

Some techniques in industrial chemistry, such as the Haber process, could be significantly improved with nanomineral catalysis; while other reactions would become feasible or economic for the first time e.g. the conversion of carbon dioxide into ethene (non-IUPAC 'ethylene') and the various reactions needed to completely recycle plastic. Eventually, the nanomineral catalysts could be arranged in production lines with the workpiece molecule being passed between them. This could be very efficient but would require specialized devices for transporting the workpiece and supplying supplementary reagents – and all of these nanomineral devices would have to be designed on computer so that we could be certain beforehand that they would fulfil their intended functions. Fortunately though the simulations would be more reliable than those of proteins because of the natural rigidity of minerals, and we could facilitate the design process by employing virtual reality – this would allow researchers to 'get a feel' for the nanominerals making their work more similar to the kind of tinkering inventors have always made use of to refine their ideas. Four more obvious applications of MNT are: the ultimate miniaturization of computer circuitry (and circuitry which is assembled, not etched), seamless brain/computer interfacing, better growth media and scaffolds for cultured meat, and better solar panels. Today's silicon solar panels have an energy conversion efficiency for natural light of 20%, but panels made from a different material (perovskite) could have an efficiency of over 40% – these would be made of layers of different types of perovskite so as to absorb different wavelengths of light. Perovskites though, while simple enough to synthesize, do require a dehydrated and deoxygenated manufacturing environment(10). MNT could enable the molecular level assembly of layered perovskite panels in an inert environment, thus simplifying the manufacturing process and making them a viable replacement for silicon panels.

Inevitably, MNT would break down the distinction between machines and the materials they are made from, because why not have a material *consisting* of molecular machines? A 'smart' material consisting of a mass of such nanometre scale machines (i.e. nanobots) could be programmed to form certain shapes or behave in a certain way when experiencing particular environmental conditions. And nanobots could also be designed to operate independently. They could, for example, move through the bloodstream and perform something equivalent to surgery on individual cells – neuron-like nanobots could integrate into the brain and amplify our abilities or heal brain damage. Other nanobots could be designed to join together to form artificial organs or indeed entire 'living' organisms. We could for example build mini farming drones able to precisely apply nutrients and deal with pests – organic farming would thereby become cheaper and easier than modern chemically assisted farming. Indeed, the final form of MNT would enable us to create a range of artificial but lifelike machines equipped with sensors and tools able to do all sorts of jobs. They could also be

designed to withstand and operate in harsher conditions than we ourselves are able to endure.

Conclusion

Clearly the development of molecular nanotechnology would have profound consequences for both society and the individual. It would seem to be the ultimate technological capability – because if an enzyme can evolve in nature to catalyze any organic reaction, it is safe to conclude that we can develop *artificial* molecular machines to synthesize any inorganic material. Note that since rigorous computer simulations – which are done with conservative physical assumptions – attest to MNT being possible the only real issue with MNT was confusion about how it could be created (which this paper clears up). In addition to the applications given above MNT is a prerequisite for the successful exploration of space, because a 'universal constructor' (these arise in discussions of the so-called Fermi Paradox) consisting of the machinery needed for essential industrial manufacturing processes would be difficult if not impossible to fit inside an appropriate spacecraft. By contrast, a complete MNT 'industrial complex' could be the size of a protozoan – by utilizing self-replication and mass production it could be used to generate any other viable machine or structure. If by contrast we do not develop MNT, technology will cease improving prematurely and a vast range of novel materials and devices will never be available for use. Realizing this and then deciding against MNT development would defy human nature; we should instead kick-start the technology with a focused research and development project. The first step will be carrying out a proof-of-concept test of directed evolution; and this would be followed by creating the first dynamic nanomineral catalysts, thus demonstrating the benefit of having better synthetic techniques in inorganic chemistry. To a large extent our current capabilities in chemical synthesis are constrained to the standard forms of organic chemistry – rings, polymers, branches, functional groups and ligands. We need to open up material science for exploration so that *both* divisions of the molecular realm can be exploited to the full.

NB One substantive change has been made to the paper for version 2 (regarding the initial experimental material) – see page 6, Directed Evolution section, and references 7 & 8. Edits have been made throughout for readability.

Acknowledgements

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References

(1) **There's Plenty of Room at the Bottom; Richard Feynman; 1959;** https://www.zyvex.com/nanotech/feynman.html **(p2):**

But I am not afraid to consider the final question as to whether, ultimately – in the great future – we can arrange the atoms the way we want; the very atoms, all the way down! What would happen if we could arrange the atoms one by one the way we want them (within reason, of course – you can't put them so that they are chemically unstable, for example). Up to now, we have been content to dig in the ground to find minerals. We heat them and we do things on a large scale with them, and we hope to get a pure substance with just so much impurity, and so on. But we must always accept some atomic arrangement that nature gives us. We haven't got anything, say, with a "checkerboard" arrangement, with the impurity atoms exactly arranged 1,000 angstroms apart, or in some other particular pattern. What could we do with layered structures with just the right layers? What would the properties of materials be if we could really arrange the atoms the way we want them? They would be very interesting to investigate theoretically. I can't see exactly what would happen, but I can hardly doubt that when we have some control of the arrangement of things on a small scale we will get an enormously greater range of possible properties that substances can have, and of different things that we can do.

(2) **Tiny Machines; Richard Feynman; 1984; Muon Ray** https://www.youtube.com/watch?v=4eRCygdW—c&t=0s **(p3).** Feynman says this about molecular scale machines (26:33):

But I said that this talk was about machines and of course a computer is a kind of machine, but the machine you usually [associate with the word] is machines with movable parts. Now let us talk about the possibility of making machines of movable parts which are very tiny – the immediate look in all the faces [says] what for? Mental entertainment. Maybe someday they'll find a use for it okay. How small can we make machines? It's just thinking for the fun of it okay. Don't worry about it that [it] hasn't any application. It doesn't cost you anything not to have an application. It's just fun okay so we're not going to worry about how we use these dumb things we're just going to try to make them. How could we make movable matter, little machines, tiny machines that would operate that are very very small?

He goes on to discuss a 'top down' approach to building such machines which can be contrasted with the 'bottom up' approach advocated in this paper (fixed scanning tunnelling microscope tips in contact with individual molecular devices might be a way of connecting the two).

(3) **Engines of Creation: The Coming Era of Nanotechnology; K Eric Drexler; 1986; ISBN 0-385-19973-2 (p3).**

(4) **Richard Smalley and K Eric Drexler; 2001-03;** https://en.wikipedia.org/wiki/Drexler%E2%80%93Smalley_debate_on_molecular_nanotechnology **(p3).** In the initial Scientific American article Smalley wrote:

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.

to which Drexler replied:

This ubiquitous biological molecular assembler [the ribosome] 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?

and later:

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.

Of course, it is possible that Smalley was not familiar with biochemistry (or metalworking) and so lacked the experience necessary to appreciate Drexler's point. But ribosomes do exist, so was Smalley perhaps alluding to a problem only present in the initial stages of MNT?

(5) **Synthesis of Higher Diamondoids and Implications for Their Formation in Petroleum; Dahl, Moldowan and Wei *et al;* 2010; Angewandte Chemie (p4).** This paper sets out current difficulties with synthesizing nanodiamonds in any kind of controlled manner in explicit fashion:

The mechanism for formation of these nanodiamonds for a long time was attributed to thermodynamically controlled carbocation rearrangements. Such mechanisms enable the practical synthesis of 1–3 but they fail in the production of the higher diamondoids. A detailed analysis of the mechanism for adamantane formation from a single starting material shows an amazing 2897 pathways; a more limited analysis of triamantane formation through carbocation pathways indicates at least 300 000 potential intermediates. Prospects for higher diamondoid syntheses by these pathways are bleak due to a lack of large polycyclic precursors, problems with intermediates trapped in local energy minima, disproportionation reactions leading to side products, and the exploding numbers of isomers as the size of target higher diamondoid products increases. With the failure of syntheses of higher diamondoids through carbocation rearrangements, attempts at their preparation were abandoned in the 1980s.

Molecular Nanotechnology: the Best Tech on Offer is an attempt to deal with "the exploding numbers of isomers as the size of target higher diamondoid products increases" – this is seen as the most serious problem of those listed. I first noted directed evolution as a potential solution to the problem in 2011, quite possibly as a response to reading the here referenced paper; the full solution though required additional innovations (see **Ref 6** and **8**).

(6) **'A new day for chemistry': Molecular CT scan could dramatically speed drug discovery; Robert F Service; 2018;** https://www.sciencemag.org/news/

2018/10/new-day-chemistry-molecular-ct-scan-could-dramatically-speed-drug-discovery **(p5):**

In chemistry, structure rules because it determines how a molecule behaves. But the two standard ways to map the structure of small organic molecules... have drawbacks. This week, two research teams report they've adapted a third technique, commonly used to chart much larger proteins, to determine the precise shape of small organic molecules. The new technique works with vanishingly small samples, is blazing [sic] fast, and is surprisingly easy... Instead of firing their electron beam from one direction at a static crystal, they rotated the crystal and tracked how the diffraction pattern changed. Instead of a single image, they got what was more like [a] molecular computerized tomography scan. That enabled them to get structures from crystals one-billionth the size of those needed for x-ray crystallography.

(7) **On the Potential of Silicon as a Building Block for Life; Petkowski, Bains and Seager; 2020;** https://www.ncbi.nlm.nih.gov/pmc/articles/PMC7345352 **(p6).**

(8) **Nanodiamonds: Synthesis, properties, and applications in medicine; Qin, Yang and Lv *et al*; 2021; Materials and Design** https://www.sciencedirect.com/science/article/pii/S0264127521006468 **(p6):**

Yang *et al* used laser ablation of graphite targets in water to synthesize diamonds, and the thermodynamics of ablation of graphite targets in water, acetone, and ethanol to synthesize NDs has also been studied [in 2007]. The synthesis of NDs by laser ablation is actually based on the interaction of a laser-generated cavitation bubble with a solid boundary, which facilitates the nucleation, growth, and solidification of the nanoparticles under the fast quenching conditions. Wang *et al* prepared NDs by bombarding graphite targets in water with laser irradiation and proposed the kinetic principle of diamond formation [in 2005]. NDs can be synthesized by laser ablation at room temperature, and the preparation efficiency is ideal. In addition, because of the reaction in the liquid phase, impurities are not easy to intervene [sic]. But its disadvantage lies in the high consumption of energy and low productivity.

The directed evolution procedure will be significantly easier to carry out if we can grow the nanodiamonds in aqueous solution, and this possibility would raise some interesting questions – could nanodiamond catalysts be used to catalyze nanodiamond growth in water if aided by laser irradiation? And would the catalysts inevitably be damaged in the process?

(9) **Diamonds are a Chemist's Best Friend: Diamondoid Chemistry Beyond Adamantane; Schwertfeger, Fokin and Schreiner; 2008; Angewandte Chemie** https://www.researchgate.net/publication/216574201 **(p6):**

Adamantane chemistry has been studied and reviewed very extensively in the last 50 years... These amino derivatives are important compounds in terms of further functionalization, especially for the preparation of peptides. The best counterparts for a peptide bond are arguably carboxylic acids. These diamantane carboxylic acids, their methyl esters, acyl chlorides, acetic acids derivatives, and their bromine- or hydroxy-substituted derivatives have been prepared and studied very intensively by various groups in the past few years.

(10) **How Physicists Broke the Solar Efficiency Record; Ben Miles; 2024;** https://www.youtube.com/watch?v=J1QDq5Ggz6s&t=0s **(p7).**