Nano-tech/science education at a research university

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***Abstract* — This author summarizes the insights he gained from preparing teaching material for his courses on "nanotechnologies" for over a decade at both the undergraduate and graduate student levels at a research university. A distinction is made between advanced courses that can be classified as some kind of workforce training and 300 level undergraduate courses that are mainly concerned with the development of critical thinking skills as part of inter- and trans-disciplinary science and engineering education. Didactic uses of 3D printed models in introductory nano-tech/science courses are mentioned. Information on how to obtain the print files of such models is included.**

***Keywords* — Nanotechnology education, incremental and evolutionary nanotechnologies, 3D printed models**

I. INTRODUCTION

The author of this paper has been engaged with the teaching of nano-science, nano-materials science and engineering, as well as nano-technologies subjects at both the undergraduate and graduate student levels for over a decade [1-5]. His advanced undergraduate/graduate course "Introduction to nano-materials science and engineering" has been part of the curriculum of a PhD program in Applied Physics for more than ten years and may be classified as some form of workforce training. As that course has already been described in [1] seven years ago, it will not be discussed here. That course has recently been complemented with an advanced undergraduate/graduate course on "Materials Physics" [6], which is a part of the curriculum of the same PhD program.

The author's 300 level undergraduate courses are, on the other hand, part of the general education curriculum at his research university [2-5]. While a group of faculty members from the departments of Electrical and Computer Engineering, Biology, and Physics offered a sequence of three nano-tech courses and a laboratory in the past [3-5], the retirement of one colleague reduced the number of currently existing courses to two, i.e. "Introduction to Nanoscience and Nanotechnology", and "From Nanoscience to Sustainable Nanotechnologies".

These two courses are not intended to constitute some kind of workforce training because they can be taken by any junior in good standing regardless of her or his major and minors. This feature of these courses attracts students from the whole university and many different walks of life. The course with "introduction" in the title is typically taken first and deals to a large extent with the clearing up of misconceptions that many students initially have about the relationships between science and technology, science and pseudo-science, real engineering and "exploratory engineering" [7], the illusion that there will be technological fixes to all problems of human societies, and the nature of technological progress. Also discussed is what has been presented under the umbrella term "nanotechnology" in the popular culture. When applicable, the pseudo-scientific nature of the underlying ideas is carefully revealed and science separated from science fiction.

II. ATOMICALLY PRECISE MANUFACTURING FACT OR FICTION?

The only "nanotechnology" that most students are initially aware of is of the "Drexlerian universal assembler/replicator (nanobot)" [8] and "nanofactory" [9] variety. The course work assignment of the introductory 300 level course is, therefore, the students' own analysis of the "Drexler-Smalley debate" on the basis of Rudi Baum's 2003 article [10] where Eric Drexler and Chemistry Nobel Laureate Richard Smalley present their arguments (without higher-level technical details) in a dialog with each other but can only agree to disagree.

It is interesting to note that Drexler shifted the emphasis of his "teachings" in the year 2004 from the by then highly controversial "assembler/replicator" that may accidentally generate "gray goo" and end life on earth [8] to the less scary and allegedly highly productive atomically precise manufacturing in a "nanofactory" [11]. No technically sound objective was given in [11] for this change of the visionary's mind, who has been dubbed the "Apostle of Nanotechnology" [12]. There were no experimental proofs of concept for either of his ideas by that time and still none exist at the present time. The gray goo scenario was/is not disproven either, but just became yesteryears news. Perhaps shifting doctrines is what prophets have to do from time to time to stay in business. It is too early to tell if Drexler has by now abandoned his mechano-synthesis fantasy and is trying to establish his "exploratory engineering" [7] concept in order to disguise a renewed shift in doctrines.

Much cited pseudo-evidence in favor of Drexler's grand vision are numerous experimental demonstrations since the early 1990s that allegedly "individual" atoms and small molecules can be moved with the tip of a scanning tunneling microscope that is controlled by a human operator [13]. Left out of the casual discourse are often the very special (artificial) environments in which these atoms or small molecules were moved, i.e. ultralow temperatures, ultrahigh vacuum, and surfaces of precious or semi-precious metal crystals.

Physics Nobel Laureate Richard Feynman was surely right when he stated in 1959 that theoretical physics does not forbid the moving of individual atoms by human beings [14], but that does by no means imply that an all encompassing technology as proclaimed by Drexler could in an economically feasible manner be built on that fact. Physics Nobel Laureate Hans Dehmelt is also right when he categorically states that these kinds of demonstrations are not about individual atoms or molecules and their movements at the discretion of a human being because the essence of these kinds of experiments are a crystal surface "*with pimples on it*" [15], see endnote[16] for longer quotes from Dehmelt in this matter. In other words, the essence of these kinds of experiments is just *one* enormously complicated quantum mechanical entity, i.e. the scanning probe tip *plus* the atom or small molecule *plus* the precious or semi-precious metal crystal underneath and to the sides.

Technologies are always conditioned on the prevailing state of economic prosperity and the wider needs of society and individual customers alike. So the question arises, given that it is an exceedingly expansive (hubristic) proposition to move individual atoms around in order to build any kind of device that might be useful in the macroscopic world that humans inhabit, is there any problem in society that can only be solved by doing so? Similarly, does atomically precise manufacturing of everyday goods have *anything* to offer for mankind? As most of my students are aware of the concept of a mole, i.e. assemblies of atoms on the order of magnitude 10^{23} weighing a gram to some 200 grams, the answers to these questions from the vast majority of the students of this nano-tech/science educator are overwhelmingly negative after some reflection.

Dealing with this particular misconception seems to have become a permanent fixture in the job of a nano-tech/science educator who wants to foster critical thinking in her or his students. In spite of thorough debunkings of Drexler's vision over more than 20 years [17-25], an allegedly scientific article still appeared in the year 2017 that stated without any references to experimental proofs of principle work that had actually been accomplished: "*Once a specific "bottom-up" process for building atomically precise structures has been worked out, the design of new nanomachines and nanofabrication systems closely resembles mechanical engineering … reactions are performed by a "molecular mill", in which the reactants are held in accurate orientations by jigs on belts and then pressed together at the proper angle and force. The belts move as the reaction occurs*" [9], see also endnote[26].

III. Virtual versus Real Reality

Another issue this nano-tech/science educator has to contend with is the projected primacy of "artificial intelligence" (AI) over humanity in the near future. A 2008 opinion piece by former editor-in-chief of *Wired* magazine Chris Anderson proclaims, for example, that the scientific method is obsolete simply because Google exists [27]. While this idea was rebutted on philosophical [28] and epistemological [29] grounds, it may[30] seem to some young students that this might indeed be the case. It is the pervasiveness of these kinds of ideas in the popular culture that qualify them for coverage in courses that aim at the development of critical thinking skills.

Many students have also not realized that the perpetual progress in computing hardware they grew up with as exemplified by Moore's law came to an end [31] a few years ago. In popular culture and the science fiction genre, this progress continues and will allegedly lead within the students' lifetime all the way to "immortality/transhumanism" by means of "mind uploading", and the "technological singularity". As the public cannot be fooled forever about the factual end of Moore's law, it seems to be the case that spectacular advances in software, i.e. general AI, are now called for to guarantee the reaching of these futuristic goals within a few decades. Almost needless to say that these are unscientific extrapolations of a pseudo-religious[32] character which may well be neither achievable nor desirable [33].

Human intelligence surpassing "superintelligence" (general/strong AI) is according to recently polled AI researchers not imminent to appear within the next decade [34], see Fig. 1. With a total of 92.5 % of the experts putting the realization of that kind of software capabilities more than a quarter of a century or indefinitely into the future, clearly there are much more pressing issues to be dealt with both in society and nano-tech/science classrooms.

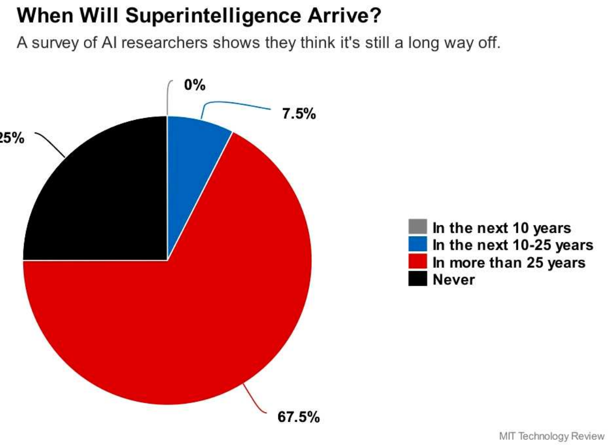

Fig. 1: Results of a survey of the MIT Technology Review [34] about the feasibility of superintelligence in the future to which eighty fellows of the American Association for Artificial Intelligence contributed.

IV. Incremental and Evolutionary Nano-tech leading inter alia to Functioning Molecular Machines

Besides fostering the clearing up of the above mentioned misconceptions in his classes, this nano-tech/science educator distinguishes between incremental and evolutionary nano-tech on the one hand and non-existing (fantastical/Drexlerian) radical "nanotechnology", on the other hand. Incremental nano-tech [23] is to a very large degree contemporary materials science and engineering (MSE) [35] so that the opportunity arises to introduce the students to this field while running a nano-tech/science course. Evolutionary nano-tech [23,35] can be considered to be at the forefront of MSE, modern applied physics, macro- and supramolecular chemistry, synthetic and structural biology, as well as nano-crystallography alike [36]. Based on multiple incremental advances, evolutionary nano-tech leads to successive generations of useful artifacts/ products including non-Drexlerian molecular machines [37]. The key to progress is thereby always the application of the scientific method.

The science behind the 2016 Nobel Prize in Chemistry award to Jean-Pierre Sauvage, Sir J. Fraser Stoddart, and Bernard L. Feringa, *"for the design and synthesis of molecular machines"* [38] by means of their self-assembly provides a good example of evolutionary nano-tech that utilizes "mechanical bonds" (as coined by Sir[39] Fraser himself) as well as both covalent and non-covalent bonds. It is, therefore, discussed in our classes.

The left hand side of Fig. 2 shows a 3D printed model of a "Solomon link" molecule" [40] that features such bonds in the hands of one of this author's colleagues. A virtual reality visualization of this particular molecule as created from a Crystallographic Information Framework (CIF) file that is in open access [41], utilizing an openly accessible windows executable program [42] is shown on the right hand side of that figure. Such links are in popular culture referred to as Solomon Knots [43], see top-right inset in Fig. 2, after King Solomon of the Old Testament. While a Solomon link molecule was first synthesized in the year 1999 by Sauvage's group, Stoddart's group created such a molecule in the year 2007 by a transition metal-cation template directed twelve-component self-assembly process followed by a kinetics controlled crystallization process that resulted in a racemate [44].

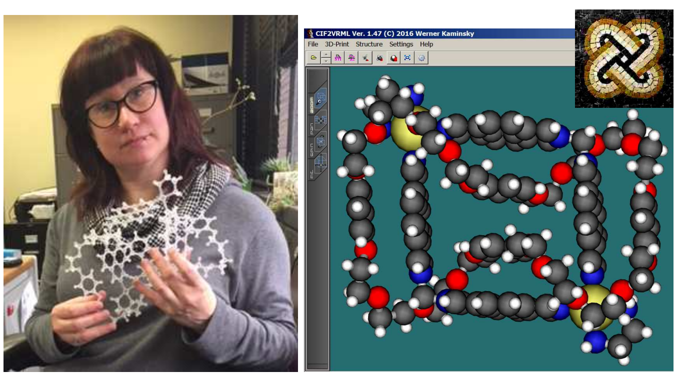

Fig. 2: Left: Office administrator Laurie Tull of the author's department at Portland State University holding a 3D printed model of a Solomon link molecule [40]. Right: The same Solomon link molecule as represented by a CIF file [41] read into the CIF2VRML program [42], which allows for the creation of 3D print files. Inset (top right): Photo of a Roman "Il nodo di Salomone" mosaic, featuring a King Solomon Knot (courtesy of an on-line article at https://phys.org [43]).

In the context of this author's 300 level nano-tech/science courses, a molecular Solomon link molecule (and its 3D printed model, Fig. 2) is an illustration of what has already been possible to create by chemical synthesis and subsequent crystallization roughly a decade ago [40]. This example is at odds with the claims by Drexler followers that a "diamondoid mechano-synthesis" approach to creating molecular machines (based on covalent bonds only) will be the dominating fabrication method of the future and that its products will (eventually? or perhaps in 2026/2027, by the time of the 50th anniversary of Drexler's vision [12,15]) even surpass the performance of biological macromolecule-machines and their supra-molecular assemblies, e.g. ribosomes [23], as far as the sustaining of the phenomenon of life on earth goes. Note in this connection that Drexler conjectured in the year 1992 that about 15 years would suffice for some noticeable uprooting of advanced synthetic chemistry by his brand of mechano-syntheses [15].

V. Employing Lakatos' Concept of Gauging Progress by Comparisons of Competing "Research Programs"

The example of the last section allows this nano-tech/science educator to bring some philosophy of science into the classroom. Imre Lakatos' central thesis of progress on the basis of the competition of "research programs" (i.e. sophisticated methodological falsificationism, as explained by the master himself in a BBC broadcast in 1973 [45]) is used in class to contrast Sauvage - Stoddart - Feringa Nobel Prize winning science that resulted in functioning molecular machines from Drexler's fantasies (that essentially resulted in both excitement and confusion of the general public). By employing the scientific method (that Anderson claims to be obsolete [27]), the research programs of the three Chemistry Nobel Laureates are demonstrably progressive, as they lead on an ongoing basis to predictions that withstand falsification by the observations of the end results (artifacts) of rationally designed synthetic routes.

Drexler's (pseudo-)research program, on the other hand, is demonstrably regressive, as it has not led to *any* observable nano-structured real-world artifact for over 40 years. Out of Drexler's program came so far only a bunch of *simulations* of hypothetical "machine parts" which one could call "artificial molecules" as they are atomically precise per design. In keeping with his mechanical engineering background, Drexler even designed an atomically precise analog computer [15]. Some of the hypothetical nanomachine parts that Drexler simulated might actually be stable in the real world as they were evaluated with quantum simulation software. Because that software can not be refined with insight that would result from the experimental testing of the simulated entities in the intended working environments under real-world conditions, one cannot claim that these kinds of simulations constitute *real* (as opposed to imaginary) scientific progress.

Most importantly, there is a complete lack of methods to produce these hypothetical nanomachine parts and to assemble them into something much bigger that could be useful to human beings. Drexler's mechano-synthesis itself has never been simulated; only hypothetical results of such a synthesis exist so far. By ignoring all real world details such as the nature of the quantum mechanical problem of manipulating individual atoms in some real world environment, one can surely program a stream of bits to create any kind of "propaganda" on a computer screen [46]. Despite the high level of sophistication of a related video from the Nanorex Corporation, most of the students of this nano-tech/science educator are not convinced after "seeing" and discussing "Drexler's nanofactory" in action [46] in the classroom that it has actually anything to do with the real world.

Most students realize in class the obvious, i.e. that electronic bits are not atoms and both types of entities belong to completely different domains. As nobody seems to have any idea at present what form a method to do "mechano-synthesis" with real-world atoms could take, Drexler's whole program seems to be doomed. Note that any such method would require complete mastery of the enormously complicated quantum mechanics of multiple chemical and physical interactions.

VI. Feynman's Foresights versus Drexler's Vision

Feynman's response [47] to Drexler's vision may have been [18] him classifying it as *"cargo cult science"*[48]. Edward Regis referred to Drexler as one of the world's *"finest hubristic thinkers"* [49]. From the following direct quote, it is clear that Drexler resents being held to the standards of the scientific method: *"critics will"* … *"deny that anything short of a physical demonstration can provide solid evidence for the feasibility of something new like molecular manufacturing"*. [15]. Note in this connection that Drexler coined the word "exploratory engineering" [7] around the year 2011 in order to exempt himself from being held to such standards. Any scientist and most likely almost any practicing engineer will, however, do precisely that whenever she or he wants to gauge real scientific and technological progress! This is because the scientific method has time and again been proven to be the most reliable way to obtain both knowledge about the world and a better life for human beings. "Exploratory engineering" [7], on the other hand, is just a fancy new word for both computer-assisted science fiction and armchair speculations.

It is somewhat tempting to associate Drexler's "brand of nanotechnology" [8-11] with the techno-science concept of the philosophy of science [50,51], but that would *still require* that experimental proof of principle demonstrations exist rather than mere simulations. Techno-science has been identified with "*what happens to the sciences once an engineering mentality gets hold of them"* and *"theorizes things as simple so as to render a world that is subject to technical control"* [50]. By means of an embracing of the techno-science label, real nano-tech achievements that made it onto the covers of high-status scientific journals can often be summarized as "*we made a nanowidget*" in the *real world* rather than just simulated it [51].

Because of the above mentioned lack of tangible outcomes of Drexler's (pseudo-)research program, his claim to be taken seriously rests largely on his assertion that what he proposes follows naturally from Feynman's after dinner talk [14] at a meeting of the American Physical Society in the year 1959. This is actually a gross misrepresentation! Feynman was most of the time talking about what became to be known as micro-electro-mechanical systems (MEMS). His famous after dinner talk was, therefore, republished in the first volume of the *Journal of Microelectromechanical Systems* in the year 1992. The second volume of this journal published a second talk [52] that Feynman gave in the year 1983 [15].

That talk had "There is Plenty of Room at the Bottom, Revisited" as alternative title and was largely concerned with quantum computing [52]. Feynman stated in that second talk that he could *not* foresee *any* genuinely useful application of individual "micro/nano-machines" [15,53]. He had already put syntheses of individual molecules by not precisely stated "physical means" so far into the future in his 1959 talk that chemist would by then have *"figured out how to synthesize absolutely anything, so that this will really be useless"* [14].

One can only speculate why the great physicist incorporated ideas from science fiction into his after dinner talk [14]. That he did is without question! Robert Heinlein's 1942 novella "Waldo" and Feynman's friend Albert Hibbs were actually the inspiration for his idea of human hands controlling smaller robotic hands, which control even smaller robotic hands and so forth until individual atoms and molecules could allegedly be manipulated by the tiniest of hands [15,53,54].

For forty-odd years, Feynman's (in-)famous after dinner talk [14] was largely ignored by the scientific community [53,55]. The talk and its science fiction parts were, however, endorsed by some policy makers (on Drexler's advice) in preparation of President William J. Clinton's National Nanotechnology Initiative [15]. For a rhetorical effect [56], it is, therefore, quite acceptable to regard that former president of the USA as the "founding father" of "nanotechnology" and to consider it as a political project of the neo-liberals. Because of this kind of muddled history, one cannot avoid the conclusions that: (*i*) casual usages of the word "nanotechnology" derive partly from science fiction and (*ii*) are driven by the politicization of science and technology [51,57]. This explains much of the hype that surrounds this field [58] and will probably continue to do so for a long time in spite of the best efforts of nano-tech/science educators.

VII. Nano-science, its Early Practitioners, and the Real Visionaries of Nano-tech

Genuine nano-science, on the other hand, is to a very large extent not contaminated by science fiction and politics. It probably began in a qualitative manner with Michael Faraday in the year 1857 [59], and became quantitative some 50 to 60 years later with, e.g., Albert Einstein's PhD thesis [60], Gustav Mie's seminal 1908 paper on the colors of gold particles in dilute solutions as function of their sizes [61], and Wolfgang Ostwald's booklet on colloids from the year 1914 [62].

Feynman's 1959 after dinner talk [14] was surely meant to be entertaining and an invitation to fellow physicists to branch out into applied physics, to adopt an attitude/practice that is nowadays often referred to as techno-science [50,51], and to join emerging fields of engineering, which the master never pursued himself. Materials science and engineering (MSE) was such an emerging field in the early 1950s.

Arthur von Hippel, one of the early leaders in this field, wrote for example in 1956 in the journal *Science*: *"instead of taking prefabricated materials and trying to devise engineering applications consistent with their macroscopic properties, one builds materials from their atoms and molecules for the purpose at hand"* [63]. Wolfgang Ostwald stated already in the 1922 edition of his (above mentioned) booklet [62] that: *"we know now that any entity acquires highly special properties and supports very peculiar phenomena when its constituent parts are of a size so that they cannot be distinguished in a light microscope, but are too large to allow for a classification as individual molecules"*. (In German in the original.)

Note that the joint focus of von Hippel's and Ostwald's statements was the creation of novel materials by chemical and physical routes that possess novel or improved properties due to their nanometer size or nanometer sized structural components even when they did not specify that size range precisely. Also note in this connection that the number of presently known molecule structures (as derived from single crystal X-ray crystallography) exceeds the number of stable atoms by four orders of magnitude. Building from molecules and utilizing all kinds of bonds is, thus, a much better idea than Drexler's attempt to outdo nature by building from individual atoms, one at a time, and using only covalent bonds.

Novel nano-structured materials that were created by MSE are the fundamental ingredients out of which all kinds of engineers are able to create novel products and technologies that are useful on the length scales of human beings. In stark contrast to this, all kinds of things, e.g. food, clothing, computers, houses, tanks, and airplanes, would according to Drexler's vision just be created by software that "directs" by means of some *magical* mechano-synthetic contraption an individual atom to form an individual covalent/diamondoid bonds with another atom while not bonding to the contraption itself. On top of that, this is all supposed to be repeated in an economically advantageous manner at least some 10^{23} times in order to obtain a few grams of that kind of "fairy tale stuff".

VIII. 3D Printed Models for Classroom Demonstrations

Because it has been beneficial [2] and to demonstrate that the future is not to be conceived as total immersion in virtual reality, self-made 3D printed models of structural prototypes of crystalline engineering materials, densest packings of spheres, individual molecules, crystal defects, crystal morphologies, and tensor representation surfaces [42,64-72] are used in our classrooms extensively. 3D print files of crystal structures and individual molecules can be created straightforwardly [71,72] in a web browser at a dedicated website [73] that is part of the sites of the author's Nano-Crystallography research group [74]. For the creation of 3D print files of crystal morphologies and tensor representation surfaces, one may use the windows executable programs WinXMorph [42,67] and WinTensor [68], which can both be downloaded freely for non-commercial purposes from Werner Kaminsky's website [75]. 3D print files of tensor representation surfaces can be downloaded from the websites of the Materials Property Open Database [76].

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