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Introduction to Nano-Materials Science and Engineering: An elective course within an Applied Physics PhD program

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***Abstract* — A graduate/undergraduate course that gives an introduction to the science and engineering of materials at the nanometer length scale is briefly described. The course is an elective within an Applied Physics PhD program at Portland State University. Definitions for nanoscience and engineering are quoted and contrasted with popular conceptualizations of nanotechnology.**

Index Terms – gradate/undergraduate education

Introduction and Course Background

The author of this paper developed in 2003 and taught (from 2003 to 2006) the course "Introduction to Materials Science and Engineering (IMSE)" as a modern alternative to a course on "Introduction to Physical Metallurgy" for undergraduates of mechanical engineering. Both courses were so called "service courses", i.e. courses given by the faculty of one department to students of another department.

There is nothing wrong with the idea of service courses because all professions require the mastery of mixtures of concepts from various science and engineering disciplines. When university administrators simplify assessments of the productivity of departments down to monetary concepts such as a "cost per credit hour ratio", departments and colleges may fight over the question who gets to teach required courses with large enrolments. The outcome of such fights may not necessarily be in the best interest of the students since their educational needs do not factor directly into departmental cost per credit hour ratios.

This happened in the case of the above mentioned IMSE course, which was in 2007 converted back to an undergraduate course in "Physical Metallurgy" (that covers metals and alloys only) and which is taught by the home department of the mechanical engineering students. From that time onwards, more or less coinciding with the hiring of materials scientists to the mechanical engineering department and its renaming into Department of Mechanical and Materials Engineering, two higher level materials science and engineering courses were developed: "Engineering Material Science" and "Advanced Physical Metallurgy". Both courses can be taken by graduates and undergraduates simultaneously. As it is typical for such courses, the required coursework for graduates is at a significantly higher level than that for undergraduates.

While teaching IMSE from 2003 to 2006, it became clear that the students wanted to learn more and more about how consumer products that were labeled as "nanotech enabled" actually work and also to a somewhat lesser degree how they are made. This kind of feedback from the students caused me first to expand the "nanometer scale content" of the IMSE course year after year and eventually to develop an entirely new course which will be briefly described below.

As a materials scientists and crystallographer by both education and career choices, I have to confess to a dislike of the word nanotechnology and will expand on that further below. Clear definitions are always required for effective communication. A significant part of this paper will, therefore, define the subject of the new course and clarify its place within materials science and engineering. It is the author's opinion that a lack of clear definitions in the initial phases of nanoscience and engineering is partly to blame for the confusing situation that exists now, e.g. that a technology (i.e. nanotechnology) is in the public perception often equated to a science (i.e. nanoscience). The paper aims to help clear up this confusion.

A frequently quoted 2002 science policy document by the National Nanotechnology Initiative [1] spelled out the magnitude of the challenge to graduate education, i.e. that "*about 2 million nanotechnology workers will be needed worldwide in 10-15 years*" and that by 2007 "*nanoscience and engineering education*" needs to be "*enabled in at least 25 % of research universities"*. Except for the projected size of the "nanotech workforce" [2], many of the predictions of 2002 were borne out by the actual developments [3]. On the basis of these developments, it was extrapolated that both the number of worldwide "nanotech-workers" and the size of the "nanotech-enabled products market" would double approximately every three years [3]. According to these trends, the forecasted 2 million required "nanotech-workers" and the $1 trillion market of 2015 should triple to 6 million workers and $3 trillion in 2020.

Anticipating significant economic benefits, the State of Oregon created in 2003 the Oregon Nanoscience and Microtechnologies Institute (ONAMI), which puts "*nanotechnology to work in microsystems"* [4]. This motto clarifies the nature of "nanotech" developments that the state of Oregon supports. Functional nanostructured materials and devices on their basis, (i.e. *incremental* and *evolutionary* "nanotech" according to ref. [5]), are developed within a materials science and engineering context in order to enhance the functionality of existing and novel microsystems.

Following the lead of the policy makers at the national and state levels, the above mentioned INMSE course was developed in 2006. It has been taught since 2007 annually and is now a regular elective graduate/undergraduate course offering at Portland State University. About one third of the students that have taken this course so far were graduates from the Materials Science Program of the University of Oregon (at Eugene). The course is held twice a week in the early evenings so that these students can attend since they are busy during the daytime working as interns in Portland's high tech industries.

WIDER CONTEXT OF THE COURSE

The INMSE course is outlined at a dedicated website [6]. The wider context of this course is classical materials science and engineering. Materials science and engineering (MSE) courses are in so far unique in the curriculum of higher education that they consider their subject as a double discipline, where applied science and engineering are both taught on an equal footing. The INMSE course emulates this tradition and an attempt is made to give balanced introductions to all four corners and six edges of the Materials Science and Engineering Tetrahedron as introduced in an influential study that defined the whole field [7], Fig. 1.

The beauty of this conceptualization of the whole double discipline materials science and engineering into one well known Platonian body lies in its comprehensiveness. While materials scientists will be often concerned with work that lies metaphorically speaking along the "Structure/Composition" to "Properties" edge, materials engineers may work often along the diametrically opposite edge that connects "Synthesis/ Processing" with "Performance". One may classify a paper or talk as being about materials science and engineering when at least two of the MSE Tetrahedron corner concepts are dealt with. The performance corner may be expanded further by related concepts such as "performance under some environmental constraint" or a "production cost to consumer satisfaction ratio". This makes clear that this corner represents the connection of the whole double discipline to society at large. It also makes clear that society determines which materials products and services will be ultimately successful on the market.

In order to develop a materials product that is accepted by society, i.e. that can be sold to customers at a profit, materials scientist and engineers need to collaborate closely. This requires, with necessity, communication between the involved scientists (regardless if they are physicist, chemists, crystallographers, structural biologists, …) and engineers (who might have specialized in materials, mechanical, electrical, civil, … or computer engineering).

Obviously the size of nanomaterials, the morphology of isolated nanocrystals, and also the "quantization-effective dimensionality" of a nanostructure are "not covered" by any of the four MSE Tetrahedron corner concepts. The INMSE course puts Size, Shape & Dimensionality, therefore, symbolically into the center of this tetrahedron, i.e. at an equal distance to all of the four corner concepts, Fig. 1.

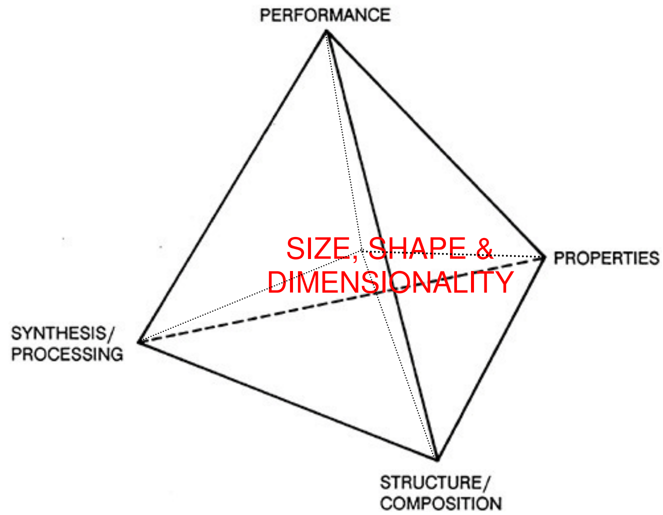

Fig. 1 The well known Materials Science and Engineering (MSE) Tetrahedron (taken from ref. [7] and sketched with five full and one dotted line) with **Size, Shape & Dimensionality** added as inset right at its center.

Shape is to be understood here in general terms, referring for example to the habit and form of an engineered nanocrystal as well as to its possible core-shell structure, the inner and outer diameters of a nanotube macromolecule, or simply the thickness of a quantum well. The quantization-effective dimensionality of a nanostructure is often implicitly connected to its shape. As a concept, it is derived from basic quantization effects when the size reduction is anisotropic. Examples for this are the formulation of the electronic density of states for 2D, 1D and 0D entities.

While structure/composition is mainly taught on the basis of ref. [8], the material for synthesis/processing is mainly taken from ref. [9]. The concepts for discussing the properties and performance of nanomaterials come mainly from ref. [10]. It is not required that the students purchase any of these textbooks. Undergraduates are advised to read one of the dedicated undergraduate textbooks [5,11-13] in parallel to the course so that they can keep up in classroom discussions.

Two of the undergraduate textbooks [12,13] feature large sections on introductory quantum mechanics. This is very different from traditional "Introduction to Materials Science and Engineering" textbooks where Schrödinger's equation is hardly mentioned. For an INMSE course, on the other hand, it makes perfect sense to emphasize quantum mechanics so that it is an integral part of the new course.

Finally, do note that defining the wider context of nanoscience and engineering as being classical materials science and engineering is neither new nor particularly original. A large fraction of freely downloadable "nanotech course material" at the nanoHUB [14] and the websites of the National Center for Learning and Teaching in Nanoscale Science and Engineering at Northwestern University [15] follows similar approaches.

GOALS AND DELIVERY OF THE COURSE

The main goals of the course are two-fold, to introduce students to the double discipline materials science and engineering and to continuously highlight the importance of doing science and engineering at the nanometer length scale. One may, therefore, say that the course goals are well aligned with the motto of the Oregon Nanoscience and Microtechnologies Institute. Because much of nanomaterials science and engineering is in practice about collaborations between people from different scientific and engineering disciplines, the paramount importance of communicating effectively between professionals in order to "get a job done" is stressed throughout the course.

Relevant information is transmitted from the instructor to the students more or less "top down" in the classical lecture format with support of modern teaching technologies such as youtube.com [6], movies from ref. [13], and Internet based computer simulations [13-15]. The assessment of the students' learning, on the other hand, follows a more "bottom up" approach and is discussed in the following section.

STUDENT LEARNING ASSESSMENT

Weekly homework assignments consist of the reading of both "classical texts" of nanoscience, e.g. the transcript of Feynman's well known "There is plenty of room at the bottom" after dinner talk [16], as well as contemporary review and research papers [6]. Following the reading of these texts, the students have to answer sets of questions on the technical and scientific details of the texts and provide an effective communication/synthesis piece concerning these texts. The students' reading of both classical texts and a selection of contemporary research and review papers aims at getting them into the habit of life-long learning and boosting their confidence that they can actually extract useful information from research papers.

Because the students are encouraged to express their *personal* opinion about the "nanoscience papers" they were asked to read and are assured that it is perfectly okay for them to express an opinion that differs from that of the instructor, the homework assignments are not only an activity that supports the lectures, but also serve as direct feedback to the instructor of what the students have learned. When necessary, technical and scientific misconceptions of the students in their personal opinion pieces are clarified at the beginning of the weekly lecture sessions.

NANOSCIENCE AND –ENGINEERING VERSUS NANO/PICO-TECHNOLOGY, HYPE AND NOVELTY

The author's dislike of the word nanotechnology is due to both its lack of a *coherent* definition and its unclear relation to nanoscience as far as popular culture is concerned. Also the classical definition of technology as "knowledge and tools that are used by humans for some *specific* purpose" [17] is not amenable to the general quantifying label *nano*. The historically first definition of nanotechnology: *"mainly consists of the processing of, separation, consolidation, and deformation of materials by one atom or by one molecule*" [18] has its roots in the field of top-down precision engineering and emphasizes only materials engineering aspects so that it is of limited utility. It has also been argued that *"... there is no such thing as nanotechnology. Nanotechnology is now the buzzword and an umbrella term to designate nothing less than the state-of-the-art in science and technology in what is the normal progression and evolution of the relationship of humankind with its habitat and environment."* [19].

Being well aware of its severe limitations and low value in a scientific context, some anecdotal evidence might serve nevertheless as illustration of the "nanotechnolgy hype" [20] of recent years. Using the search engine Google and taking the number of returned results for searches on the Internet for "–science" and "–engineering" with the Greek prefixes for 10^{-6} to 10^{-15} as measures of their current popularity, one may infer a "severe popularity gap" between –science and –technology for both prefixes "nano" and "pico", Table 1.

	–science	**–technology**
micro	322,000	624,000
nano	1,420,000	14,100,000
pico	801	114,000
femto	4,470	2,590

Table 1: Results of Google searches (on 05/05/2011) for "–science" and "–technology" with qualifying prefixes as given in the first column.

With science and technology both being important concepts on which our society thrives and micro–science and –technology both well established, the first row in Table 1 might be considered as some sort of a "baseline measure" for the "hype-free popularity" of science and technology in the general public. This would give an about 1 to 2 "popularity ratio" in favour of technology. Nano– and pico–technology would then stand out as being more popular than is merited as results of hype. (Note that pico–technology is in popular culture often referred to as sub-nanotechnology, i.e. something "even cooler" than nano–technology.)

Engineering at the nanometer length scale has been envisioned and science at this length scale actually practiced for at least half a century. Arthur von Hippel's 1956 vision for the then emerging field of materials science and engineering proposes that "*… 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.*" [21].

One may count Albert Einstein's physics theory led (but indirect experimental data based) determination of the size of a sugar molecule [22] 50 years earlier as the beginning of quantitative nanoscience. Going back in time for another 49 years, one may consider Michael Faraday's 1857 conjecture *"a mere variation in the size of particles gave rise to a variety of resultant colours."* [23] as the beginning of the (purely empirical) qualitative phase of nanoscience. This science may be coherently defined as *"the science of materials whose properties scale with size"* [24]. So nanoscience is definitely neither a technology nor a recent development. With massive support from the federal government, a whole new industry is, however, about to emerge from recent and contemporary nanoscience and engineering efforts.

DEFINING THE COURSE FURTHER BY STATING WHAT IT IS NOT

After defining the INMSE course by its context and goals it is further defined by what it does *not* cover. This needs to be done because a minority of students has preconceptions about the whole field and course that may have resulted from both media hype and science fiction literature.

A clear distinction is made at the beginning of the INMSE course between *incremental* and *evolutionary* nano-science and engineering (as supported by ONAMI) on the one hand and *radical* "nanotech" on the other [5]. This and a brief excursions into "quantitative nanobiology" [6] (supported by a homework assignment [25]) reveals the true nature of Drexler's radical ideas of "self replicating assembles" [26], "nanobots", and automated "mechanochemical fabrication" on the basis of individual atoms in a "nanofactory" [27] as unscientific scenarios that have ***no*** place in a graduate/under-graduate science and engineering classroom. Figures 2 and 3 may serve as examples to illustrate this point. The hypothetical transportation technology device of Figure 2 was conceived (and sketched) by a truly great artist and engineer some 400 years before the device could be physically built due to restraints in the then available materials synthesis/processing technologies.

Fig. 2 Sketch of a hypothetical transportation technology device by **Michelangelo** di Lodovico Buonarroti Simoni, March 6th, 1475 – February 18th, 1564. From http://www.virginiawind.com/byways/history_01.asp.

The hypothetical "microbot" of Fig. 3, on the other hand, may never be built and function as some nano-medical technology device because it proposes to utilize "macro-scopic medical principles", i.e. to grab something tightly with "universal pincers" in order to be able to inject something into it. The existing marvelous molecular (soft) machines of nature [28] are, however, known to utilize highly site specific and evolutionary well proven "lock and key" mechanisms for both "holding on to" and "entering into" something and do ***not*** bear any resemblance to whatever is shown in the center of Fig. 3.

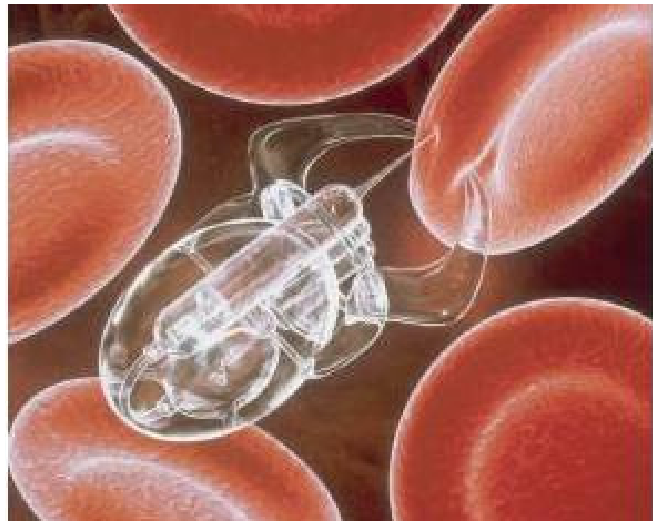

Fig. 3 Sketch of some hypothetical "microbot", pinching "something" by an **unknown artist**. (Since it seems to be a red blood cell that the "bot" is attacking and because these cells possess a size of several µm, it should be labeled as "microbot" regardless of its classification as "nanobot" in the corresponding undergraduate textbook [11].) With all due respect, the creator of this image cannot be compared to Michelangelo. His or her depicted vision may never be realized because the existing biological "nanomachines" [28] operate on completely different principles! Slightly modified version of openly accessible teaching material at http://www.panstanford.com/books/nanosci/v004.html.

ARE THERE UNIQUE OR SPECIAL SOCIETAL IMPLICATIONS THAT THE COURSE NEEDS TO COVER?

Defining nano-materials science and engineering as above on the basis of the MSE Tetrahedron with the core "nano-concepts" at its center, Fig. 1, there is at least for products of the *incremental* and *evolutionary* approaches to "nanotech" [5] *no need* for further discussions of unique or special societal implications. This is also implicit from the lack of novelty of nanoscience. The performance corner of the *nano*-MSE Tetrahedron makes it abundantly clear that the technical sides of such implications are just an integral part of everyday materials engineering!

In this connection, a revisiting of the "Magic Nano Story" of 2006 [29-31] is illuminating. The facts are briefly: the company Kleinmann GmbH of Sonnenbühl/Germany (a subsidiary of Illinois Tool Works Inc. of Glenview/Illinois), distributed a bath and toilet (glass and ceramic) cleaner/ sealant as "Magic Nano" which they did not develop by themselves and that did *not* actually contain nanometer-scaled materials for the intended purpose of creating a hydrophobic surface sealing after a thorough cleaning [29,30]. The cleaner/sealant was supposed to be sprayed from a can and it is believed that the solvents in the aerosol caused respiratory irritations for about one hundred customers when the product was used in enclosed (and possibly poorly ventilated[1]) spaces such as bathrooms [31].

The incident let to an (in hindsight) entirely avoidable "nano-hype media-field day" in 2006 and there was even a renewed call for a world-wide moratorium on the develop-ment of nanoproducts by a non-governmental organization [32]. Had the synthesis/processing corner and most importantly the "nano-center" of the nano-MSE Tetrahedron, Fig. 1, been duly considered as part of the scaling up to industrial production, different properties and the intended product performance would have resulted and the whole incidence would probably[1] *not* have happened! According to ref. [30], the manufacturer (which was neither Kleinmann GmbH nor Illinois Tool Works Inc.) did not follow through with implementing the synthesis/processing procedures as prescribed by the developers from academia so that the beneficial nanoparticles simply fell out of solution and never made it into the final product.

Finally, there are serious doubts in the community that the *radical* (Drexlerian) approach [5] to "nanotech" might be feasible. According to a 2007 poll, only about 5 % of the participating "nano-scientists" have concerns about "self-replicating robots" [34]. In any case, *radical* "nanotech" is likely to be at least decades away [5]. To this author, it seems to be sensible to postpone debates until such times. The good news for educators in the meantime is that the proportion of participants in three different studies which judged nanotechnology as more beneficial than risky did rise with their level of familiarity with the field [34].

SUMMARY AND CONCLUSIONS

Portland State University's (PSU's) course "Introduction to Nano-Materials Science and Engineering" has been briefly described. The nanometer length scale has been identified by national and Oregonian policy makers as the "new frontiers" of materials science and engineering. The prospective "conquering" of these frontiers is bound to deliver the means to sustain the lifestyle North-Americans have become used to in the last few decades. Almost needless to say, higher education is supposed to follow the lead of policy makers.

Since this course is an elective for which students have "voted with their tuition dollars" in the past (because they found it interesting and prospectively useful for their future careers), it is hoped that it will not be closed down due to short term cost per credit hour ratio considerations that may get exacerbated by mounting shortfalls in the budget of the State of Oregon.

In years to come, this course may be complemented by more specialized courses as the students' interest in this field broadens and graduate education in nanoscience and applied physics becomes more widespread in Oregon. The expected long term benefits of higher education in the field of nanomaterials science and engineering for Oregon's economical base may also justify modest investments into Portland State's applied physical science PhD programs by the Oregon University System. Also Oregon's and PSU's sustainability initiatives will be well supported in the long run by "nanotech education" efforts.

REFERENCES

[1] M. C. Roco, "The Vision and Action Plan of the National Nanotechnology Initiative", *Proc. Comp. Nanosc. Techn.*, vol. 2, pp. 1-5, 2002.

[2] P. Stephan, G. C. Black, T. Chang, "The Small Size of the Small Scale Market: The Early-Stage Labor Market for Highly Skilled Nanotechnology Workers", *Res. Policy*, vol. 36, pp. 887-892, 2007.

[3] *Nanotechnology Research Directions for Societal Needs in 2020, Retrospective and Outlook*, National Science Foundation, Springer, 2010, see also http://www.wtec.org/nano2/.

[4] www.onami.us.

[5] C. Binns, *Introduction to Nanoscience and Nanotechnology*, Wiley, 2010.

[6] web.pdx.edu/~pmoeck/nanoMSE.htm.

[7] *Materials Science and Engineering for the 1990s: Maintaining Competitiveness in the Age of Materials*, A National Academies Study, National Academy Press, Washington, D.C., 1989, chapter 2, p. 29, http://www.nap.edu/openbook.php?record_id=758&page=19.

[8] S. M. Allen, E. L. Thomas, *The Structure of Materials*, Wiley, 1999.

[9] G. A. Ozin, A. C. Arsenault, *Nanochemistry, A Chemical Approach to Nanomaterials*, RSC Publishing, 2005.

[10] F. J. Owens, C. P. Poole, *The Physics and Chemistry of Nanosolids*, Wiley, 2008.

[11] C. W. Shong, S. C. Haur, A. T. S. Wee, *Science at the Nanoscale, An Introductory Textbook*, Pan Stanford, 2010.

[12] E. L. Wolf, *Nanophysics and Nanotechnology, An Introduction to Modern Concepts in Nanoscience*, Wiley-VCH, 2006

[13] S. M. Lindsay, *Introduction to Nanoscience*, Oxford University Press, 2010; teaching material including movies on an accompanying CD.

[14] http://nanohub.org.

[15] http://community.nsee.us.

[16] http://www.zyvex.com/nanotech/feynman.html.

[17] abbreviated after the wikipedia entry on technology.

[18] N. Taniguchi, "On the basic concept of nano-technology", *Proc. Int. Conf. Prod. Eng.* Part 2, pp. 18, 1974.

[19] D. Jost, "Nanotechnology for Policymakers, An Introduction from the Physical Science Perspective", *nccr trade regulations*, Swiss national center of competence in research, working paper no. 2009/21, May 2009; http://phase1.nccr-trade.org/images/stories/publications/IP9/ed. Nanotechnology Introduction v9 march2009.pdf

[20] D. M. Berube, *Nano-Hype: the Truth Behind the Nanotechnology Buzz*, Prometheus, 2007.

[21] A. R. von Hippel, "Molecular Engineering", *Science*, vol. 123 (issue 3191), pp. 315-317, 1956; MIT *Techn. Rep.* 101, October 1955; *Molecular Science and Molecular Engineering*, Technology Press of MIT Press and Wiley & Sons, New York, 1959.

[22] A. Einstein, "Eine neue Bestimmung der Molekül-dimensionen", *Annalen der Physik*, vol. 19, pp. 289-306, 1906, Erratum: *ibid* vol. 34, pp. 591-592, 1911.

[23] M. Faraday, "Experimental relations of gold (and other metals) to light; the Bakerian lecture", *Phil. Trans. Royal Soc. London*, vol. 147, pp. 145-181, 1857.

[24] J. W. Steed, J. L. Atwood, *Supramolecular Chemistry*, Wiley 2009.

[25] R. Phillips, S. R. Quake, "The Biological Frontier of Physics", *Physics Today*, May 2006, pp. 38-43.

[26] E. Drexler, *Engines of Creation*, Garden City, New York, 1986.

[27] C. Pheonix, E. Drexler, "Safe exponential manufacturing", *Nanotechnology*, vol. 15, pp. 869-872, 2004; see also http://www.youtube.com/watch?v=zqyZ9bFl_qg

[28] R. A. J. Jones, *Soft Machines: Nanotechnology and Life*, Oxford University Press, Oxford 2004.

[29] http://nano.foe.org.au/no-nano-recalled-magic-nano.

[30] http://www.electroiq.com/index/display/semiconductors-article-display/270664/articles/small-times/environment/2006/05/study-shows-no-nano-in-magic-nano-the-german-product-recalled-for-causing-breathing-problems.html.

[31] http://nanohype.blogspot.com/2006/04/on-magic-nano-201.html.

[32] http://www.etcgroup.org/upload/publication/14/01/nrnanorecallfinal.pdf.

[33] C. C. M. Mody, "The larger world of nano", *Physics Today*, October 2008, pp. 38-44.

[34] T. Satterfield, M. Kandlikar, C. E. H. Beaudrie, J. Conti, B. Herr Harthorn, "Anticipating the perceived risk of nanotechnologies", *Nature Nanotechnology*, vol. 4, pp. 352-358, 2009.

[1] Suspecting a lack of proper ventilation in at least some cases, one might think that some of the Magic Nano customers may have avoided their respiratory irritations if only they had sprayed the cleaner/sealant somewhat more considerately.