Editorial

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Do We Know Nanotechnology?

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Despite unprecedented government funding and public interest in nanotechnology, few can accurately define the scope, range or potential applications of this technology. One of the most pressing issues facing nanoscientists and technologists today is that of communicating with the non-scientific community. As a result of decades of speculation, a number of myths have grown up around the field, making it difficult for the general public, or indeed the business and financial communities, to understand what is a fundamental shift in the way we look at our interactions with the natural world. This article attempts to address some of these misconceptions, and explain why scientists, businesses and governments are spending large amounts of time and money on nanoscale research and development.

Take a random selection of scientists, engineers, investors and the general public and ask them what nanotechnology is and you will receive a range of replies as broad as nanotechnology itself. For many scientists, it is nothing startlingly new; after all we have been working at the nanoscale for decades, through electron microscopy, scanning probe microscopies or simply growing and analysing thin films. For most other groups, however, nanotechnology means something far more ambitious, miniature submarines in the bloodstream, little cogs and gears made out of atoms, space elevators made of nanotubes, and the colonization of space. It is no wonder people often muddle up nanotechnology with science fiction.

Although a metre is defined by the International Standards Organization as `the length of the path travelled by light in vacuum during a time interval of 1/299 792 458 of a second' and a nanometre is by definition 10^{-9} of a metre, this does not help scientists to communicate the nanoscale to non-scientists. It is in human nature to relate sizes by reference to everyday objects, and the commonest definition of nanotechnology is in relation to the width of a human hair.

Unfortunately, human hairs are highly variable, ranging from tens to hundreds of microns in diameter (10^{-6} of a metre), depending on the colour, type and the part of the body from which they are taken, so what is needed is a standard to which we can relate the nanoscale. Rather than asking anyone to imagine a millionth or a billionth of something, which few sane people can accomplish with ease, relating nanotechnology to atoms often makes the nanometre easier to imagine. While few non-scientists have a clear idea of how large an atom is, defining a nanometre as the size of 10 hydrogen, or 5 silicon atoms in a line is within the power of the human mind to grasp. The exact size of the atoms is less important than communicating the fact that nanotechnology is dealing with the smallest parts of matter that we can manipulate.

While there is a commonly held belief that nanotechnology is a futuristic science with applications 25 years in the future and beyond, nanotechnology is anything but science fiction. In the last 15 years over a dozen Nobel prizes have been awarded in nanotechnology, from the development of the scanning probe microscope (SPM), to the discovery of fullerenes. According to CMP Científica, over 600 companies are currently active in nanotechnology, from small venture capital backed start-ups to some of the world's largest corporations such as IBM and Samsung. Governments and corporations worldwide have ploughed over $4 billion into nanotechnology in the last year alone. Almost every university in the world has a nanotechnology department, or will have at least applied for the funding for one.

Even more significantly, there are companies applying nanotechnology to a variety of products we can already buy, such as automobile parts, clothing and ski wax. Nanotechnology is already all around us if you know where to look.

The confusion arises in part because many people in the business world do not know where to look. Over the last decade, technology has become synonymous with computers, software and communications, whether the internet or mobile telephones. Many of the initial applications of nanotechnology are materials related, such as additives for plastics, nanocarbon particles for improved steels, coatings and improved catalysts for the petrochemical industry. All of these are technology based industries, maybe not new ones, but industries with multi-billion dollar markets.

It is increasingly common to hear people referring to `the nanotechnology industry', just like the software or mobile phone industries, but will such a thing ever exist? Many of the companies working with nanotechnology are simply applying our knowledge of the nanoscale to existing industries, whether it is improved drug delivery mechanisms for the pharmaceutical industry, or producing nanoclay particles for the plastics industry. In fact nanotechnology is an enabling technology rather than an industry in its own right. No one would ever describe Microsoft or Oracle as being part of the electricity industry, even though without electricity the software industry could not exist. Rather, nanotechnology is a fundamental understanding of how nature works at the atomic scale. New industries will be generated as a result of this understanding, just as the understanding of how electrons can be moved in a conductor by applying a potential difference led to electric lighting, the telephone, computing, the internet and many other industries, all of which would not have been possible without it.

While it is possible to buy a packet of nanotechnology, a gram of nanotubes for example, it would have zero intrinsic value. The real value of the nanotubes would be in their application, whether within existing industry, or to enable the creation of a whole new one.

Shrinking machines down to the size where they can be inserted into the human body in order to detect and repair diseased cells is a popular idea of the benefits of nanotechnology, and one that even comes close to reality. Many companies are already in clinical trials for drug delivery mechanisms based on nanotechnology, but unfortunately none of them involve miniature submarines. It turns out that there are a whole range of more efficient ways that nanotechnology can enable better drug delivery without resorting to the use of nanomachines.

Just the concept of navigating ones way around the body at will does not bear serious scrutiny. Imagine attempting to go against the flow in an artery—it would be like swimming upstream in a fast flowing river, while boulders the size of houses, red and white blood cells, rained down on you. Current medical applications of nanotechnology are far more likely to involve improved delivery methods, such as pulmonary or epidermal methods to avoid having to pass through the stomach, encapsulation for both delivery and delayed release, and eventually the integration of detection with delivery, in order for drugs to be delivered exactly where they are needed, thus minimizing side effects on healthy tissue and cells. As far as navigation goes, delivery will be by exactly the same method that the human body uses, going with the flow and `dropping anchor' when the drug encounters its target.

Another common misconception is that nanotechnology is primarily concerned with making things smaller. This has been exacerbated by images of tiny bulls, and miniature guitars that can be strummed with the tip of an AFM, that while newsworthy, merely demonstrate our new found control of matter at the sub-micron scale. While almost the whole focus of micro-technologies has been on taking macro-scale devices such as transistors and mechanical systems and making them smaller, nanotechnology is more concerned with our ability to create from the bottom up. In electronics, there is a growing realization that with the end of the CMOS roadmap in sight at around 10 nm, combined with the uncertainly principal's limit of Von Neuman electronics at 2 nm, that merely making things smaller will not help us. Replacing CMOS transistors on a one for one basis with some type of nano device would have the effect of drastically increasing fabrication costs, while offering only a marginal improvement over current technologies.

However, nanotechnology offers us a way out of this technological and financial cul-de-sac by building devices from the bottom up. Techniques such as self assembly, perhaps assisted by templates created by nano imprint lithography, a notable European success, combined with our understanding of the workings of polymers and molecules such as Rotoxane at the nanoscale open up a whole new host of possibilities. Whether it is avoiding Moore's second law by switching to plastic electronics, or using molecular electronics, our understanding of the behaviour of materials on the scale of small molecules allows a variety of alternative approaches, to produce smarter, cheaper devices. The new understandings will also allow us to design new architectures, with the end result that functionality will become a more valid measure of performance than transistor density or operations per second.

It often comes as a surprise to learn that the Romans and Chinese were using nanoparticles thousands of years ago. Similarly, every time you light a match, fullerenes are produced. Degusssa have been producing carbon black, the substance that makes car tyres black and improves the wear resistance of the rubber, since the 1920s. Of course they were not aware that they were using nanotechnology, and as they had no control over particle size, or even any knowledge of the nanoscale they were not using nanotechnology as currently defined.

What is new about nanotechnology is our ability to not only see, and manipulate matter on the nanoscale, but our understanding of atomic scale interactions.

One of the defining moments in nanotechnology came in 1989 when Don Eigler used a SPM to spell out the letters IBM in xenon atoms. For the first time we could put atoms exactly where we wanted them, even if keeping them there at much above absolute zero proved to be a problem. While useful in aiding our understanding of the nanoworld, arranging atoms together one by one is unlikely to be of much use in industrial processes. Given that a Pentium 4 processor contains 42 million transistors, even simplifying the transistors to a cube of 100 atoms on each side would require 42×10^2 operations, and that is before we start to consider the other material and devices needed in a functioning processor.

Of course we already have the ability to build things atom by atom, and on a very large scale; it is called physical chemistry, and has been in industrial use for over a century producing everything from nitrates to salt. To do this, we do not need any kind of tabletop assembler as in Star Trek, usually a few barrels of readily available precursor chemicals and maybe a catalyst are all that is required.

Compare this with the difficulty of producing anything organic atom by atom, a sausage for example. Everyone is familiar with the macroscale ingredients of a sausage, some meat, maybe some fat, cartilage or other kinds of tissue, even some bone, all encased in animal gut. Never mind, argue the proponents of assemblers, things are simpler at smaller scales.

Zooming down to the microscale we still have far more complexity than we would like to attempt to replicate, with cells, cytoplasm, mitochondria, chromosomes, ribosomes and many other highly complex items of natural engineering. Moving closer to the nanoscale, we still have to deal with nucleic acids, nucleotides, peptides and proteins, none of which we fully understand, or expect to even have the computing power to understand in the near future.

In terms of return on our investment, a farmyard containing a few pigs is a far more effective sausage machine than we could ever design, and has several other by-products such as hams and a highly effective waste disposal system. This serves to illustrate just how far we are away from being able to replicate nature.

In terms of capturing the public imagination, unleashing hordes of self-replicating devices that escape from the lab and attack anything in their path is always going to be popular. Unfortunately nature has already beaten us to it, by several hundred million years. Naturally occurring nanomachines, that can not only replicate and mutate as they do so in order to avoid our best attempts at eradication, but can also escape their hosts and travel with alarming ease through the atmosphere. No wonder that viruses are the most successful living organisms on the planet, with most of their `machinery' being well into the nano realm. However, there are finite limits to the spread of such `nanobots', usually determined by their ability, or lack thereof, of converting a sufficiently wide range of material needed for future expansion. Indeed, the immune systems of many species, while unable to completely neutralize viruses without side effects such as runny noses, are so effective in dealing with this type of threat as a result of the wide range of different technologies available to a large complex organism when confronted with a single purpose nano-sized one. For any threat from the nano world to become a danger, it would have to include far more intelligence and flexibility than we could possibly design into it.

Our understanding of genomics and proteomics is primitive compared with that of nature, and is likely to remain that way for the foreseeable future. For anyone determined to worry about nanoscale threats to humanity should consider mutations in viruses such as HIV that would allow transmission via mosquitoes, or deadlier versions of the influenza virus, which deserve far more concern than anything nanotechnology may produce.

Nanotechnology, like any other branch of science, is primarily concerned with understanding how nature works. We have discussed how our efforts to produce devices and manipulate matter are still at a very primitive stage compared to nature. Nature has the ability to design highly energy efficient systems that operate precisely and without waste, fix only that which needs fixing, do only that which needs doing, and no more. We do not, although one day our understanding of nanoscale phenomena may allow us to replicate at least part of what nature accomplishes with ease.

While many branches of what now falls under the umbrella term nanotechnology are not new, it is the combination of existing technologies with our new found ability to observe and manipulate at the atomic scale that makes nanotechnology so compelling from scientific, business and political viewpoints.

For the scientist, advancing the sum total of human knowledge has long been the driving force behind discovery, from the gentleman scientists of the 17th and 18th centuries to our current academic infrastructure. Nanotechnology is at a very early stage in our attempts to understand the world around us, and will provide inspiration and drive for many generations of scientists.

For business, nanotechnology is no different from any other technology: it will be judged on its ability to make money. This may be in the lowering of production costs by, for example, the use of more efficient or more selective catalysts in the chemicals industry, by developing new products such as novel drug delivery mechanisms or stain resistant clothing, or the creation of entirely new markets, as the understanding of polymers did for the multi-billion euro plastics industry.

Politically, it can be argued that fear is the primary motivation. The US has opened up a commanding lead in terms of economic growth, despite recent setbacks, as a result if the growth and adoption of information technology. Of equal significance is the lead in military technology as demonstrated by the use of unmanned drones for both surveillance and assault in recent conflicts. Nanotechnology promises far more significant economic, military and cultural changes than those created by the internet, and with technology advancing so fast, and development and adoption cycles becoming shorter, playing catch-up will not be an option for governments who are not already taking action.

Maybe the greatest short term benefit of nanotechnology is in bringing together the disparate sciences, physical and biological, who due to the nature of education often have had no contact since high school. Rather than nanosubmarines or killer nanobots, the greatest legacy of nanotechnology may well prove to be the unification of scientific disciplines and the resultant ability of scientists, when faced with a problem, to call on the resources of the whole of science, not just of one discipline.