

“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.”

Richard P. Feynman, American Nobel Physicist, 1959.

Nanotechnology

By Karen Hussey & Jennifer Yarnold

Definition

Nanotechnology can be straightforwardly defined as the manipulation and manufacture of materials and devices at the ‘nanoscale’; which is typically considered to be at dimensions between 1 and 100 nanometers. To put that in perspective, imagine 1 mm on a ruler, now cut that into a million pieces; or comparatively speaking, if the diameter of a marble was one nanometer, then the diameter of the Earth would be about one metre.^[1]

Of course, nanotechnology is not a uniquely human invention. Nature has been exploiting processes at nano-scales (i.e. nanotechnologies) for billions of years – the process of photosynthesis, the creation and repair of cells, and the replication of DNA all rely on an organism’s capacity to organise different kinds of atoms and molecules into complex microscopic structures. These sorts of nanoscale processes underlie the fundamental biochemistry of life. Nor are nanoscale materials new – nanotechnology has been used in sunscreens for many years in the form of titanium dioxide and zinc oxide nanoparticles.

Today, nanotechnology is used to describe our capacity to manipulate materials at that nano scale and encompasses:

nanoscience – advancements in our understanding of the physical, chemical, and biological properties at atomic and near-atomic scales, and

nanotechnologies – which employ controlled manipulation of these properties to create materials with unique capabilities. In many ways, nanotechnology is our attempt to replicate the natural processes, functions and properties of the natural world by emulating those features – as such, nanotechnology is a form of biomimicry.

It is the ‘unique capabilities’ of these nanomaterials that offer such promise and which have elicited much interest in recent years. For example, using nanotechnology, materials can be made stronger, lighter, more durable, porous, reactive, or residue-repellent, and/or they can be designed as better electrical conductors or to resist wrinkling, or to repel heat better.

Figure 10. Technology and innovation pipeline of nanotechnology



There are already many products on the market and in everyday use which employ nanoscale materials and processes, with applications across medicine, healthcare, industrial products and processes, cosmetics, information technology, and agriculture. Commonly cited examples of contemporary nanotechnology include nanoscale film on eyeglasses, nanoscale additives in fabrics to make them resist to wrinkling, so-called carbon nanotubes used to manufacture lightweight air vehicles, and the use of nanoscale design for drug delivery and new drug therapies. In the agricultural sector, nanotechnology can be used in food processing and packaging, irrigation and water filtration, animal feed, more efficient delivery of animal vaccines, aquaculture, and waste management. With this

incredible spread of applications across economic sectors, nanotechnology reflects very neatly the ‘technology splitting’ phenomenon referred to earlier in this report.

In short, nanotechnology is not one technology – it refers to a vast suite of technologies that have been developed using our recent, highly advanced understanding of subatomic physical, chemical and biological properties which in turn have enabled us to create new materials with enhanced features.

But while the very *smallness* of nanotechnology is what makes its potential so significant, that smallness is also what makes some nanotechnologies so difficult to regulate – **materials behave differently at the atomic level.**

Context

Leaving aside the prevalence of nanotechnology in natural processes, humankind's first forays into the nanoscale date back to the mid-1800s, well before *nano* – was even defined. However the term itself – 'nanotechnology' – was coined in 1974 by the Japanese scientist Norio Taniguchi in a paper describing the separation, consolidation and deformation of materials by one atom or molecule.^[2]

Arguably the most strident early advocate for nanotechnology was K. Eric Drexler, the first scientist to receive a PhD in molecular nanotechnology. In the 1980s Drexler envisaged a world where molecular machines and nanocomputers could be used to support the human body's immune system, by being programmed to search out and destroy viruses and cancer cells. But while scientists' interest in the potential for nanoscale science to offer new ways to manipulate the properties of materials dates back to the 1950s, the lack of tools with which to operate at that scale meant little progress was made until the 1980s and 1990s.

Indeed, as with all science, advancements made in nanotechnology have been iterative, with the development of new insights and discoveries, tools and methods providing the building blocks for yet more discovery. For nanotechnology, advancements made in quantum mechanics, molecular biology, organic electronics and a vast array of other scientific fields have seen it evolve from early applications in semiconductors, through to the development of new materials and processes in almost every sphere of life. At the time of writing, there are more than 145,000 patents involving nanotechnology listed with the World Intellectual Property Organisation.

Drivers

Food manufacture – The vast range of applications of nanotechnology correspond with an array of drivers that are encouraging its development. In the agricultural sector, the constraints imposed by resource scarcity and a changing climate, population growth, and shifting markets and consumer expectations, mean the opportunities offered by nanotechnology to improve nutrient delivery and flavour, extend storage life of agricultural products, and allow for the detection of pathogens, toxins and pesticides are especially promising.^[3]

Advanced Manufacturing – The potential to manipulate the properties of materials at the nanoscale is also promising in relation to advanced

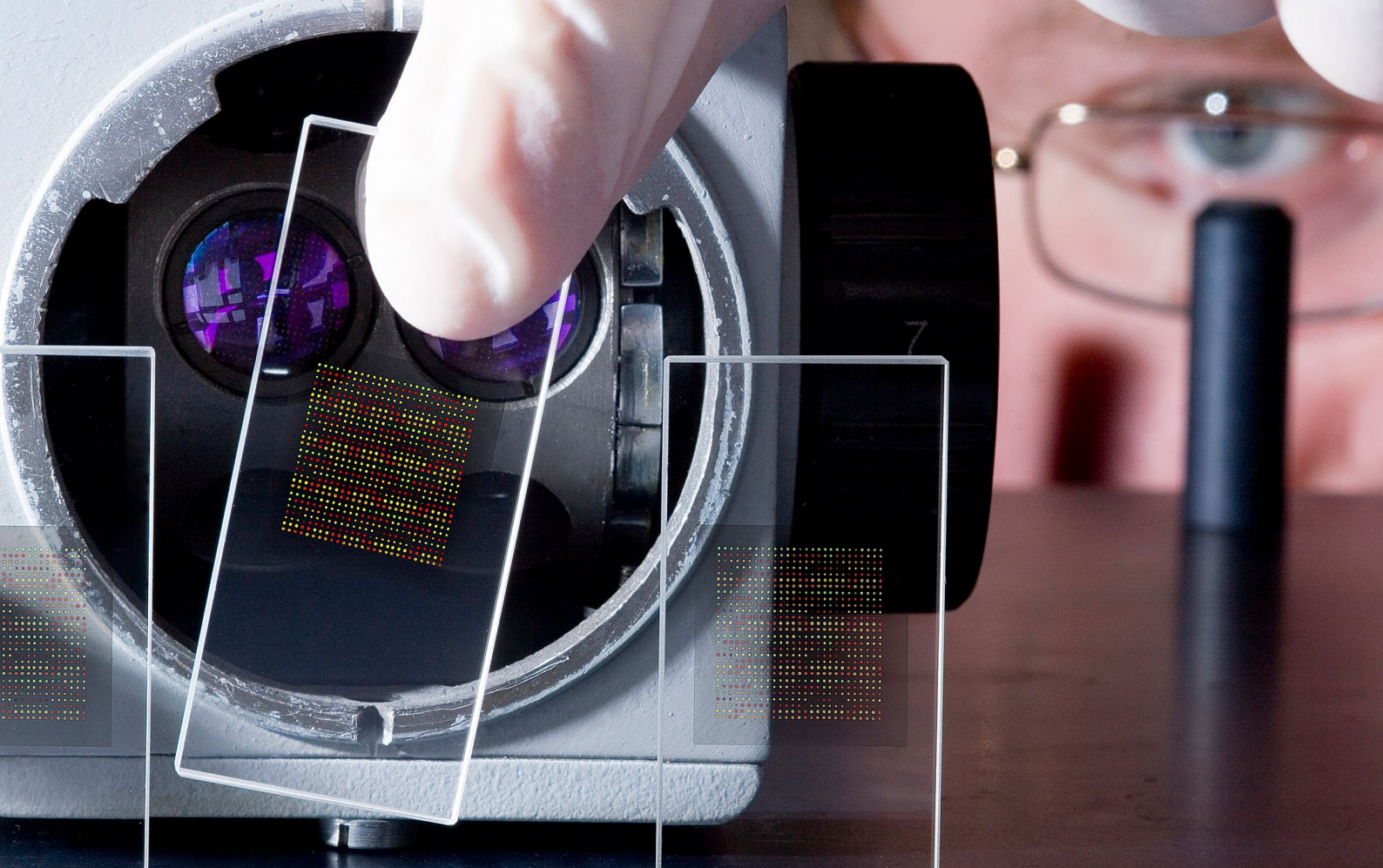
manufacturing, where durability and energy efficiency are key drivers. For example, some nanotechnologies relate to new types of product coatings or polymers, with one process increasing the strength of steel by as much as 10 times, which in turn means it is more resistant to corrosion. Other nanomaterials can be engineered to increase not only strength, but also temperature and corrosion resistance, while still others can be engineered to provide lubricity and wear resistance. The potential for ultra-lightweight nanomaterials to be used in vehicles, especially aircraft where weight is so critical, is also being explored.

In medicine, the opportunity to exploit nanotechnology to produce more precise and targeted therapeutics could see patients potentially experience shorter and more cost-effective medical treatments. For example, researchers have developed nanoscale electronic devices, sensors and microscopic robots which can travel through the vascular system and target particular cancer tumours.

In the **defence sector**, the potential for nanotechnology is already being realised with new equipment being developed that is stronger and lighter, and in some cases resistant to chemical and biological agents. The defence sector is also developing communications systems that can be woven into specially coated polymer threads in soldiers' garments. The threads can emit light at different wavelengths, thus allowing for silent signalling between soldiers and preventing eavesdropping or detection by enemy units. Ultimately, the drivers behind nanotechnology use in the defence force relate to energy and cost efficiency, and military advantage.

The overall driver, therefore, is the potential to develop more energy and resource efficient products that last longer, cost less over their life cycle, and which consequently offer social, economic and environmental benefits from their development and application.

Those benefits notwithstanding, a key consideration for policy makers, regulators and societies more broadly is the extent to which nanotechnologies *per se* are the most effective means by which to achieve the supposed benefits they offer. For example, if addressing food insecurity is the objective, how significant will the use of nanotechnologies in food packaging be, compared to efforts to genuinely address the underlying economic and institutional constraints that lie at the heart of food insecurity? Somewhat ironically, such considerations strike at the heart of the complexities and contradictions in the drivers behind innovation policy.



Enablers

Microscopy – like many other innovations, the development and application of nanotechnology has been enabled by significant advancements made in many other fields. Crucially, the invention of the scanning tunnelling microscope and the atomic force microscope in the 1980s allowed scientists to see materials at the subatomic level. Without those imaging tools, and indeed those which have subsequently been enhanced in recent years, nanotechnology would not have been possible.

Computational Modelling – similarly, the revolution in information and communications technologies has seen the development of much more powerful computers (supercomputers) which enabled large scale simulations of material systems, in turn providing greater insight into structures and properties of nanoscale materials. Combined with advancements in modelling and simulation, atomic scale visualisation and characterisation, and experimental synthesis, these activities fuelled the contemporary development of nanoscience and nanotechnology.

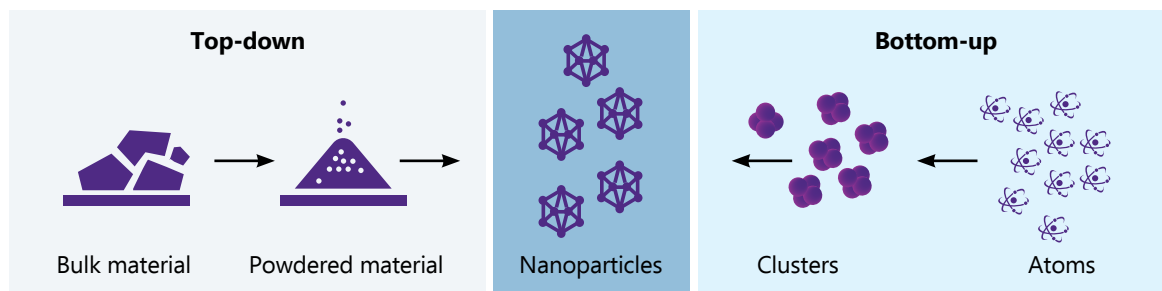
Lithography – a further catalytic advancement in nanoscience was achieved through developments in lithography (a technology originally developed in the eighteenth century), brought about by the

extraordinary growth in the semiconductor industry, which in turn saw new techniques for etching, writing, and printing of nanometer-scale structures.

“I think the biggest innovations of the twenty-first century will be at the intersection of biology and technology. A new era is beginning.” – Steve Jobs

Inputs

The inputs to nanotechnology are fundamentally not a radical departure from existing biochemical and materials inputs in use today. What is new are the processes and outputs which involve their manipulation at the nanoscale. Thus, the inputs required are simply specialised microscopic and lithographic equipment along with molecular building blocks, nanoparticles and atoms, many of which are in common use in nature or industry already. From a top down approach, the inputs are bulk materials such as graphite, which are thinned down into layers. In this context nanotechnology is a good example of an emerging technology which is process rather than input driven – it is a new way of achieving an end.

Figure 11. Basic schematic of the top-down versus a bottom-up approach to nanotechnology.

Processes

Nanotechnologies are developed using either a top-down or bottom-up approach (**Figure 11**). The top-down approach to fabrication and manufacture is almost like traditional printing – scientists use highly sophisticated tools (photo/optical lithography) to manipulate (using short wavelength light beams or lasers) the atomic and molecular structures of materials to achieve a particular property (greater strength, durability etc.). This method evolved from our experience with manufacturing integrated circuit boards and microelectronic circuit boards, and in very basic terms can be thought of as ‘etching’ the designed subatomic pattern *in situ*.

Conversely, the bottom-up approach uses chemical or physical forces to encourage the self-assembly of new clusters of atoms and molecules into small building blocks, which build upon one another to create more elaborate structures with the desired properties. Like so many other technological advancements, the bottom-up approach draws on a range of scientific disciplines and approaches, including physics, chemistry, information technology, advanced engineering, metrology and characterisation techniques and biomimetics.

For example, a breakthrough in the emerging field of quantum computer development adopted a bottom up approach to create the world’s smallest transistor. In 2010, Australian researchers manipulated individual atoms with extremely high precision, where a scanning tunnelling microscope was used to remove a single silicon atom from a silicon crystal and substitute it with a single phosphorus atom to an accuracy of just 0.5 nanometres.^[7]

Considerations for regulators: While the inputs into nanotechnologies are not particularly new or different to past materials production, there are several characteristics and processes unique to nanotechnologies which challenge traditional risk

management frameworks and demand attention from regulators. For example, the physical, chemical and biological properties of nanomaterials may differ in important ways from the properties of single atoms, molecules or bulk materials, which makes identifying any direct, indirect and/or cumulative impacts of nanomaterials and nanotechnologies hard to predict. Similarly, the fact that nanoparticles are so small raises concerns about their ability to migrate through organisms and body tissues, which is why the use of nanomaterials in cosmetics, health products, agriculture and food products has been of particular concern for regulators, insurers and consumers.^[8] There are also challenges surrounding the impacts of whether a top-down or bottom-up approach is used to fabricate the material, owing to concerns that “subtle changes in the method of preparation can lead to significant alterations in the physicochemical properties and morphologies of the resulting nanoparticles.”^[9] As such, the need for long term studies to assess the impacts of nanomaterials and nanotechnologies on humans and the environment is needed and such issues are the subject of intense study internationally.

Outputs

There are literally tens of thousands of nanotechnologies either in production or on the market. In the agricultural sector, nanoscience is being used to create new fertilisers, food packaging and coating, and water filtration methods; in the defence sector, lighter and more durable equipment is in development; in the medicine and health sectors, there are new bandages, new drug delivery methods and diagnosis tools on the market; and in the ICT domain, nanoscience is heralding a whole suit of new displays, sensors and semiconductors. For regulators, the challenge is to ascertain the public’s level of comfort with different applications

of nanotechnologies, and to develop responses which enable the benefits of nanotechnologies to be realised while the necessary science is undertaken to assess the direct, indirect and cumulative risks. It is clear from recent research that consumers are far more comfortable with the use of nanotechnologies in the energy sector, than in the health and medical sectors.

References

1. United States National Nanotechnology Initiative. <https://www.nano.gov/nanotech-101/what/nano-size>. Accessed 27 June 2019.
2. Picraux, T. (2018). Nanotechnology, Encyclopaedia Britannica, Published 21 November 2018, <https://www.britannica.com/technology/nanotechnology> Accessed: June 27, 2019
3. N. Taniguchi. (1974). On the Basic Concept of 'Nano-Technology', Proc. Intl. Conf. Prod. Eng. Tokyo, Part II, Japan Society of Precision Engineering.
4. Mitter, N. & Hussey, K. (2019). Moving policy and regulation forward for nanotechnology applications in agriculture, Nature Nanotechnology 14, pp. 508-510
5. TryEngineering.org. <http://www.trynano.org/about/history-nanotechnology>. Accessed: 20 June 2019.
6. AZoNano (2004). <https://www.azonano.com/article.aspx?ArticleID=659>. Accessed: 20 June 2019.
7. Fuechsle, M., et al. (2012). A single-atom transistor. Nature Nanotechnology, 7(4): p. 242.
8. Australian Pesticides and Veterinary Medicines Authority (2015). Nanotechnologies for pesticides and veterinary medicines: regulatory considerations. Final report. Canberra: Australian Pesticides and Veterinary Medicines Authority.
9. Gehrke, P. J. (2019). Nano-Publics: Communicating Nanotechnology Applications, Risks, and Regulations. (Springer)
10. Larsson, S., Jansson, M. & Boholm, Å. (2019). Expert stakeholders' perception of nanotechnology: risk, benefit, knowledge, and regulation. Journal of Nanoparticle Research 21, 57.

Recommended further reading

1. Mitter, N. & Hussey, K. (2019). Moving policy and regulation forward for nanotechnology applications in agriculture. Nature Nanotechnology, 14(6), 508-510.
2. Marchant, G. Et al. (2012). 'Big Issues for Small Stuff: Nanotechnology Regulation and Risk Management'. Jurimetrics 52(3): 243-277



Contributors: This publication was authored and edited by Karen Hussey, Jennifer Yarnold, Christopher McEwan, and Amelia Radke. Date of publication: 30 June 2019. Important disclaimer: This content has been prepared by the UQ Centre for Policy Futures for the purpose of general education. It does not constitute professional advice, nor is it a substitute for such advice. Questions about the topics discussed may be directed to the UQ Centre for Policy Futures by email: policyfutures@uq.edu.au or phone: +61 7 3443 3118. © The University of Queensland. All material published in 'Policy Futures' is licensed under a Creative Commons - Attribution - Non-Commercial 4.0 International (CC BY-NC 4.0) licence. In essence, you are free to copy, distribute and adapt the work, as long as you attribute the work and abide by the other licence terms. To view a copy of this licence, visit: <http://creativecommons.org/licenses/by/4.0/>.

Image: self-assembled mono layers of gold nanocages.

