PRIMER

MAGNIFYING NANOMATERIALS

KOBI LEINS

UNIDIR UNITED NATIONS INSTITUTE FOR DISARMAMENT RESEARCH

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ABOUT UNIDIR

The United Nations Institute for Disarmament Research (UNIDIR) is a voluntarily funded, autonomous institute within the United Nations. One of the few policy institutes worldwide focusing on disarmament, UNIDIR generates knowledge and promotes dialogue and action on disarmament and security. Based in Geneva, UNIDIR assists the international community to develop the practical, innovative ideas needed to find solutions to critical security problems.

NOTE

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ABOUT THE AUTHOR

Kobi Leins is a Senior Research Fellow in Digital Ethics with the University of Melbourne, Australia, and a non-resident Fellow of the United Nations Institute for Disarmament Research. Leins' PhD, submitted in 2019, is entitled 'International Law Applicable to the Use of Nanomaterials in Wars' and will appear as a monograph in 2021 with Cambridge University Press.

LIST OF ACRONYMS AND ABBREVIATIONS

BTWC	Biological and Toxin Weapons Convention
CCW	Convention on Certain Conventional Weapons
CWC	Chemical Weapons Convention
UNIDIR	United Nations Institute for Disarmament Research

INTRODUCTION

For more than three decades, the manipulation of nanomaterials has been subtly changing the world around us, including how wars are fought. The use of nanomaterials has increased military capabilities in numerous ways already and will continue to shape battlefield capacity as our understanding of the human brain and body, and the ways we can intervene in their functions, increases.

Although the idea of manipulating atoms was first recorded at a talk by Richard Feynman in 1959,[1] the term "nanotechnology" was first coined by a Japanese professor in 1974,[2] and it has since become shorthand for a wide range of ideas, meanings and applications.

Research into the use of nanomaterials for neurological and biological applications is racing alongside advances in understanding of the human brain. Such research includes:

- Connection of brain function with external physical structures, including increasing the capability of soldiers[3]
- Provision of physical function for people with disabilities[4]
- Devices that can infiltrate electronics and seize control at crucial moments[5]
- Artificial "disease" agents that can rest harmlessly in victims' bodies until activated by an external signal[6]
- Rapid advances in genetic intervention and modification,[7] including the recent genetic modification of living twin children[8]

Part of the challenge of speaking of nanomaterials is that they are a category of scale that includes a very broad range of materials, and the definitions of what constitutes a nanomaterial are not entirely consistent. Further, the way that engineered nanomaterials interact with the human body is not yet entirely understood.[9] Deploying these types of nanoscale material in war requires contemplation of existing limits on use, particularly given their potentially deleterious effects on humans and on the environment, some of which are long term and potentially not yet known.

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[1] Feynman (1959).
[2] Taniguchi (1974).
[3] Gross (2018).
[4] The White House (2014).
[5] Hearn (2001).
[6] Gross (2018); Hall (2014); Henschke (2017).
[7] Li & Qian (2015).
[8] Regalado (2019).
[9] Maynard (2014); Nasu (2012).

When thinking about nanomaterials, there are security and strategy implications to contemplate and a large swathe of existing law – including the law of armed conflict, environmental law and human rights law – in addition to the potential long-term environmental and health implications.

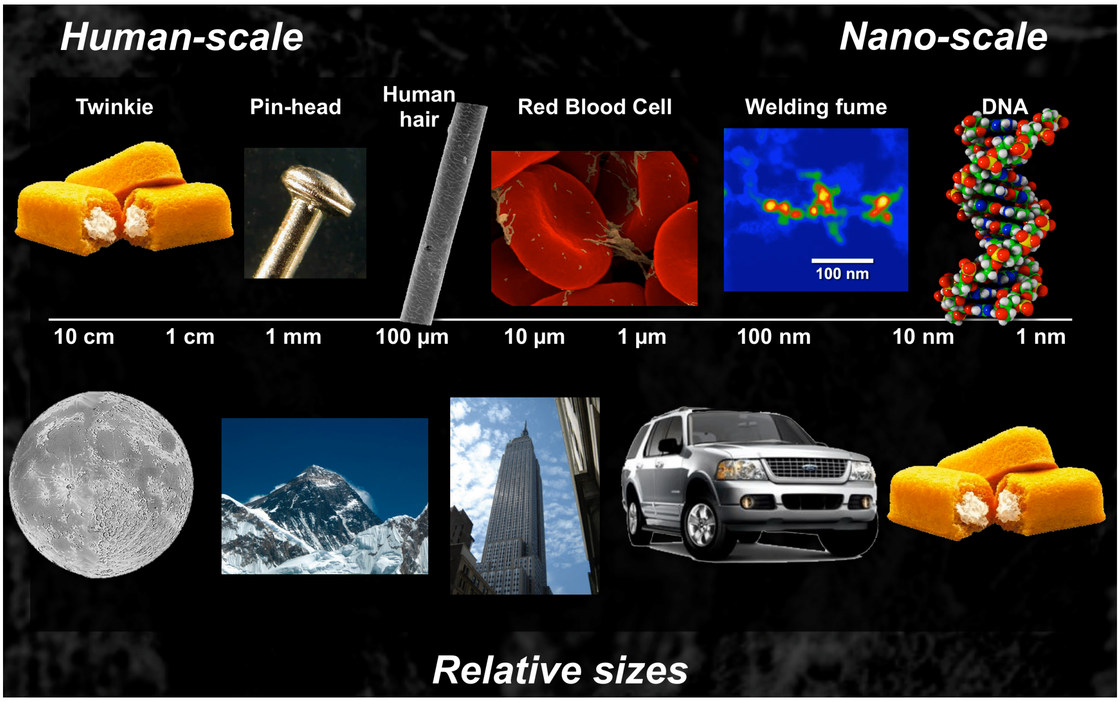
This primer aims to provide a foundation from which to engage with these ideas and to help policymakers participate in conversations, including asking the right questions, about applications of nanomaterials that may have consequences for national and international security now and in the future.

This primer defines nanomaterials, provides examples of their popular applications (both generally and in relation to security and defence), discusses their risks and introduces the issue of regulation.

2. WHAT ARE NANOMATERIALS?

"Nano" is a prefix meaning "a billionth" (a factor of 10^9 of a metre) derived from the Greek νᾶνος, meaning "dwarf". By way of illustration, a nano-sized object is to an apple what an apple-sized object is to the Earth. Or to give another example, one nanometre particle could fit approximately 80,000 times across the width of a human hair (see Figure 1).[10]

FIGURE 1: NANOSCALE MAP



Nanoparticles have occurred naturally for thousands, perhaps millions, of years: in volcanic ash, in sea spray and as mineral deposits, to name just a few examples.[11] These naturally occurring nanoscale particles, for the most part, pose few challenges to human health, as human bodies have adapted to deal with these materials over the years.[12] It is not these types of nanomaterial that attracted concern in the early 2000s from consumer groups, non-governmental organizations and academics. Rather, it was the increase in the creation and use of purposefully engineered nanomaterials that generated discussion and debate across multiple disciplines and jurisdictions. In this primer, it is these purposefully engineered nanomaterials to which are being referred.[13]

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[10] Kahn (2006).
[11] Thakur & Thakur (2016, 688).
[12] Buzea et al. (2007).
[13] See, for example, Balbus et al. (2007); Borm et al. (2006); Hansen et al. (2008); Hoet et al. (2004); Maynard et al. (2006).

3. BENEFITS OF THE USE OF NANOMATERIALS

In the last two decades, the ability to deliberately create, manipulate or modify existing matter at the nanoscale has resulted in rapid innovation in, and across, many fields. Most of this development is driven by the fact that materials at the nanoscale have different properties from their macroscale or microscale counterparts, such as increased permeability (due to their large surface area to volume ratio), greater strength, higher chemical resistance or heightened conductivity.

Nanomaterials have improved practices and functions in areas as diverse as agriculture, biological science, biotechnology, chemistry, defence, energy conversion and storage, engineering, information technology, material sciences, medicine, microelectronics, and pharmaceuticals. In many instances, the different applications overlap disciplines as scientists increasingly collaborate with and draw from other fields to improve their own technologies.[14] Some of these advances are improving health, sun protection and membrane functions, as well as the function and longevity of electronics. The benefits of harnessing the power of nanomaterials are apparent across many areas of our lives already.

For defence, nanomaterials have helped decrease the size of military energy sources and increase how long they last, [15] helped convert solar power to usable energy (also known as "photovoltaics") on the battlefield, and improved military equipment.[16] In addition, much research is being undertaken by militaries to incorporate nano-elements to enhance the function of existing military applications, including gas filters, masks, materials for tanks, and protective clothing (that deflects water or heat, for example) for soldiers. These benefits, however, are not without certain risks.[17]

3.1 MILITARY APPLICATIONS

Military interest in nanomaterials is significant.[18] For some years, there has been notable investment in both military and civilian uses of nanomaterials. For example, since its inception in 2001, a total of nearly $24 billion has been invested in nanomaterials by the

[14] Kivivali (2016); Pennisi (2016).
[15] Cho et al. (2016).
[16] See Defence Science Institute (2013).
[17] Altmann & Gubrud (2002); Balbus et al. (2007); Maynard et al. (2006).
[18] DARPA (2014); NSTC (2016).

National Nanotechnology Initiative in the United States of America (including the 2017 budget).[19]

The European Union is also proactively seeking a research agenda that includes nanomaterials.[20] Other countries are not necessarily as public with their agendas or budgets, but it can be assumed that research into uses of nanomaterials in defence continue apace worldwide.

Figure 2 illustrates the range of military applications for nanomaterials.

FIGURE 2: MILITARY USES OF NANOTECHNOLOGY

MILITARY USES OF NANOTECHNOLOGY	
Enabling Technologies	Micro/Nano Fabrication: Materials, Coatings, Devices
	Visualize Molecules: Natural, Synthetic, Bio
Small, Lightweight, Incredible Performance Platforms	Materials: Armour, Fuselage, Textile, Energetic
	Structures: Membranes, Electrodes
	Sensors: Pressure, Chemical, Biological
	Devices: MEMS, Actuators, Optical, Lab on a chip
	Computers: Processors, Displays, I/O
	Lasers
Systems and Sub-Systems	Guidance & Control
	Power Systems
	Propulsion
	Signature Control
	Intelligent Materials/ Self Healing
Evolutionary and Revolutionary Military Applications	Military Vehicles
	Unmanned Vehicles and Robots
	Armaments
	Command and Control
	Soldier Warfare
	Human Performance

SOURCE: ADAPTED FROM NANOTECHNOLOGY NOW (2019)

19 NSTC (2016).
20 EC (2019).

Military and civilian research in nanomaterials continues to slowly forge new frontiers, with direct implications for new military equipment and associated regulatory mechanisms. Detailed predictions for the possibility of storage, dispersal and transport of chemical and biological agents in the bodies of humans, animals and plants have been provided by scientists in the field, looking to the future.[21]

Nanomaterials, it has been suggested, will enable nanorobots to self-replicate, with no currently developed countermeasures. These nanorobots could, just as one example, be used as "markers" for individuals to be targeted or, conversely, provide specific protections for particular populations.[22] Another example of the benefits of nanomaterials is in the possibility of connecting soldiers with platforms through advanced smart fabrics that use the properties of nanomaterials to link to other devices on the battlefield, such as drones or unmanned vehicles.

3.2 OTHER POPULAR APPLICATIONS

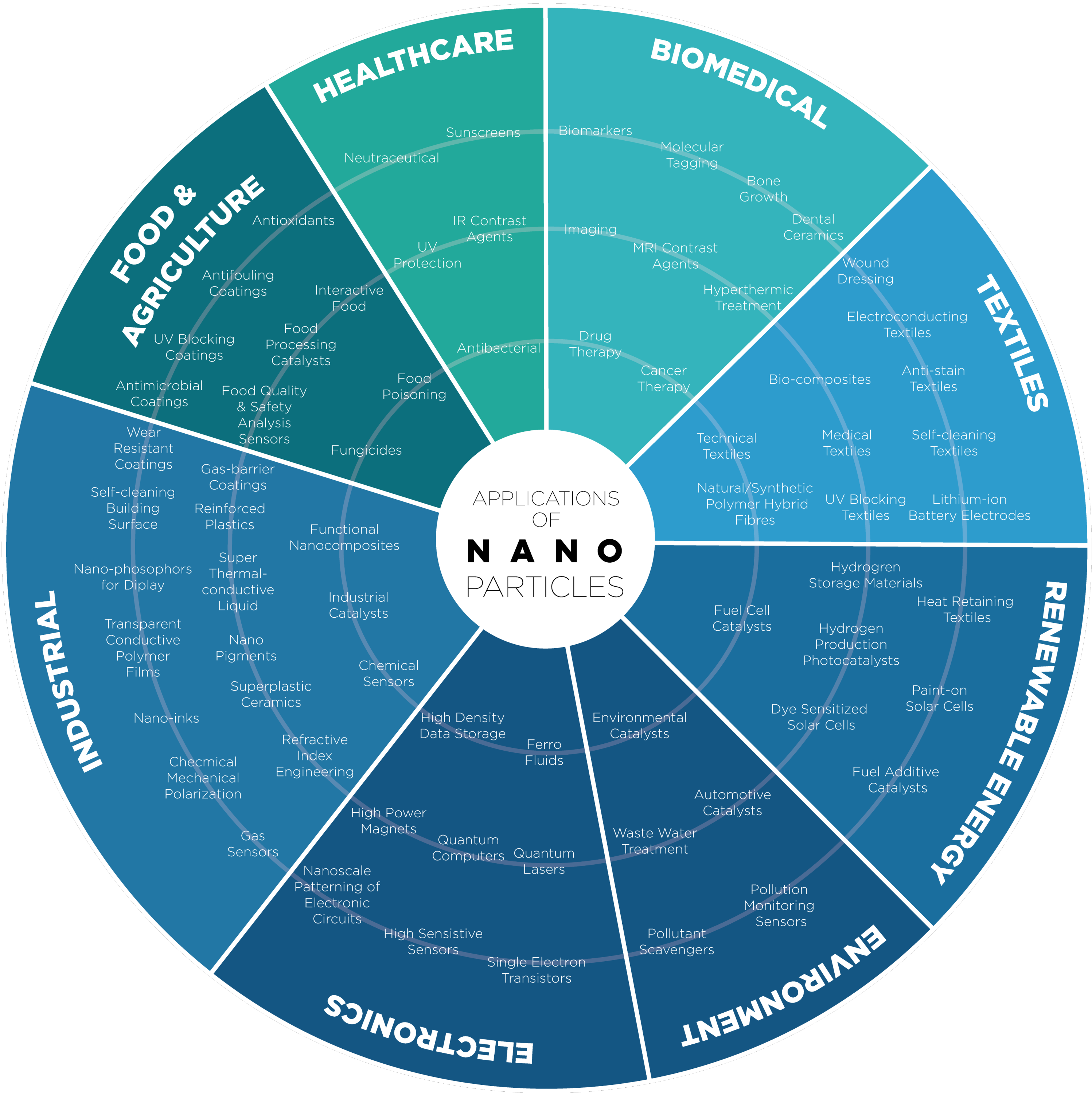
Commercially, nanomaterials are being used in the manufacture of scratchproof eyeglasses, crack-resistant paints, anti-graffiti coatings for walls, transparent sunscreens, stain-repellent fabrics, self-cleaning windows and ceramic coatings for solar cells, to name a few examples.

Promoters of the use of nanomaterials have argued that the technology has the potential to improve the performance of existing products, to offer new capabilities – especially through convergence with other emerging technologies – and to be of fundamental assistance in addressing global problems such as climate change and food security.[23]

It is therefore not surprising that a number of national governments have heavily invested in a nanomaterials future, given the seemingly endless number of potential uses for these materials (see Figure 3).[24]

[21] Altmann & Gubrud (2002, 2–3).
[22] Altmann & Gubrud (2002, 2–3).
[23] Som et al. (2010).
[24] Roco (2005).

FIGURE 3: APPLICATIONS OF NANOPARTICLES



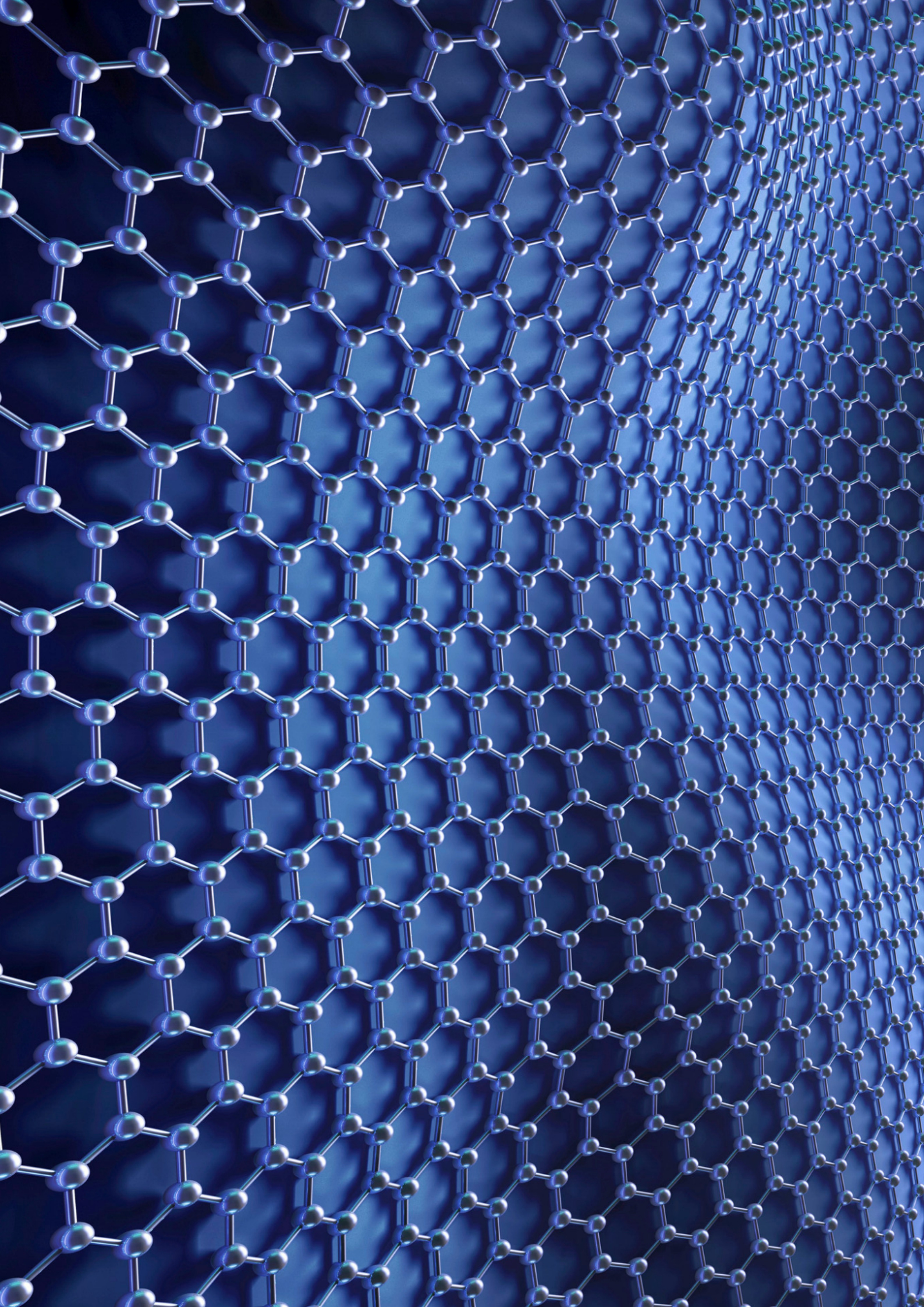
SOURCE: ADAPTED FROM GENESIS NANOTECHNOLOGY (2019)

3.3 COMBINED USE OF NANOMATERIALS WITH OTHER EMERGING TECHNOLOGIES

Nanotechnology is advancing not in isolation, but alongside many other technologies. The use of new computing algorithms to manipulate artificial intelligence and data, combined with physically embedded nanomembranes or materials in humans, is one example of the interplay and capabilities of multiple technologies. How emerging technologies may engage with nanomaterials in the medium term (and this is largely speculative) is in the way that increased computing capacity may expedite the development of new nanomaterials by providing faster modelling based on existing nanomaterials.

As cloud labs increase in popularity, the cybersecurity of such simulations will need to be a consideration, not only to protect intellectual property but also to ensure that developments remain in the hands of the user. In this regard, many lessons can be learned from how advances in biological and chemical science have been considered in the past.

With an increased focus on human behavioural analytics through big data (noting that the usefulness of this type of approach is not entirely clear), it is imaginable that the use of nanomaterials in human biology may be coupled with tracking, increasing or decreasing certain body functions. In some instances, this may arguably be a form of “enhancement”, so it would need to comply with existing treaties and customary law if used in non-civilian contexts.



4. RISKS OF THE USE OF NANOMATERIALS

Just as they need to know of the potential benefits, policymakers need to also be aware of the potential risks of the use of nanomaterials, particularly where their use may violate existing international obligations or have potential health or environmental risks.

Attention should be paid to certain families of nanomaterials, and policymakers should ensure that they have the most recent data regarding the safety of nanomaterials. Safe exposure levels for all nanomaterials are not known at present.[25]

To contemplate the risks of use beyond civilian uses, it is helpful to contemplate the breadth and depth of research already in existence more generally.[26] For example, Table 1 provides a non-exhaustive list of potentially toxic families of nanomaterial.

As long-term risks to the environment posed by nanomaterials remain largely unknown, research on the impact of nanomaterials on human health is ongoing.

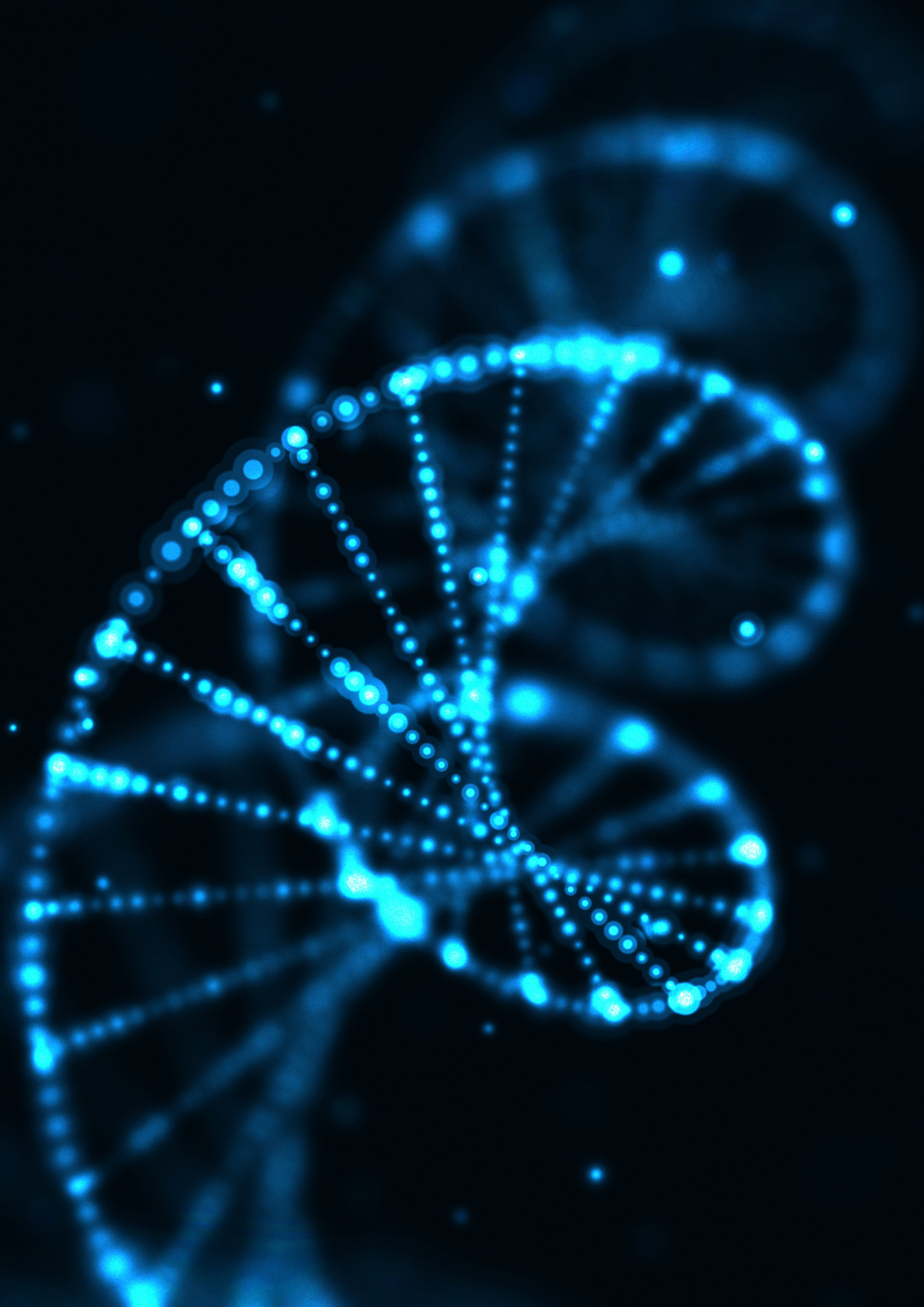
TABLE 1[27]

POSSIBLE RISKS OF NANOMATERIALS

NANOMATERIALS	POSSIBLE RISKS
Carbon nanomaterials, silica nanoparticle	Pulmonary inflammation, granuloma and fibrosis
Carbon, silver and gold nanomaterials	Distribution into other organs, including the central nervous system
Quantum dots, carbon and TiO_2 nanoparticles	Skin penetration
MnO_2, TiO_2 and carbon nanoparticles	May enter brain through nasal epithelium olfactory neurons
TiO_2, Al_2O_3, carbon black, Co and Ni nanoparticles	May be more toxic than micron-sized particles

Finally, it has become clear that some of these engineered nanomaterials may be harmful to human health or cause as yet unknown side effects.[28] The many unknowns of engineered nanomaterials pose governance challenges in the face of increasing knowledge about how nanomaterials affect the human body.[29]

[25] Hull & Bowman (2018).
[26] Leins & Bowman (2019).
[27] Ray et al. (2009).
[28] Abbott & Maynard (2010).
[29] Johnson (2016).



5. REGULATION AND GOVERNANCE OF NANOMATERIALS

For the purpose of disarmament and arms control, given their inability to be seen, nanomaterials may pose particular challenges to existing verification and transfer regimes. Enabling technologies, such as materials, coatings and devices, will make soldiers more comfortable, but they will not necessarily be game-changers. Synthetic biomaterials that react with the human body, on the other hand, pose risks to the long-standing ban on the use of chemical and biological weapons.

Much has been written about the use of nanomaterials in the civilian sector, as well as about the potential risks and challenges in its regulation,[30] but very little has been written about, and too little consideration has been given to, the use of nanomaterials in security and defence contexts.[31]

Many unknowns remain regarding nanomaterials, including their long-term safety, how to regulate them effectively in the face of the unfolding data about their risks, and the challenge of recapturing any nanomaterials "released" into water tables and food chains. In the context of international and multilateral negotiations, the use of nanomaterials is often contemplated without commensurate understanding of their complexity.

Different applications of nanomaterials may raise different issues and require contemplation of different legal frameworks. The real possibility of the use of nanomaterials to genetically modify humans (and their offspring), as well as the ability to manipulate human emotions or control them remotely, raises questions about existing limitations and where there may be gaps. One such example is optogenetics, which is driving the understanding of advances in neuroscience and the human brain. The nanolasers used in optogenetics pose completely different challenges to traditional lasers., This is largely because nanolasers can target human cells with great specificity and can temporarily alter functions of the human brain.[32] The use of nanomaterials to alter human biology is at the forefront of threats to the security and defence landscape, but issues regarding contamination and long-term health implications (whether intentional or unintentional) also pose risks.

The metaphorical regulatory wheel does not need to be reinvented for every new and emerging technology, and this includes the use of nanomaterials. Existing legal frameworks

[30] Abbott et al. (2010); Altmann (2006); Bowman & Bennett (2013); EC (2005); Hodge et al. (2007); Hodge et al. (2014); Kosal (2009); Kosta & Bowman (2011); Matsuura (2006); Maynard & Bowman (2014); Nasu & Faunce (2009); NRC (2009).
[31] Leins & Bowman (2019).
[32] Leins (2016).

should be referred to in assessments of future uses of nanomaterials in war, or indeed of any new or emerging technology used in a military context. Most importantly, each application of nanomaterials (e.g. thermobaric weapons, optogenetics, genetic modification) will each be regulated by different existing international legal frameworks if used in non-civilian contexts.

Before calling for additional law, and in addition to understanding the science, policymakers need to consider areas of the law not necessarily within their immediate specialty and always start with the application of the specific technology in a problem-based approach. A detailed survey and application of the existing scientific and legal landscapes needs to be undertaken for each and every use of nanomaterials in a non-civilian context. Although no international treaties have been created regarding nanomaterials specifically, much existing treaty law has relevance and should be applied to weapons utilizing nanomaterials. The Geneva Protocol,[33] the Biological and Toxin Weapons Convention (BTWC),[34] the Chemical Weapons Convention (CWC),[35] and the relevant Additional Protocols of the Convention on Certain Conventional Weapons (CCW),[36] including Protocol I prohibiting non-detectable fragments,[37] Protocol III prohibiting incendiary weapons[38] and Protocol IV prohibiting blinding laser weapons,[39] may each have relevance depending on the use of nanomaterials in question. These treaties are not exhaustive, but they are treaties that may be relevant to these technologies and their applications. Other legal frameworks may be relevant to non-military or other uses of nanomaterials. Many lessons can be learned from the regulation of nanomaterials in the civilian context, which is more advanced, and a more detailed analysis can be found in Leins & Bowman (2019).

Despite the speed of the scientific development, it is important that the existing laws of war are thoughtfully applied. Weapons reviews, as provided for in article 36 of Additional Protocol I to the Geneva Conventions,[40] are required for all "means or method of warfare" containing nanomaterials to ensure compliance with well-established treaties; customary international law; and principles of the laws of war, environmental law and human rights law. The tension between the desire for security and humanity is not new; what is new is the speed and scale at which the tools are being developed and interconnected.[41] This speed

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[33] Geneva Protocol (1925).
[34] BTWC (1972).
[35] CWC (1992).
[36] CCW (1980).
[37] Protocol I to the CCW (1980).
[38] Protocol III to the CCW (1980).
[39] Protocol IV to the CCW (1995).
[40] Protocol Additional to the Geneva Conventions of 12 August 1949, and relating to the Protection of Victims of International Armed Conflicts (Protocol I), opened for signature 8 June 1977, 1125 UNTS 3 (entered into force 7 December 1978) art 36 ('Additional Protocol I').
[41] Mathews & McCormack (1999, 70). There is "a gap between the articulation of commitment to the general principles and the effective application of those general principles to specific weapons categories".

and scale of development should not be an impediment to thoughtful review and consideration regarding compliance with the law, much of which already exists and applies to new applications of nanomaterials.

Risk management frameworks, codes of conduct and reporting apparatus, and interdisciplinary research crossing sectors and geographical boundaries have profoundly and permanently changed the governance of nanomaterials. This multipronged approach sets a new standard not only for the use of nanomaterials in war but also for the use in war of any new technologies. Expertise from one field is no longer sufficient to ensure compliance with international law. This requirement is symptomatic of new and emerging technologies more broadly, the effective regulation of which requires interdisciplinary and creative governance approaches beyond the role of the individual specialist. Applying international law to the use of nanomaterials in war requires awareness of and compliance with the law by scientists, academia and industry; governments, lawmakers and lawyers; and armed forces.

A broader issue that is not specific to nanomaterials, but more of a general challenge, is that much of the military research (including research undertaken in collaboration with civilian scientists) does not result in readily available scientific reports or public patents and is therefore difficult to track or evaluate. The Institute for Soldier Nanotechnologies is one example of an organization where "team members collaborate on basic research to create new materials, devices, processes, and systems … to transition promising results toward practical products useful to the Soldier".[42] Although militaries will, of necessity, seek out technologies that meet their needs, they also actively seek to collaborate with civilian researchers to find innovative uses of new science that could be of potential military use. As the separation between science and the military is increasingly blurred, challenges for the legal review of new weapons harnessing the properties of nanomaterials will emerge. This lack of separation poses an additional challenge for the governance of potentially dual-use applications of nanomaterials.

Finally, some existing legal frameworks, such as protection of the environment during armed conflict, are not adequate and urgently require strengthening. States and policymakers can play an active role in raising awareness of the environmental risks (some of which are not yet entirely understood) and negotiate to prevent further harm. Other legal frameworks, such as those of the BTWC and CWC, already apply to some nanomaterials, which may operate at the nanoscale as both biological and chemical agents. States and governments may wish to clarify and strengthen the existing prohibition on chemical and biological weapons to include materials at the nanoscale within the existing framework of the Review Conferences of the BTWC and within the Science Advisory Board for the CWC. States need to be clear that any materials that contravene the BTWC or the CWC, whether at the regular,

[42] Institute for Soldier Nanotechnologies (2019).

micro or nanoscale, remain prohibited. States also need to reiterate that States will be held to account if these treaties are not upheld. The CWC, in particular, which has the ability to inspect, should review its procedures to enable inspections of potentially malevolent research using nanomaterials. This will require (i) greater scrutiny of toxic nanomaterials as their properties become clear and (ii) consideration of mechanisms to quantify or qualify when such matter would fall within the mandate of the CWC. An additional list of prohibited materials at the nanoscale may be necessary to ensure that the transfer and use of nanomaterials is compliant with the requirements of the CWC.[43]

[43] Leins & Bowman (2019).

CONCLUSION

The broader debates surrounding the use of new and emerging technologies show the significance, the complexity and the challenges of governing new and emerging technologies in our lives. While debates on developments in the use of automated systems and cyberattacks in armed conflict have proliferated, consideration of the use of nanomaterials has arguably lagged and the development and use of nanomaterials has raced ahead. In particular, consideration of the use of nanomaterials in conjunction with some of these other technologies remains underscrutinized.

Given the current pace of research and development in the field of nanomaterials, it is reasonable to expect that their applications in the defence and security context will become increasingly pervasive, shaping the future of warfare in a variety of ways. It is therefore important that multilateral disarmament and arms control processes continue to engage with and keep abreast of scientific developments in this field.

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PRIMER

MAGNIFYING NANOMATERIALS

Nanomaterials, which have many possible applications in many sectors, are among the top potential disruptive innovations of current times. While clear benefits to their use are beginning to emerge in the context of defence and security, little is known of the associated risks.

This primer aims to provide a foundation from which to engage with these ideas and to help policymakers participate in conversations, including asking the right questions, about applications of nanomaterials that may have consequences for national and international security now and in the future.

With this objective in mind, this primer defines nanomaterials, provides examples of their popular applications (both generally and in relation to security and defence), discusses their risks and introduces the issue of regulation.

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