Emergence & Convergence

Risk Assessment Survey

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Subject Matter Expert Survey
Results Analysis

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Since its inception in 1994, the Center for the Study of Weapons of Mass Destruction (WMD Center) has been at the forefront of research on the implications of weapons of mass destruction for U.S. security. Originally focusing on threats to the military, the WMD Center now also applies its expertise and body of research to the challenges of homeland security. The Center's mandate includes research, education, and outreach. Research focuses on understanding the security challenges posed by WMD and on fashioning effective responses thereto. Education programs, including its courses on countering WMD and consequence management, enhance awareness in the next generation of military and civilian leaders of the WMD threat as it relates to defense and homeland security policy, programs, technology, and operations. The Chairman of the Joint Chiefs of Staff has designated the center as the focal point for WMD education in the joint professional military education system. As a part of its broad outreach efforts, the WMD Center hosts annual symposia on key issues, bringing together leaders and experts from the government and private sectors. Visit the center online at http://wmdcenter.ndu.edu/.

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Introduction

SLIDE 1: Introduction

This report provides a written overview of the results of the **Emergence and Convergence** subject matter expert survey that took place from June 2016 to December 2016 and is best read alongside the corresponding slide deck.

SLIDE 2: Survey

Emerging technologies are transforming life, industry, and the global economy in positive ways, but they also have significant potential for subversion by states and non-state actors. National security experts, lawmakers, and policymakers have become increasingly concerned about the interactions among a number of emerging technologies that could alter and increase the threats from weapons of mass destruction (WMD).[1]

To assess the impact of various emerging technologies, it is important to understand how they might be game-changers both for state and non-state actors actively seeking to develop WMD as well as for policymakers attempting to prevent the proliferation and the use of WMD. Policymakers with responsibilities for countering WMD need answers to the following questions:

- What are the national security risks posed by emerging technologies? What are their enabling effects for those seeking to develop and use WMD?
- What new opportunities or solutions do these emerging technologies offer to national security problems and/or the challenge of countering WMD?
- How will these emerging technologies impact traditional tools and approaches for countering WMD? What new types of governance do we need to mitigate the risks?

In its multi-year study entitled *Emergence and Convergence,* the WMD Center is exploring the risks, opportunities, and governance challenges for countering WMD introduced by a diverse range of emerging technologies. Toward this end, the WMD Center has developed an exploratory framework for first identifying the emerging technologies that will have greatest impact on the WMD space for state and non-state actors and then for evaluating the nature of that impact on the current tools and approaches for countering WMD.

As part of the study, the WMD Center conducted a **Delphi method subject matter expert (SME) survey** to assess the risks and opportunities posed by emerging technologies and their impact on the WMD space. The Delphi method is a structured technique for eliciting expert opinion, developed by RAND in the 1960s. Since then, it has become an important tool for forecasting, risk analysis and exploring the potential of future technology. The method is designed to encourage debate in a group of experts that takes place independent of personality and to build an expert consensus. In this way, the Delphi method functions akin to a "controlled" focus group.

Surveys employing the Delphi method engage a small number of respondents, which are not considered a random sample or representative of a broader population. In other words, these surveys are not intended to produce statistically significant results and represent the synthesis of opinions of a particular group. Nonetheless, the results, which describe how this population responded, can provide a valuable source of information for risk assessment.

The subject matter expert survey consisted of **95 questions** to assess the risks and opportunities associated with **five technology groups**: additive manufacturing, advanced robotics, nanotechnology, nuclear technology, and synthetic biology. The survey also included evaluation of near-term capabilities of state and non-state actors for using specific emerging technologies to develop or deliver WMD **within the next 5 years**.

The survey was launched on **30 June 2016** and remained open for completion until **31 December 2016**. We sent survey invitations to about **3,500 subject matter experts** (SMEs) across the DoD, the interagency, academia, industry, think tanks, etc. Although **176 SMEs** agreed to complete the survey, we received **120 completed surveys**, with a total **response rate of 68%** (among those who agreed to take it).

To identify our experts, we used a **chain sampling approach** (also known as a snowball network). We started reaching out to people we know and branched out from there with further recommendations. We leveraged existing networks of the WMD Center such as the Program for Emerging Leaders (PEL) and the CWMD Graduate Fellows. We also sent invitations to the contact lists of the J8/Joint Requirements Office and AAAS Fellows to spread the word about the survey. Finally, we used LinkedIn and Twitter to get the word out about the survey.

The problem with the chain sampling approach is that it misses people who are not connected to our network and who may have something to contribute. It also runs the risk of identifying a group of people with a particular perspective. To address this problem, we attempted to identify experts through Internet searches to expand our current network, but this was time intensive and resources were limited.

SLIDE 3: Emerging and Converging

Understanding the **concepts of emerging and converging technologies** provides important context for the WMD Center's interest in emerging technologies and the new challenges faced by policy makers concerned about WMD.

There is **no accepted definition** for the term emerging technology. The term is used frequently in the news media to describe anything and everything that is perceived as a new feature of technology. In other cases, the term is used to discuss profound technological changes that are under way. In either case, there are marketing reasons to label each and every technology as emerging, and this helps to distort understanding about emerging technologies.

Emerging technologies are often considered to be "**new technologies**" that are currently developing or will be developed over the **next five to ten years**.

The **“newness” of a technology**, however, is relative to the field, domain, or even the country under consideration. In other words, the specific context matters for the designation of a technology as emerging. For example, the Internet is no longer an emerging technology in developed countries, but some Internet-based applications would still be considered emerging technologies in less developed countries. And only in recent years, have policymakers begun to consider the implications of some emerging technologies for national security. In other words, technologies that have been around for several decades such as additive manufacturing and nanotechnology are “new” to national security policymakers.

Despite the lack of definition, there are certain key characteristics. Today’s emerging technologies tend to be **cheaper, simpler, smaller, digital and often more convenient** to use. They **empower a broader range of actors**, **remove barriers to economic activity** and **diffuse power away from governments**, industrial manufacturers, and other large organizations into the hands of ever-greater numbers of smaller entities—small private sector companies, startups and individuals.

Today’s emerging technologies are **fueled by the Internet**, which provides unprecedented access to information and a cheap forum for real-time communication and sharing of knowledge, allowing individuals to make and do amazing things—for good or for bad purposes. In the digital age, the pace of progress is rapid, volatile and hard to predict.

Today’s emerging technologies also exhibit **high degree of convergence**, which poses a direct challenge to the silos of excellence within government, academia, and elsewhere. More and more, technological innovations do not emerge and evolve within a single discipline, but rather across multiple disciplines and between different fields of knowledge. Convergence refers to the synergistic integration of new technologies, each of which advances at a rapid rate and interacts with more established fields, leading to increasing complexity and the blurring and redefining of boundaries.[2]

Converging technologies interact with other technologies and enable each other in the pursuit of a common goal.[3] Critical convergences among emerging technologies are often dynamic, reinforcing, and/or abridging, providing synergistic effects. Convergences may offer societal benefits, but could also lead to unexpected consequences, including for national security and the WMD space.

Emerging technologies are considered broadly **transformative and disruptive** for business, government, and society. In the business world, emerging technologies may spur a new industry or transform an existing one. In the consumer world, they remove barriers and empower individuals with new capabilities. They also provide more powerful tools to malicious actors seeking to harm the United States and our allies. In the policy world, emerging technologies disrupt the governance and tools for national security and more specifically for countering WMD. These technologies are widening gaps in our ability to prevent the worst scenarios from happening.

For the purposes of this study, emerging technologies are **best understood as science-based innovations**. Each technology has the potential to create a new industry or transform an existing one.[4] An emerging technology can arise as an entirely new technology or have a more incremental character, resulting from an existing technology or the convergence of several existing technologies.[5]

SLIDE 4: Technology Groups

Many emerging technologies may bring about changes that have an indirect impact on the WMD space. Not every emerging technology has direct relevance as a game changer for WMD. Only a handful are expected to have direct enabling effects for state and non-state actors seeking WMD. Such technologies are expected to have serious effects on both the nature of the WMD challenges faced by policymakers and options for countering WMD.

Forbes Magazine, MIT Technology Review, Scientific American, the McKinsey Global Institute, and many other technology firms and magazines have compiled various predictive and vetted lists of the most disruptive technologies. For example, in 2013, the McKinsey Global Institute identified 12 technologies with the most disruptive potential from a list of over 100 technologies drawn from academic journals and business and technology press: mobile internet, automation of knowledge work, Internet of things, cloud technology, advanced robotics, autonomous and near-autonomous vehicles, next-generation genomics, energy storage, 3D printing, advanced materials, advanced oil and gas exploration.[6]

After surveying many lists of emerging technologies, we chose five technology groups most widely expected to shape the WMD space:

- **Additive Manufacturing**—The process of joining materials to make objects from 3D model data, usually layer upon layer, as opposed to subtractive manufacturing methods. Additive manufacturing is used to build physical models, prototypes, patterns, tooling components, and production parts.[7]

- **Advanced Robotics**—A branch of mechanical engineering, electrical engineering, electronics engineering and computer science that focuses on the development of robotics and artificial intelligence. A robot is a reprogrammable, multifunctional manipulator designed to move material, parts, tools, or specialized devices through various programmed functions for the performance of a variety of tasks.[8]

SLIDE 5: Technology Groups

- **Nanotechnology**—Applied science, engineering, and technology conducted at the nanoscale, which is about 1 to 100 nanometers. Nanotechnology refers to a group of technologies which manipulate and control nanoscale materials to exploit special properties (quantum effects) and produce new applications.[9]

- **Nuclear Technology—**New ways to exploit the atom to generate electricity (such as nuclear fusion), new types of nuclear reactors, or new ways for producing fissile material.

- **Synthetic Biology—**Synthetic biology aims to make biology easier to engineer. Synthetic biology is the convergence of advances in chemistry, biology, computer science, and engineering that enables us to go from idea to product faster, cheaper, and with greater precision than ever before. It can be thought of as a biology-based “toolkit” that uses abstraction, standardization, and automated construction to change how we build biological systems and expand the range of possible products.[10]

Each emerging technology group in this study represents a broad set of related technologies. SMEs were asked to assess the technology group as a whole and to assess specific technologies within each group.

SLIDE 6: Risk Assessment Framework

This study uses and adapts the decision framework for managing the risks of dual-use technologies developed by the late Dr. Jonathan Tucker, which assesses technologies for their risk of misuse and governability.[11]

Tucker outlines two categories of parameters that describe dual-use technologies and shape their **risk of misuse** and **governability**. For much of the survey, SMEs assessed the emerging technologies using this framework.

For the purpose of our study, **risk** is defined as the potential for an unwanted outcome resulting from an incident, event, or occurrence, as determined by its likelihood and the associated consequences.[12] **Misuse** is defined as any intentional misuse or application of a technology to cause harm or destruction.

The **risk of misuse** is assessed on the basis of four parameters: accessibility, ease of misuse, imminence of potential misuse, and magnitude of potential harm.

- **Accessibility** measures how easy it is to acquire the technology and the barriers to entry. It also takes into account the amount of money needed to purchase or develop the technology and whether this level of expenditure is within the means of an individual, a group, or nation-state.

- **Ease of misuse** considers the level of expertise and tacit knowledge required to master the technology, as well as the extent to which the technology is becoming deskilled and hence available to individuals with less formal expertise and hands-on experience. Ease of misuse accounts for the fact that simply acquiring a technology is not sufficient for misuse; an actor must also possess the appropriate types and level of expertise.

- **Imminence of potential misuse** indicates how soon a malicious actor seeking to cause harm could exploit the technology based on its current level of maturity.

- **Magnitude of potential harm** is a function of both the technology itself and the vulnerability of likely targets. The magnitude of potential harm includes the approximate number of deaths and injuries that could result from malign use; the economic costs associated with an incident, including mitigation and cleanup; and the societal effects of an attack, such as disruption, terror, and loss of faith in government. In particular, this parameter considers the extent to which a technology offers a qualitative or quantitative enhancement in the ability to do harm over existing technologies.

The first two parameters—accessibility and ease of misuse—focus on how risk varies across different types of actors. For the purpose of the study, we defined three types of actors:

- **Advanced nation-state**—a sovereign state that has a highly developed economy and advanced technological infrastructure relative to other less industrialized nations.

- **Developing nation-state**—a sovereign state with little industrial and economic activity and where people generally have low incomes.

- **Non-state actor**—an individual or organization that has significant political influence and seeks to cause harm and/or destruction.

The second two parameters—imminence of misuse and magnitude of potential harm—focus more on the relative risk of technology.

The second category of parameters relates to their **governability**, which is defined as the extent to which a technology is susceptible to different types of intervention. An assessment of governability is based on five parameters: maturity, rate of advance, convergence, global diffusion and tangibility (form):

- **Maturity** considers the maturity of a technology, namely, its position in the development pipeline extending from basic research to commercialization. Examples of different levels of maturity include early research and development, advanced development and prototyping, early marketing, and widespread commercial availability.

- **Rate of Advance** refers to whether the effectiveness of a technology (as measured by its reliability, speed, throughput, accuracy or cost) is increasing linearly, increasing exponentially, plateauing or declining over time. Some technologies progress slowly and incrementally until they reach a threshold of speed, throughput, or capacity at which their dual-use potential becomes manifest. Others may advance rapidly and attain more immediate dual-use potential.

- **Convergence** refers to the number of different disciplines that are brought together to create a new device or technology. Because each discipline has its own professional community, culture, lexicon and level of awareness of dual-use issues, highly convergent technologies that draw on multiple disciplines are more difficult to govern than technologies derived from only one or two disciplines.

- **Global Diffusion** considers the extent to which a technology is available in international markets. Some technologies are limited to one or a few countries while other technologies are widely available. In general, the smaller number of countries that have access to a technology, the easier it is to govern because of reduced need for coordination and harmonization.

- **Tangibility (Form)** refers to the form of the technology. Some technologies consist primarily of hardware, others are based largely on intangible information, and still others are a hybrid of the two. Technologies in the form of hardware

are relatively easy to govern relative to technologies in the form of intangible information, especially in the form of digital files.

Like imminence of misuse and magnitude of potential harm, the point of comparison for governability parameters is the technology rather than the type of actor.

According to Tucker's framework, once the risk of misuse and governability are assessed, specific technologies can be plotted on a matrix (illustrated on the right) and placed into groups of technologies that share the same characteristics. Presumably, technologies in the same quadrant would require similar types of governance.

The quadrant of most concern to policymakers is the orange box in the top left corner of the matrix labeled High/Low. Technologies in this quadrant demonstrate a high risk of misuse and low level of governability. The quadrant of least concern is the blue box in the bottom right corner of the matrix, low risk of misuse and high level of governability.

SLIDE 7: Decision Framework

This slide is an illustration of Tucker's decision framework adapted for the purpose of our study. Tucker offers a powerful approach for determining priorities and formulating tailored governance. However, it is based on a traditional understanding of WMD, which focuses on risks. In our study, we are also assessing the technologies for new opportunities and innovative solutions for countering WMD.

The process for formulating governance begins with Step 1, which involves **monitoring** the emergence of relevant technologies. We began our study in 2016 by evaluating lists of emerging technologies for their relevance for WMD and selecting five technology groups for consideration—additive manufacturing, advanced robotics, nanotechnology, nuclear technology, and synthetic biology.

Step 2 entails **technology assessment**. Once we have a list of relevant emerging technologies, we assess the technologies in terms of their risk of misuse and governability.

In Step 3, we plan to identify policy priorities and devise a tailored package of **governance measures** to address the risks and opportunities of these technologies for the WMD space. If risk of misuse is low, policymakers should continue to monitor the technology for changes or advances that require a new assessment. If risk of misuse is medium or high, policymakers should explore what governance measures best address the risks of the technology while promoting its benefits.

As the final report of the study, we will provide a menu of governance options for managing the risks and opportunities associated with emerging technologies.

SLIDE 8: WMD Development Pathways

State and non-state actors can access new and more sophisticated **WMD development pathways** due to the increased flow of expertise and illicit, dual-use, and non-controlled items through trans-regional connections. Emerging technologies may create new WMD development pathways and enable existing ones, leading to increased capability of nation-states and non-state actors to develop and use WMD.

Moreover, these technologies might one day lead to a meaningful paradigm shift in how policymakers define WMD, view the threat of WMD, and counter WMD in the future.

A **WMD development pathway** consists of networks (links among individuals, groups, organizations, governmental entities, etc.) that enable actors to conceptualize, develop, possess, and proliferate WMD and related capabilities. These networks encompass ideas, materials, technologies, facilities, processes, products, and events.[13]

To explore how emerging technologies impact WMD development pathways, SMEs evaluated the relevance of emerging technologies for WMD by assessing the likelihood of state and non-actors using emerging technologies to advance themselves along the pathway toward WMD development.

For the purpose of this study, **likelihood** is an estimate of the potential of an incident or event's occurrence.[14] The concept of likelihood captures both capability and intent. **Capability** refers to the means to accomplish a mission, function, or objective. **Intent** is the determination to achieve an objective.

In this study, a WMD development pathway is divided into five distinct stages: 1) research and development; 2) acquisition; 3) production; 4) weaponization; and 5) delivery.

The **research and development** stage involves creative work undertaken on a systematic basis in order to increase the stock of knowledge about WMD and systematic application of knowledge or understanding directed toward the production of useful materials, devices, and systems or methods, including design, development, and improvement of prototypes and new processes to meet specific requirements:

- **Biological weapons**—Includes research on existing pathogens, microbes and toxins to isolate virulent or drug-resistant strains, genetic modification of existing pathogens and microbes, and development of novel pathogens and microbes
- **Chemical weapons**—Includes research on modification of existing chemical agents, development of novel agents, advances in chemical synthesis and aerosolization
- **Nuclear weapons**—Includes research on uranium enrichment and plutonium reprocessing techniques, new reactor technologies and nuclear fusion
- **Radiological weapons**—new techniques for developing radioisotopes, new reactors

The **acquisition** stage refers to the acquisition of required source material, equipment, technology, and production infrastructure:

- **Biological weapons**—Includes acquisition of seed culture, the digital genome of pathogen, microbe or toxin, embryos, growth media, lab equipment, PCR equipment, fermentation equipment, sterilization equipment, HEPA filters, milling equipment, freeze-dryers, protective suits and masks
- **Chemical weapons**—Includes acquisition of precursors, compound formula, reactor vessels, air quality detectors and alarms, ventilation and air-scrubbing systems, protective suits and masks, chemical showers

- **Nuclear weapons**—Includes acquisition of natural uranium, maraging steel, aluminum alloys, beryllium metal, titanium, zirconium, high-voltage power supplies, lasers, large vacuum systems, numerically controlled machine tools, robotic equipment, hot boxes, nuclear reactors, uranium enrichment parts and equipment, plutonium reprocessing parts and equipment
- **Radiological weapons**—Includes acquisition of high-risk radioactive sources such as cesium 137, cobalt-60, strontium-90, iridium-192

The **production** stage ranges from pilot-scale to the mass production of WMD materials and related equipment:

- **Biological weapons**—mass produce or harvest agent and store under refrigeration
- **Chemical weapons**—develop and pilot test production process, synthesize agent and mass produce agent for storage
- **Nuclear weapons**—produce sufficient weapons-grade uranium (uranium enrichment) or plutonium (plutonium separation and reprocessing)
- **Radiological weapons**—produce radioisotopes in a nuclear reactor

The **weaponization** stage involves converting the material to use as a weapon through stabilization, encapsulation, purification and weapon/sprayer design, weapon fabrication test and evaluation:

- **Biological weapons**—Includes stabilization through microencapsulation, freeze-drying or chemical additives, aerosolization, design of sprayer/dissemination device
- **Chemical weapons**—Includes stabilization through chemical additives (amines, freezing-point depressants, thickeners, carriers or antiagglomerants), aerosolization, and design of sprayer/dissemination device
- **Nuclear weapons**—Includes design/fabrication of high explosives or propellants, weapon design, testing and assembly
- **Radiological weapons**—includes mechanisms for spreading material or causing exposure via emission including a radiological dispersal device, radiological emission device or a radiological incendiary device.

Finally, the **delivery** stage involves developing the means of delivery:

- **Biological weapons**—Includes bomblets, crop dusters, drones, sprayers, aerosol dispersal, crude methods
- **Chemical weapons**—Includes missiles, bomblets, crop dusters, agricultural drones, other drones, sprayers, aerosol dispersal, crude methods
- **Nuclear weapons**—Includes missiles, gravity bombs, long-range artillery, mines, torpedoes, cars, trucks, boats, civil aircraft
- **Radiological weapons**—improvised explosive or incendiary devices, cars, trucks, boats, aircraft, drones, food/water

[1] In this study, WMD refer to traditional CBRN weapons and new weapons with similar effects. For further discussion on definitions, see W. Seth Carus, *Defining "Weapons of Mass Destruction,"* Occasional Paper No. 8, (Washington, DC: NDU Press, 2012), <http://ndupress.ndu.edu/Portals/68/Documents/occasional/cswmd/CSWMD_OccationalPaper-8.pdf>.

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[7] As defined by the ASTM International, www.astm.org.

[8] As defined by the Robot Institute of America, www.robots.com/education

[9] As defined by the U.S. National Nanotechnology Initiative (NNI), http://www.nano.gov/

[10] As defined by SYNBERC, https://www.synberc.org/what-is-synbio

[11] Jonathan Tucker, ed., *Innovation, Dual Use, and Security: Managing the Risks of Emerging Biological and Chemical Technologies* (Cambridge, MA: The MIT Press, 2012).

[12] As defined by DHS, https://www.dhs.gov/xlibrary/assets/dhs-risk-lexicon-2010.pdf.

[13] As defined in the DoD Strategy for Countering WMD, http://archive.defense.gov/pubs/DoD_Strategy_for_Countering_Weapons_of_Mass_Destruction_dated_June_2014.pdf.

[14] As defined by DHS, https://www.dhs.gov/xlibrary/assets/dhs-risk-lexicon-2010.pdf

The Respondents

SLIDE 9: The Respondents

Out of a total of 176 survey participants, we received **120 completed surveys**, with a **response rate of 68%.** The slides in this section provide basic data for our survey population.

SLIDE 10: Survey Population

This slide provides survey population data on gender, age and education.

Summary findings:

- 81% of the survey respondents are **male**.
- A majority of the survey respondents hold **PhDs or MDs** (63%) and an additional 32% of respondents hold a **Master's degree**.
- The **age** of survey respondents appears well distributed across the different age categories, other than ages between 22 and 29, which contained only 2% of respondents.

SLIDE 11: Survey Population

This slide delves into the relevant expertise of the survey population. If applicable, we asked respondents to identify themselves as scientists and engineers to determine the subset of respondents with technical expertise.

We asked respondents to further specify if they have any experience working on emerging technologies.

Summary findings:

- While most of the survey respondents have jobs in **government** (68%), only 25% of the survey respondents come from **academia,** and only 11% from **industry**.
- Only 16% of survey respondents identified themselves as **nontechnical,** i.e., lacking expertise in a **scientific or technical discipline**.
- 43% of the survey respondents are **biologists/life scientists** and 28% of the respondents are **engineers**.
- While 34% of the survey respondents do not have any relevant experience working with emerging technologies, 42% of survey respondents have experience in **biotechnology, genetic engineering, or synthetic biology**. Representing the next largest group, 20% of survey respondents have experience in **additive manufacturing**.

The large number of respondents from the biology and biotechnology fields is a function of our network at the WMD Center, courtesy of Senior Research Fellow, Dr. Diane DiEuliis. A special thank you to her for helping us reach out to many experts on synthetic biology.

SLIDE 12: Survey Population

Delphi studies often ask respondents to rate their own expertise as a way to ensure that panels consist of subject matter experts with appropriate levels of expertise and improve the value of the data. This information helps determine whether the responses vary across different levels of expertise. If there is evidence of significant variance, the responses can be weighted according to expertise or removed.

We received a total of **120 completed surveys**. The survey was divided into general, high-level questions about five technology groups and more specific questions about technologies within each group. All survey respondents provided answers to the general questions, whereas a smaller subset of the total respondents answered the specific questions for each technology group.

Average number of responses to **general questions** (excluding responses of "don't know"):

- Additive Manufacturing—97 responses
- Advanced Robotics—95 responses
- Nanotechnology—98 responses
- Nuclear—102 responses
- Synthetic Biology—111 responses

Average number of responses to **specific questions** (excluding responses of "don't know"):

- Additive Manufacturing—72 responses
- Advanced Robotics—74 responses
- Nanotechnology—72 responses
- Nuclear—63 responses
- Synthetic Biology—93 responses

Given the high level of expertise across the respondents, the survey results were not weighted by expertise. Rather each response is considered equally. However, survey respondents identifying themselves as **uninformed** for any technology group automatically **opted out of specific questions** pertaining to the respective technologies.

Summary Findings:

- Only **4% of survey respondents** identified themselves as an expert in advanced robotics. We had the least amount of relevant expertise for advanced robotics.
- In contrast, **18% of survey respondents** identified themselves as experts in synthetic biology. We had the most amount of relevant expertise for synthetic biology.
- For each technology group, the following percentage of survey respondents identified themselves as knowledgeable and above:
    - Additive Manufacturing—52%
    - **Advanced Robotics—41%**
    - Nanotechnology—57%
    - Nuclear Technology—44%
    - **Synthetic Biology—71%**

Risk of Misuse & Governability

SLIDE 13: Risk of Misuse & Governability

The survey was divided into **general questions** about five technology groups and more **specific questions** about technologies within each group. All survey respondents provided answers to the general questions; however, a smaller subset of the total respondents answered the specific questions for each technology group.

This section reviews the survey results from the **general questions** about risk of misuse and governability for the five technology groups:

- Additive Manufacturing
- Advanced Robotics
- Nanotechnology
- Nuclear Technology
- Synthetic Biology

SLIDE 14: The Parameters

This slide provides an overview of the relationship between the two main variables, risk of misuse and governability and the associated parameters.

The **risk of misuse** is defined as the potential or likelihood for any intentional misuse or application of a technology to cause harm or destruction. Risk of misuse is assessed on the basis of four parameters: accessibility, ease of misuse, imminence of potential misuse, and magnitude of potential harm.

The relationship between the four parameters and the risk of misuse is rather straightforward. Each parameter tracks directly with the assessed risk of misuse. An increase in each of these factors leads to an increase in the risk of misuse.

The relationship between governability and its associated parameters is a bit more complex. **Governability** is defined as the extent to which a technology is susceptible to different types of intervention. Governability is based on five parameters: maturity, rate of advance, convergence, global diffusion, and tangibility (form).

The relationship between each parameter and governability varies significantly. The **rate of advance**, **convergence,** and **global diffusion** have an **indirect relationship** with governability. For example, an increase in global diffusion would lead to a decrease in governability. As a technology spread to more countries, it becomes more difficult to govern at the domestic and global levels.

Tangibility, the extent to which a technology is physical or digital, has a **direct relationship** with governability. Technologies with low scores for tangibility are difficult to govern. Digital information can easily cross borders without detection, complicating any effort by governments to control the technology.

Understanding the impact of **maturity** on governability is especially complex and akin to Goldilocks and the Three Bears. A technology with a low level of maturity is too new to regulate and contributes to scores for low governability. In contrast, a technology with a high level of maturity is well established, and the rules of the game have been set. At this point, it becomes difficult to introduce new regulations. As a result, high maturity contributes to lower scores for governability. A technology with a medium level of maturity is mature enough for meaningful governance, but not so mature that the industry has become entrenched in a certain way of doing things.

For the heat map charts that follow, colors take into account the relationships between the parameters and risk of misuse and governability described above. The color indicates the priority for concern at the current time:

- **Green** = low priority
- **Yellow** = medium priority
- **Red** = high priority

SLIDE 15: Risk of Misuse & Governability

This slide depicts a heat map for all five technology groups across the parameters for the risk of misuse and governability and three types of actors (See Q13-22, Q24, Q75, Q81, Q87, Q94-95 in the appendix).

Each box contains the average score for all respondents and is colored to depict priority for concern.

SMEs assessed the risk of misuse, governability and associated parameters on a scale from 1 (low) to 7 (high).

Summary Findings:

Risk of Misuse

- **Synthetic biology** was assessed with the highest score (5.33) for risk of misuse.
- In all cases except for one, the risk of misuse for a technology decreased when moving from advanced state to developing state to non-state actor. The exception was **synthetic biology**. Respondents assessed a slightly higher risk of misuse for non-state actors (3.95) than for developing nation-states (3.91).

Accessibility

- Survey respondents gave consistently high scores to all five technology groups for accessibility.
- **Additive manufacturing** was assessed to be the most accessible (6.65) for all three types of actors. **Advanced robotics** (6.32) and **synthetic biology** (6.35) came in close second.

Ease of Misuse

- **Additive manufacturing** (5.64) and **synthetic biology** (5.56) were assessed the highest scores for the ease of misuse, followed closely behind by **advanced robotics** (5.36).

Imminence of Misuse

- **Nanotechnology** was assessed the lowest scores (3.35) for imminence of misuse.

Magnitude of Harm

- **Nanotechnology** (6.52) and **synthetic biology** (5.93) were assessed the highest scores for magnitude of harm, surpassing the scores for **nuclear technology** (4.55).

Governability

- **Nuclear technology** received the highest scores (5.86) for governability.
- **Additive manufacturing** and **synthetic biology** tied for the lowest scores (3.03).

Maturity

- **Additive Manufacturing** (6.27) and **nuclear technology** (6.02) were assessed the highest scores for maturity.
- Whereas the governance for nuclear technology is already established, **additive manufacturing** remains relatively ungoverned for risks posed to national security. The window for devising governance measures could be closing.

Rate of Advance

- **Synthetic biology** (6.04) and **additive manufacturing** (5.74) received the highest scores for rate of advance.
- **Nuclear technology** received the lowest scores (3.88).

Convergence

- With the exception of **nuclear technology**, which received a lower score (3.47), the technology groups received similar scores for convergence.

Global Diffusion

- **Additive manufacturing** was assessed the highest scores (5.80) for global diffusion.

Tangibility

- **Nuclear technology** received the highest scores for tangibility (5.59).
- **Synthetic biology** was assessed the lowest scores (3.85).

SLIDE 16: The Risk of Misuse

This slide depicts the scores for risk of misuse across the five technology groups and three types of actors (See Q13-15 in the appendix).

SMEs assessed the risk of misuse on scale from 1 (low) to 7 (high).

Summary Findings:

- In all cases except for one, the risk of misuse for a technology decreased when moving from advanced state to developing state to non-state actor. The exception was **synthetic biology**. Respondents assessed a slightly higher risk of misuse for non-state actors than for developing nation-states.
- **Synthetic biology**, **nuclear technology** and **advanced robotics** were rated the highest scores for risk of misuse.

SLIDE 17: The Risk of Misuse

This slide depicts the scores for two parameters, accessibility and ease of misuse, across five technology groups and three types of actors (See Q16-21 in the appendix).

SMEs assessed the parameters on a scale from 1 (low) to 7 (high).

Summary Findings:

- **Additive manufacturing** was assessed to be the most accessible for all three types of actors. **Synthetic biology** came in close second.
- **Additive manufacturing** received the highest scores for ease of misuse with synthetic biology and advanced robotics following closely behind.

SLIDE 18: The Risk of Misuse

This slide depicts the scores for two parameters, imminence of potential misuse and magnitude of potential harm, for all five technology groups (See Q22, Q24 in the appendix).

SMEs assessed the parameters on scale from 1 (low) to 7 (high).

Summary Findings:

- **Nanotechnology** received the lowest scores for imminence of misuse (3.35), but the highest score for magnitude of potential harm (6.52).
- All other technologies received similar scores for imminence of misuse.
- **Synthetic biology** came in second for magnitude of potential harm (5.93).

SLIDE 19: Advanced vs. Developing States

This slide depicts the scores for the risk of misuse and associated parameters across all five technology groups for advanced nation-states and developing nation-states (See Q13-14, Q16-17, Q19-20, Q22, Q24 in the appendix).

SMEs assessed the parameters on a scale from 1 (low) to 7 (high).

Summary Findings:

- The scores for **advanced nation-states** are higher than developing nation-states across all parameters (Note: imminence of misuse and magnitude of potential harm do not vary by actor type).
- **Accessibility** appears to be the most significant risk factor, receiving the highest scores across the board.

SLIDE 20: Developing States vs. Non-state Actors

This slide depicts the scores for the risk of misuse and the associated parameters across all five technology groups for developing nation-states and non-state actors (See Q14-15, Q17-18, Q20-21, Q22, Q24 in the appendix).

SMEs assessed the parameters on scale from 1 (low) to 7 (high).

Summary Findings:

- The scores for **developing nation-states** are higher than non-state actors across all parameters (Note: imminence of misuse and magnitude of potential harm do not vary by actor type).
- The **gap** between the scores of advanced nation-states and developing nation-states **appears slightly greater** than the difference between developing nation-states and non-state actors. In other words, advanced nation-states have a significant advantage over other actors in exploiting emerging technologies.

SLIDE 21: Governability

This slide depicts the scores for governability across the five technology groups (See Q74 in the appendix).

SMEs assessed the parameters on scale from 1 (low) to 7 (high).

Summary Findings:

- **Nuclear technology** received the highest scores for governability (5.86).

SLIDE 22: Governability

This slide depicts the scores for **maturity** and **tangibility** across the five technology groups (See Q75, Q95 in the appendix).

SMEs assessed the tangibility on scale from 1 (low) to 7 (high).

For maturity, respondents assigned scores to each technology group as follows:

- 1 – Basic Principles
- 2 – Lab Experimentation
- 3 – Proof of Concept
- 4 – Prototype
- 5 – Early Marketing
- 6 – Limited Commercial Availability
- 7 – Widespread Commercial Availability

Summary Findings:

- Respondents rated **additive manufacturing** (6.27) and **nuclear technology** (6.02) as the most mature technologies. Both are assessed to have **limited commercial availability**.
- **Advanced robotics** (5.44) and **synthetic biology** (5.44) followed closely behind and were assessed to be in the **early marketing stage**.
- **Nuclear technology** received the highest scores for tangibility (5.59) and **synthetic biology** received the lowest scores (3.85).

SLIDE 23: Governability

This slide depicts the scores for rate of advance and the type of growth (See Q81-86 in the appendix).

SMEs assessed the **rate of advance** on scale from 1 (low) to 7 (high).

Respondents also assessed the **type of growth** for each technology group by selecting one of the following descriptions:

- Declining
- Plateauing
- Advancing at a slow pace
- Advancing at a steady rate
- Exponential

Summary Findings:

- **Synthetic biology** received the highest scores for rate of advance (6.04). Moreover, **62% of respondents** characterized the growth from year to year as **exponential**.
- In contrast, **nuclear technology** received the lowest scores for rate of advance (3.88), and **64% of respondents** characterized the growth from year to year as advancing at a slow pace.

SLIDE 24: Governability

This slide depicts the scores for global diffusion and convergence (See Q87, Q94 in the appendix).

SMEs assessed the parameters on scale from 1 (low) to 7 (high).

Summary Findings:

- **Additive manufacturing** received the highest scores for global diffusion (5.80) and tied for the highest level of convergence (5.30) with **advanced robotics**. **Synthetic biology** came in close second on the level of convergence (5.13)
- **Nuclear technology** received the lowest scores for global diffusion (3.7) and convergence (3.47).

SLIDE 25: Governability

This slide depicts the scores for governability and associated parameters across the five technology groups. (See Q74-75, Q81, Q87, Q94-95 in the appendix).

SMEs assessed the parameters on scale from 1 (low) to 7 (high).

Nuclear technology is represented by the dark blue line to allow for comparison. Technologies with medium levels of maturity, high levels of tangibility, slow rate of advance, low convergence and limited global diffusion are easier to govern.

Summary Findings:

- Across most of the parameters, **nuclear technology** represents "the ideal" technology for governance. It is a highly tangible and mature technology that is advancing at a slow pace and exhibits low levels of convergence and global diffusion.
- The remainder of the technology groups have features (fast pace of advance, high level of convergence and significant global diffusion) that will make them more difficult to govern. As these technologies mature, there may be a narrow opportunity for governments to intervene.

SLIDE 26: Risk Assessment Matrix

This slide provides the risk assessment matrix based on the decision framework proposed by Jonathan Tucker (See Q13, Q74 in the appendix).

According to Tucker's framework, once the risk of misuse and governability are assessed, technologies can be plotted on a risk assessment matrix and placed into groups of technologies that share the same characteristics. Presumably, technologies sharing the same characteristics would require similar types of governance.

To plot the technologies in this study, we have divided the risk assessment matrix into four quadrants:

- **A –** Any technologies falling in this quadrant present **minimal concern** to policymakers because they have a low risk of misuse
- **B** - Any technologies falling in this quadrant present the **least concern** to policymakers since they have a low risk of misuse and a high level of governability
- **C** – Any technologies falling in this quadrant present **significant concern** to policymakers due to their high risk of misuse
- **D** - Technologies falling in this quadrant exhibit a high risk of misuse and low level of governability and present the **most concern** to policymakers.

The scores for each technology group are represented by different colors. The three types of actors are represented by different shapes. There are three data points plotted for each technology group.

The arrows indicate the predicted evolution of technologies as they mature, integrate with other technologies and spread around the globe.

Summary Findings:

- **Nuclear technology** sets itself apart from the other four technology groups on this chart. As an established technology, we have assumed that it will not change significantly across most of the parameters for risk of misuse and governability. As nuclear technology becomes more accessible and easier to use, it could move toward **quadrant C.** Given its tangibility and maturity, however, it is easier to govern than the other technologies.

- The other four technology groups are expected to move toward **quadrant D**, which is of most concern to policymakers. These technologies are expected to become more accessible, easier to use and more globally diffuse.

Additive Manufacturing

Additive manufacturing creates both new risks and opportunities for the WMD space as a digital manufacturing process. It enables states and non-state actors interested in WMD with new capabilities. Given the impressive range of manufacturing benefits, defense communities should also be able to exploit the technology to develop new solutions to counter WMD and enhance operations in hazardous environments.

SLIDE 27: Additive Manufacturing

This section provides the scores for the specific questions related to additive manufacturing.

Additive Manufacturing is the process of joining materials to make objects from 3D model data, usually layer upon layer, as opposed to subtractive manufacturing methods. Additive manufacturing is used to build physical models, prototypes, patterns, tooling components, and production parts in plastic, metal, ceramic, glass and composite materials.

Respondents assessed accessibility, ease of misuse, imminence of misuse, magnitude of potential harm, and maturity of the following technologies:

- **Bioprinting**—the use of computer-aided transfer processes for patterning and assembling living and non-living materials with a prescribed 2D or 3D organization in order to produce bio-engineered structures.[15]
- **Carbon Fiber Printing**—the use of additive manufacturing technology to print carbon fiber composites, which are made of extremely thin carbon fibers measuring about 5-10 microns in diameter, have a higher strength-to-weight ratio than almost any other manufacturing material.[16]
- **Material Extrusion**—a process in which material is selectively dispensed through a nozzle or orifice (e.g., fused deposition modeling). The raw material is typically a filament of thermoplastic coiled onto a spool that is melted as it is extruded. Material extrusion systems represent the largest installed base of additive manufacturing machines.[17]
- **Material Jetting**—a process that uses inkjet-printing heads to deposit droplets of build material such as direct-write technology. Direct-write technology atomizes nanoparticle-sized print materials and combines them with an inert carrier gas into an aerosol, and then propels the aerosol onto a surface.[18]
- **Microreactor Printing**—the use of additive manufacturing technology for making microreactors, which are miniaturized fluidic reaction ware devices that can be used for chemical syntheses, in just a few hours.[19] Micro Reactors offer many advantages over conventional scale reactors, including vast improvements in energy efficiency, reaction speed and yield, safety, reliability, scalability, on-site/on-demand production, and a much finer degree of process control.[20]

- **Powder Bed Fusion**—a process by which thermal energy fuses selective regions of a power bed (e.g., selective laser sintering). The source of the thermal energy is a laser or an electron beam.[21]

SLIDE 28: Opportunities

Respondents highlighted the following opportunities provided by additive manufacturing for enhancing capabilities to counter WMD (See Q70 in the appendix).

Detection:

- Rapid prototyping and fabrication of sample collection and sensor components and new detection technology
- Manufacturing of portable, clip-on sensors

Countermeasures:

- Local and on-demand manufacturing with a small footprint for needed military parts
- Using printed cell and organ systems for drug testing and medical countermeasures (bioprinting)
- More efficient and cost-effective production of low-volume defense systems

SLIDE 29: Heat Map

This slide provides the **heat map** for additive manufacturing and depicts the **level of expertise** on additive manufacturing across the respondents (See Q13-22, Q24, Q26-30, Q32, Q74-76, Q87, Q94-95 in the appendix).

The color in the heat map key indicates the priority for concern at the current time:

- **Green** = low priority
- **Yellow** = medium priority
- **Red** = high priority

The colors also take into account the relationships between the parameters and risk of misuse and governability described above. Colors are flipped for the **tangibility** and **governability** parameters. Colors are adjusted slightly for the **maturity** parameter.

Summary Findings:

- **23% of respondents** identified themselves as **uninformed** and therefore did not answer any of the specific questions about additive manufacturing.
- **52% of respondents** identified themselves as **knowledgeable or above**.
- **Material extrusion** received the highest scores for accessibility (5.20), ease of misuse (4.33), imminence of misuse (3.90) and maturity (6.19).
- **Microreactor printing** received the highest scores for magnitude of harm (4.28).
- **Bioprinting** was assessed low scores for accessibility (3.36), ease of misuse (3.05) and imminence of misuse (2.84).

SLIDE 30: Risk of Misuse

This slide provides the risk of misuse scores (1=low, 7=high) for additive manufacturing and specific technologies (See Q13-22, Q24, Q26-30, Q32 in the appendix).

Summary Findings:

- Compared to the general scores for additive manufacturing, specific technologies were assessed lower risk of misuse.

SLIDE 31: Governability

This slide depicts the governability scores (1=low, 7=high) for additive manufacturing (See Q74-74, Q81-82, Q87, Q94-95 in the appendix).

Summary Findings:

- Additive manufacturing received a **low score** for governability (3.03).
- A key factor could be its assessed maturity level. At a score of 6.27, respondents consider additive manufacturing to already have reached limited commercial availability. This could mean that the window for government intervention is closing.
- Other key factors could include a high level of convergence with other technologies and its global diffusion.
- 53% of respondents characterized additive manufacturing as **advancing at a steady rate** and 33% of respondents think the sector is experiencing **exponential growth**.

SLIDE 32: Ranks

To establish priorities, we asked respondents to rank different additive manufacturing technologies for their risk of misuse (See Q33 in the appendix).

Each pie chart indicates the percentage of respondents who selected a rank from 1 to 6 for a specific technology.

Summary Findings:

- As a whole, the pie charts show some clear areas of agreement and other points of contention among the respondents.
- 43% of respondents ranked **bioprinting** as the number one technology for risk of misuse. This number is in tension with earlier low scores for accessibility and ease of misuse.
- 25% of respondents ranked **microreactor printing** as the number two technology. However, 22% of respondents ranked the technology as number five.
- 31% of respondents ranked **material extrusion** as number three. This rank is in tension with earlier high scores for accessibility and ease of misuse.
- 29% of respondents ranked **material jetting** as number four. Another 22% of respondents ranked the technology as number five.
- Respondents disagreed significantly on the ranking for **carbon fiber**. 29% percent of respondents ranked the technology as number two. Another 27% of respondents ranked the technology as number four.
- 34% of respondents ranked **powder bed fusion** as number six.

SLIDE 33: WMD Pathways

To explore how emerging technologies impact WMD development pathways, SMEs evaluated the relevance of emerging technologies for WMD by assessing the likelihood of state and non-state actors using specific emerging technologies to advance themselves along the pathway toward WMD development (See Q56-59 in the appendix).

For the purposes of this chart, we grouped the five stages of the WMD development pathway into three categories: 1) research and development; 2) acquisition and production; and 3) weaponization and delivery.

SMEs assessed the likelihood (1=low, 7=high) of state and non-state actors of using **additive manufacturing** to advance along the WMD pathway within the next five years. Specifically, respondents assessed the potential of states and non-state actors doing certain things with emerging technologies:

Research and Development:
- Print novel chemical compounds
- Develop new techniques for enriching uranium
- Use 3D printers to create novel pathogens/microbes

Acquisition and Production:
- Print known chemical compounds
- Use 3D printers to create known pathogens/microbes
- Print components for uranium enrichment
- Print fissile components of a nuclear weapon
- Print non-nuclear components of a nuclear weapon

Weaponization and Delivery:
- Print missile components
- Print high explosives
- Test and evaluate new nuclear weapon designs
- Test and evaluate weapon designs for biological and chemical weapons
- Develop delivery systems for biological and chemical weapons
- Print and assemble drones capable of delivering a biological and chemical weapon

Summary Findings:

- Based on respondent scores, additive manufacturing will have a greater impact on the **acquisition and production** and **weaponization and delivery** stages than research and development. Compared to the other technology groups, additive manufacturing appears to have the broadest impact on the WMD development pathway, its effects spanning across all stages.
- In the research and development stage, both state and non-state actors are mostly likely to **create novel chemical compounds** using additive manufacturing.
- In the acquisition and production stage, state actors are most likely to use additive manufacturing to **print non-nuclear components** of a nuclear weapon and least likely to print the fissile material components of a nuclear weapon. In contrast, non-state actors are considered most likely to **print known chemical compounds** using additive manufacturing techniques.

SLIDE 34: WMD Pathways

This slide provides the scores for the final stage of weaponization and delivery (See Q56-59 in the appendix).

Summary Findings:

- Based on respondent scores, additive manufacturing will have the greatest impact on the **weaponization and delivery** stage.
- State actors are most likely to **print missile components**; non-state actors are most likely to **print and assemble**

drones capable of delivering biological or chemical weapons.

SLIDE 35: Other Enabling Effects

Respondents suggested that we missed the following enabling effects of additive manufacturing for development or use of WMD (See Q60 in the appendix).

Weaponization and Delivery

- Printing cell or organ systems to test toxicity, pathogenicity, and "effectiveness" of biological and chemical weapons
- Multi-material printing (especially electronics and electromagnetic devices) may facilitate the development of WMD delivery systems
- Aerosolization technologies for the delivery of stabilized pathogens/microbes

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[15] As defined here: http://www.ncbi.nlm.nih.gov/pubmed/20811115

[16] As defined here: http://www.3ders.org/articles/20160229-the-strongest-players-in-carbon-fiber-3d-printing-today.html

[17] As defined by the Wohler's Report, http://www.wohlersassociates.com/

[18] As defined by the Wohler's Report.

[19] As defined here: https://digitalmatternet.wordpress.com/2013/03/01/3d-printed-micro-reactors-chemistry-world/

[20] As defined here: http://www.chemtrix.com/info/Micro-Reactor

[21] As defined by the Wohler's Report, http://www.wohlersassociates.com/

Advanced Robotics

Advanced robotics generates both new risks and opportunities for the WMD space. Increasingly, sophisticated robots are available commercially for industrial and domestic use, with commercial drones at the forefront of this trend. Whereas commercial drones offer states and non-state actors a potential delivery system for WMD, the wide range of robotics across the sea, land, and air domains enhances defense capabilities for countering WMD by providing agile and cheap platforms for detecting WMD and operating in a hazardous environment.

SLIDE 36: Advanced Robotics

This section provides the scores for the specific questions related to advanced robotics.

Advanced Robotics is a branch of mechanical engineering, electrical engineering, electronics engineering and computer science that focuses on the development of robotics and artificial intelligence. A robot is a reprogrammable, multifunctional manipulator designed to move material, parts, tools, or specialized devices through various programmed functions for the performance of a variety of tasks.[22]

Respondents assessed accessibility, ease of misuse, imminence of misuse, magnitude of potential harm, and maturity of the following technologies:

- **Autonomous Systems**—intelligent machines capable of performing tasks in the world by themselves, without explicit human control.
- **Unmanned Aerial Vehicles**—powered, aerial vehicles that do not carry a human operator, use aerodynamic forces to provide vehicle lift, can fly autonomously or be piloted remotely, can be expendable or recoverable, and can carry a lethal or nonlethal payload.
- **Strong Artificial Intelligence**—intelligence and creativity similar to a human brain.
- **Weak Artificial Intelligence**—the cognitive ability to solve specific problems or perform specific tasks.

SLIDE 37: Opportunities

Respondents highlighted the following opportunities provided by advanced robotics for enhancing capabilities to counter WMD (See Q71 in the appendix).

Detection:
- Equip drones or other robotics with detectors to sense CBRN
- Enhanced surveillance of state and non-state actor activities
- Swarms of CBRN detectors to enable persistent surveillance

Response:
- Use robotics to investigate a scene for CBRN contamination

- Rapid delivery of countermeasures (e.g., treatment after a biological attack)
- Use robotics for decontamination after a CBRN attack

SLIDE 38: Heat Map

This slide provides the **heat map** for advanced robotics and depicts the **level of expertise** on advanced robotics across the respondents (See Q13-22, Q24, Q34-37, Q74-75, Q77, Q81, Q87, Q94-95 in the appendix).

The color in the heat map key indicates the priority for concern at the current time:

- **Green** = low priority
- **Yellow** = medium priority
- **Red** = high priority

The colors also take into account the relationships between the parameters and risk of misuse and governability described above. Colors are flipped for the **tangibility** and **governability** parameters. Colors are adjusted slightly for the **maturity** parameter.

Summary Findings:

- **29% of respondents** identified themselves as **uninformed** and therefore did not answer any of the specific questions about advanced robotics.
- **41% of respondents** identified themselves as **knowledgeable or above**.
- **Unmanned aerial vehicles (UAVs)** received the highest scores for accessibility (6.32), ease of misuse (6.28), imminence of misuse (5.91), magnitude of potential harm (5.47) and maturity (6.63).
- **Strong AI** was assessed the lowest scores for accessibility (3.04), ease of misuse (3.91), imminence of misuse (3.12) and maturity (2.95). However, it was assessed a higher score for magnitude of potential harm (5.32).

SLIDE 39: Risk of Misuse

This slide provides the risk of misuse scores (1=low, 7=high) for advanced robotics and specific technologies (Q13-22, Q24, Q34-37 in the appendix).

Summary Findings:

- Compared to the general scores for advanced robotics, **unmanned aerial vehicles** were assessed higher scores for ease of misuse, imminence of misuse and magnitude of potential harm.

SLIDE 40: Governability

This slide depicts the governability scores (1=low, 7=high) for advanced robotics (See Q74-75, Q81, Q83, Q87, Q94-95 in the appendix).

Summary Findings:

- Advanced robotics received a low score for governability (4.04).
- Key factors include maturity level (5.44), rate of advance (5.43) and level of convergence (5.38).
- The level of tangibility (4.9) and low global diffusion (4.55) appears to offset the other factors, keeping the window for governance open at this time.
- 52% of respondents characterized advanced robotics as growing at a steady rate. Another 29% of respondents thought the sector is experiencing exponential growth.

SLIDE 41: Ranks

To establish priorities, we asked respondents to rank different advanced robotics technologies for their risk of misuse (See Q38 in the appendix).

Each pie chart indicates the percentage of respondents who selected a rank from 1 to 4 for a specific technology.

Summary Findings:

- As a whole, the pie charts show some clear areas of agreement.
- 78% of respondents ranked **UAVs** as the number one technology for risk of misuse.
- 63% of respondents ranked **autonomous systems** as the number two technology.
- 47% of respondents ranked **weak AI** as number three.
- 49% of respondents ranked **strong AI** as number four.

SLIDE 42: WMD Pathways

To explore how emerging technologies impact WMD development pathways, SMEs evaluated the relevance of emerging technologies for WMD by assessing the likelihood of state and non-actors for using specific emerging technologies to advance themselves along the pathway toward WMD development (See Q61-62 in the appendix).

For the purposes of this chart, we grouped the five stages of the WMD development pathway into three categories: 1) research and development; 2) acquisition and production; and 3) weaponization and delivery.

SMEs assessed the likelihood (1=low, 7=high) of state and non-state actors of using **advanced robotics** to advance along the WMD pathway within the next five years. Specifically, respondents assessed the potential of states and non-state actors doing certain things with emerging technologies:

Weaponization and Delivery:

- Develop drones capable of swarming
- Develop autonomous robots capable of weapon delivery
- Develop drones capable of conducting intelligence, surveillance and reconnaissance mission
- Develop drones capable of targeting individuals for harm/injury
- Develop drones capable of disseminating biological, chemical, or radiological material

Summary Findings:

- Based on respondent scores, advanced robotics will have the greatest impact on the **weaponization and delivery** across all technology groups. All the identified elements of weaponization and delivery received high scores.
- Both state and non-state actors are most likely to use advanced robotics to **develop drones capable of delivering explosives** and least likely to develop drones capable of **swarming**.
- The likelihood of non-state actors using advanced robotics to do harm was assessed to be lower than state-actors.

SLIDE 43: Other Enabling Effects

Respondents suggested that we missing the following enabling effects of advanced robotics for development or use of WMD (See Q63 in the appendix).

Weaponization and Delivery:

- Use of unmanned ground vehicles for delivery of explosives and/or WMD
- UAVs as a potential weapon against aircraft
- Use of simulation/modeling to determine WMD effects for purposes of targeting
- Delivery of biological agents against agriculture (plants and animals)

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[22] As defined by the Robot Institute of America, www.robots.com/education

Nanotechnology

Nanotechnology produces new risks and opportunities for the WMD space. Mostly considered a materials science to date, nanotechnology functions as an enabling technology by making other technologies work better or do things not previously possible.

SLIDE 44: Nanotechnology

This section provides the scores for the specific questions related to nanotechnology.

Nanotechnology refers to applied science, engineering, and technology conducted at the nanoscale, which is about 1 to 100 nanometers. Nanotechnology refers to a group of technologies which manipulate and control nanoscale materials to exploit special properties (quantum effects) and produce new applications.[23]

Respondents assessed accessibility, ease of misuse, imminence of misuse, magnitude of potential harm, and maturity of the following technologies:

- **Carbon nanotubes**—Carbon nanotubes are large molecules of pure carbon that are long and thin and shaped like tubes, about 1-3 nanometers (1 nm = 1 billionth of a meter) in diameter, and hundreds to thousands of nanometers long. As individual molecules, nanotubes are 100 times stronger-than-steel and one-sixth its weight. Some carbon nanotubes can be extremely efficient conductors of electricity and heat; depending on their configuration, some act as semiconductors.[24]
- **Nanoelectronics**—technologies that could allow computation and memory storage to occur using devices far smaller than current silicon technologies.[25]
- **Nanoencapsulation**—the coating of various substances within another material at sizes on the nano scale.[26]
- **Nanoenergetics**—energetic materials that can store higher amounts of energy than conventional energetic materials and can increase the lethality of weapons.[27]
- **Nanomachines**—nanoscale devices, composed of a small number of atoms, that perform useful tasks on other nanoscale structures.[28]
- **Nanomedicine**—use of nanomaterials for biomedical applications such as targeted drug delivery.[29]

SLIDE 45: Opportunities

Respondents highlighted the following opportunities provided by nanotechnology for enhancing capabilities to counter WMD (See Q72 in the appendix).

Detection:

- Sensors for environmental detection
- Nanotechnology-based tags applied to dual-use components to enhance export control efforts and IAEA safeguards

Countermeasures:

- Catalytic nanomaterials for degrading chemical agents, possibly for incorporation into PPE
- Increased stability of medical countermeasures (longer storage at ambient temperatures)
- Possible distribution of medical counter measures through water supply

Response:

- New materials for decontamination
- Improved delivery and targeting of medical countermeasures

SLIDE 46: Heat Map

This slide provides the **heat map** for nanotechnology and depicts the **level of expertise** on nanotechnology across the respondents (See Q13-22, Q24, Q39-44, Q74-75, Q78, Q81, Q87, Q94-95 in the appendix).

The color in the heat map key indicates the priority for concern at the current time:

- **Green** = low priority
- **Yellow** = medium priority
- **Red** = high priority

The colors also take into account the relationships between the parameters and risk of misuse and governability described above. Colors are flipped for the **tangibility** and **governability** parameters. Colors are adjusted slightly for the **maturity** parameter.

Summary Findings:

- **18% of respondents** identified themselves as **uninformed** and therefore did not answer any of the specific questions about nanotechnology.
- **57% of respondents** identified themselves as **knowledgeable or above**.
- Compared to the general scores for nanotechnology, specific technologies received lower scores. Respondents assessed nanotechnology as a whole with higher risk. The high scores for magnitude of potential harm for nanotechnology could be a factor. Much of the potential of nanotechnology still remains untapped.
- **Carbon nanotubes** received the highest scores for accessibility (4.29) and maturity (5.52).
- **Nanoencapsulation** received the highest scores for ease of misuse (4.13) and imminence of misuse (3.53).
- **Nanoenergetics** received the highest score for magnitude of potential harm (4.95).
- Based on respondent scores, **nanomachines** and **nanomedicine** are not likely to be misused in the near-term due to low accessibility and ease of misuse.

SLIDE 47: Risk of Misuse

This slide provides the risk of misuse scores (1=low, 7=high) for nanotechnology and specific technologies (See Q13-22, Q24, Q39-44 in the appendix).

Summary Findings:

- Compared to the general scores for nanotechnology, specific technologies were assessed lower risk of misuse. Respondents assessed nanotechnology as a whole with higher risk. The high scores for magnitude of potential harm for nanotechnology could be a factor.

Much of the potential of nanotechnology still remains untapped.

- Compared to other technology groups, nanotechnology received high scores for magnitude of harm. This appears to be the key factor in the risk assessment.
- Overall, **nanoencapsulation** received the highest scores for risk of misuse, followed closely behind by **nanoenergetics** and **nanomedicine** (bolstered by its score for magnitude of potential harm).

SLIDE 48: Governability

This slide depicts the governability scores (1=low, 7=high) for nanotechnology (See Q74-75, Q81, Q84, Q87, Q94-95 in the appendix).

Summary Findings:

- Nanotechnology received a low score for governability (3.88).
- Key factors include maturity level (5.00), rate of advance (4.92) and level of convergence (4.82).
- The level of tangibility (4.29) and low global diffusion (4.17) appears to offset the other factors, keeping the window for governance open.
- 46% of respondents characterized nanotechnology as advancing at a steady rate; 33% of respondents thought that the pace of growth was at a slow rate.

SLIDE 49: Ranks

To establish priorities, we asked respondents to rank different nanotechnologies for their risk of misuse (See Q45 in the appendix).

Each pie chart indicates the percentage of respondents who selected a rank from 1 to 6 for a specific technology.

Summary Findings:

- As a whole, the pie charts show some significant points of contention among the respondents.
- 28% of respondents ranked **nanomedicine** as the number one technology for risk of misuse. This rank contradicts earlier low scores for accessibility and ease of misuse.
- 21% of respondents ranked **nanoelectronics** as the number two technology. However, more respondents (33%) ranked the technology as number three.
- 22% of respondents ranked **nanoencapsulation** as number one, three and four, indicating significant disagreement.
- 23% of respondents ranked **nanoenergetics** as number four. Another 22% of respondents ranked the technology as number one, again revealing disagreement among respondents.
- 27% of respondents ranked **nanomachines** as number five; a greater number of respondents ranked the technology as number six
- 32% of respondents ranked **carbon nanotubes** as number six.

SLIDE 50: WMD Pathways

To explore how emerging technologies impact WMD development pathways, SMEs evaluated the relevance of emerging technologies for WMD by assessing the likelihood of state and non-actors for using specific emerging technologies to advance themselves along the pathway toward WMD development (See Q64-65 in the appendix).

For the purposes of this chart, we grouped the five stages of the WMD development pathway into three categories: 1) research and development; 2) acquisition and production; and 3) weaponization and delivery.

SMEs assessed the likelihood (1=low, 7=high) of state and non-state actors of using **nanotechnology** to advance along the WMD pathway within the next five years. Specifically, respondents assessed the potential of states and non-state actors doing certain things with emerging technologies:

Research and Development:

- Develop nanoscale chemical particles to induce genetic damage or cause physiological effects

Acquisition and Production:

- Develop stronger and lighter weight nanomaterials
- Stabilize harmful pathogens/microbes or chemicals using nanoencapsulation

Weaponization and Delivery:

- Develop stronger and lighter weight nanomaterials
- Develop nanoparticles as a method for delivering drugs and medical treatment
- Develop nanoparticles as a delivery system for harmful pathogens and microbes
- Stabilize harmful pathogens/microbes or chemicals using nanoencapsulation
- Develop nanoenergetics for use in explosive devices

Summary Findings:

- Based on respondent scores, nanotechnology will have a greater impact on the **acquisition and production** and **weaponization and delivery** stages than research and development.
- In the research and development stage, the scores for both state and non-state actors are low for **developing nanoscale chemical particles**. There is a significant gap between the perceived risk of state actors versus non-state actors.
- In the acquisition and production stage, state actors are most likely to use nanotechnology to **develop stronger and lighter weight nanomaterials** and least likely to **stabilize harmful pathogens/microbes or chemicals**. Respondents assessed the opposite to be true for non-state actors. However, both activities in this stage were assessed low scores.

SLIDE 51: WMD Pathways

This slide provides the scores for the final stage of weaponization and delivery (See Q64-65 in the appendix).

- In the weaponization and delivery stage, states are most likely to **develop stronger and lighter weight nanomaterials** and **develop nanoparticles as a method for delivering drugs,** and non-state actors are more likely to develop nanoenergetics for use in explosive devices.

[23] As defined by the U.S. National Nanotechnology Initiative (NNI), http://www.nano.gov/

[24] As defined by Azonano, http://www.azonano.com/article.aspx?ArticleID=1381

[25] As defined by NDU's CTNSP, http://ctnsp.dodlive.mil/files/2014/09/DTP106.pdf

[26] As defined here: https://www.azonano.com/article.aspx?ArticleID=1875

[27] As defined by Andrzei W. Miziolek, U.S. Army Research Lab, http://infohouse.p2ric.org/ref/34/33115.pdf

[28] As defined by NDU's CTNSP, http://ctnsp.dodlive.mil/files/2014/09/DTP106.pdf

[29] As defined by NDU's CTNSP, http://ctnsp.dodlive.mil/files/2014/09/DTP106.pdf

Nuclear Technology

In contrast to emerging technologies, the wide range of nuclear technologies has been understood for many decades. Still, given their direct relevance for the WMD space, it is worth considering whether recent technological innovations might lead to unanticipated leaps forward in nuclear capabilities by states and create new risks and/or opportunities for the WMD space.

SLIDE 52: Nuclear Technology

This section provides the scores for the specific questions related to nuclear technology.

Nuclear technology leverages nuclear energy which is released through a nuclear reaction or radioactive decay process. Of particular interest is the process known as fission, which occurs in a nuclear reactor and produces energy primarily in the form of heat.[30] This technology group includes new ways to exploit the atom to generate electricity (such as nuclear fusion), new types of nuclear reactors, or different ways to produce fissile material.

Respondents assessed accessibility, ease of misuse, imminence of misuse, magnitude of potential harm, and maturity of the following technologies:

- **Laser Enrichment**—a process for uranium isotope separation using laser excitation. This process could be used to produce nuclear fuel for power reactors for fissile material for nuclear weapons.
- **Nuclear Fusion**—A reaction in which at least one heavier, more stable nucleus is produced from two lighter, less stable nuclei. Reactions of this type are responsible for enormous release of energy, such as the energy given off by stars.[31] As an emerging technology, nuclear fusion may be used to generate electricity in the near future.
- **Next Generation Nuclear Reactors**—new, smaller modular reactors that are designed to be portable and pre-fabricated with enhanced safety features.[32]

SLIDE 53: Heat Map

This slide provides the **heat map** for nuclear technology and depicts the **level of expertise** on nuclear technology across the respondents (See Q13-22, Q24, Q46-48, Q74-75, Q79, Q81, Q87, Q94-95 in the appendix).

The color in the heat map key indicates the priority for concern at the current time:

- **Green** = low priority
- **Yellow** = medium priority
- **Red** = high priority

The colors also take into account the relationships between the parameters and risk of misuse and governability described above. Colors are flipped for the **tangibility** and **governability** parameters. Colors are adjusted slightly for the **maturity** parameter.

Summary Findings:

- **21% of respondents** identified themselves as **uninformed** and therefore did not answer any of the specific questions about nuclear technology.
- **44% of respondents** identified themselves as **knowledgeable or above**.
- **Next generation reactors** received the highest scores for accessibility (3.32) and maturity (4.58).
- **Laser enrichment** received the highest scores for ease of misuse (4.07), imminence of misuse (3.56) and magnitude of harm (6.02).
- Overall, the scores for the specific technologies were lower than the scores for nuclear technology as a whole.

SLIDE 54: Risk of Misuse

This slide provides the risk of misuse scores (1=low, 7=high) for nuclear technology and specific technologies (See Q13-22, Q24, Q46-48 in the appendix).

Summary Findings:

- Compared to the general scores for nuclear technology, specific technologies were assessed lower risk of misuse, with the exception of magnitude of harm which generated higher scores for all three specific technologies. This appears to be the key factor in the risk assessment.
- Overall, **laser enrichment technology** received the highest scores for risk of misuse.

SLIDE 55: Governability

This slide depicts the governability scores (1=low, 7=high) for nuclear technology (See Q74-75, Q81, Q85, Q87, Q94-95 in the appendix).

Summary Findings:

- Nuclear technology received a high score for governability (5.86).
- Key factors include maturity level (6.02), slow rate of advance (3.88), low level of convergence (3.47) and limited global diffusion (3.70). While a high level of maturity usually would suggest less susceptibility to governance, the other factors point the other way. The features of nuclear technology make it relatively easy to regulate (e.g., its tangibility, limited global diffusion and lack of digitization).
- Nuclear technology received the highest scores for tangibility (5.59) across the five technology groups.
- 64% of respondents characterized nuclear technology as advancing at a slow pace. Another 18% of respondents suggested that nuclear technology may have stopped growing. Finally, 4% of respondents thought that nuclear technology is in decline.

SLIDE 56: Ranks

To establish priorities, we asked respondents to rank different nuclear technologies for their risk of misuse (See Q49 in the appendix).

Each pie chart indicates the percentage of respondents who selected a rank from 1 to 3 for a specific technology.

Summary Findings:

- As a whole, the pie charts show some clear areas of agreement among the respondents.
- 54% of respondents ranked **laser enrichment** as the number one technology for risk of misuse. This number correlate to earlier scores for ease of misuse, imminence of misuse and magnitude of potential harm.
- 57% of respondents ranked **next generation nuclear reactors** as the number two technology.
- 65% of respondents ranked **nuclear fusion** as number three.

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[30] As defined by NRC, http://www.nrc.gov/reading-rm/basic-ref/glossary/atomic-energy.html

[31] As defined by NRC, http://www.nrc.gov/reading-rm/basic-ref/glossary/fusion-reaction.html

[32] http://www.scientificamerican.com/article/next-generation-nuclear/

Synthetic Biology

Synthetic biology creates new risks and opportunities for the WMD space that leverage new genome editing tools, growing collections of genomic data, and expansion of computing power. Advances in the life sciences can create new pathways for biological weapons development but at the same time will provide new capabilities for countering those weapons.

SLIDE 57: Synthetic Biology

This section provides the scores for the specific questions related to synthetic biology.

Synthetic biology aims to make biology easier to engineer. Synthetic biology is the convergence of advances in chemistry, biology, computer science, and engineering that enables us to go from idea to product faster, cheaper, and with greater precision than ever before. It can be thought of as a biology-based "toolkit" that uses abstraction, standardization, and automated construction to change how we build biological systems and expand the range of possible products.[33]

Respondents assessed accessibility, ease of misuse, imminence of misuse, magnitude of potential harm, and maturity of the following technologies:

- **Bioinformatics**—the collection, classification, storage, and analysis of biochemical and biological information using computers especially as applied to molecular genetics and genomics.[34]
- **CRISPR**—CRISPR is an acronym for Clustered Regularly Interspaced Short Palindromic Repeat. This name refers to the unique organization of short, partially palindromic repeated DNA sequences found in the genomes of bacteria and other microorganisms. CRISPR is a gene editing technology that is more precise than any prior tools.
- **Gene Drives**—genetic systems that circumvent traditional rules of genetic transfer. Gene drives greatly increase the odds that the genes will be passed on to offspring.[35]
- **Precision Medicine**—an emerging approach for disease treatment and prevention that takes into account individual variability in genes, environment, and lifestyle for each person.[36]

SLIDE 58: Opportunities

Respondents highlighted the following opportunities provided by synthetic biology for enhancing capabilities to counter WMD (See Q73 in the appendix).

Detection

- Enhanced environmental sensing capabilities and surveillance
- New detection capabilities
- Rapid threat analysis and enhanced diagnostics

Countermeasures

- Development of vaccines, anti-bacterials, and therapeutics

- Faster, cheaper production of existing vaccines and anti-bacterials
- Targeted drugs and treatment through precision medicine

SLIDE 59: Heat Map

This slide provides the **heat map** for synthetic biology and depicts the **level of expertise** on synthetic biology across the respondents (See Q13-22, Q24, Q50-53, Q74-75, Q80, Q81, Q87, Q94-95 in the appendix).

The color in the heat map key indicates the priority for concern at the current time:

- **Green** = low priority
- **Yellow** = medium priority
- **Red** = high priority

The colors also take into account the relationships between the parameters and risk of misuse and governability described above. Colors are flipped for the **tangibility** and **governability** parameters. Colors are adjusted slightly for the **maturity** parameter.

Summary Findings:

- **18% of respondents** identified themselves as experts, indicating the high level of expertise in synthetic biology compared to the other technology groups.
- **An additional 53% of respondents** identified themselves as **knowledgeable or very knowledgeable**.
- **Only 12% of respondents** identified themselves as **uninformed** and therefore did not answer any of the specific questions about synthetic biology.
- **Bioinformatics** received the highest scores for accessibility (5.41) and maturity (6.27).
- **CRISPR/gene editing** received the highest scores for ease of misuse (4.74), imminence of misuse (4.02) and magnitude of harm (5.55).
- Overall, the scores for the specific technologies were lower than the scores for synthetic biology as a whole.

SLIDE 60: Risk of Misuse

This slide provides the risk of misuse scores (1=low, 7=high) for synthetic biology and specific technologies (See Q13-22, Q24, Q50-53 in the appendix).

Summary Findings:

- Compared to the general scores for synthetic, specific technologies were assessed lower risk of misuse. Respondents assessed synthetic biology as a whole with higher risk. The high scores for magnitude of potential harm for synthetic biology could be a factor. Much of the potential of this field still remains untapped.
- Compared to other technology groups, synthetic biology received high scores for magnitude of harm. This appears to be the key factor in the risk assessment.
- Overall, **CRISPR/gene editing** received the highest scores for risk of misuse, followed closely behind by **bioinformatics** and **gene drives**.

SLIDE 61: Governability

This slide depicts the governability scores (1=low, 7=high) for synthetic biology (See Q74-75, Q81, Q86, Q87, Q94-95 in the appendix).

Summary Findings:

- Synthetic biology received a low score for governability (3.03).
- Key factors include maturity level (5.44), rate of advance (6.04), level of convergence (5.13), and global diffusion (5.15). These factors complicate any effort by policymakers to intervene with governance measures to mitigate risk.
- Compared to other technology groups, synthetic biology received the lowest scores for tangibility (3.85).
- An overwhelming 62% of respondents characterized synthetic biology as experiencing exponential growth.

SLIDE 62: Ranks

To establish priorities, we asked respondents to rank different synthetic biology technologies for their risk of misuse (See Q54 in the appendx).

Each pie chart indicates the percentage of respondents who selected a rank from 1 to 4 for a specific technology.

Summary Findings:

- As a whole, the pie charts show some clear areas of agreement and other points of contention among the respondents.
- 48% of respondents ranked **CRISPR/gene editing** as the number one technology for risk of misuse.
- Respondents indicated significant divergence on the risk of **gene drives.** 28% of respondents ranked the technology as number two. However, 35% of respondents ranked the technology as number three.
- The ranks for **bioinformatics** were similarly diverse. 31% respondents ranked the technology as number three. About a quarter of respondents ranked the technology as one, two and four.
- 50% of respondents ranked **precision medicine** as number four.

SLIDE 63: WMD Pathways

To explore how emerging technologies impact WMD development pathways, SMEs evaluated the relevance of emerging technologies for WMD by assessing the likelihood of state and non-actors for using specific emerging technologies to advance themselves along the pathway toward WMD development (See Q67-68 in the appendix).

For the purposes of this chart, we grouped the five stages of the WMD development pathway into three categories: 1) research and development; 2) acquisition and production; and 3) weaponization and delivery.

SMEs assessed the likelihood (1=low, 7=high) of state and non-state actors of using **synthetic biology** to advance along the WMD pathway within the next five years. Specifically, respondents assessed the potential of states and non-state actors doing certain things with emerging technologies:

Research and Development:

- Create novel pathogens/microbes to harm individuals, agriculture or livestock
- Create novel pathogens/microbes to contaminate food or water
- Create novel pathogens/microbes to harm materiel or commodities

- Create novel pathogens/microbes to target population groups
- Enhance existing pathogens/microbes to be resistant to treatment, vaccines and countermeasures
- Enhance the environmental stability of existing pathogens/microbes
- Modify existing pathogens/microbes to be capable of rapid growth in the laboratory
- Enhance the capacity of existing pathogens/microbes for evading detection
- Make an existing pathogen/microbe more infectious and/or lethal
- Increase the transmissibility of an existing pathogen/microbe

Acquisition and Production:
- Enhance existing pathogens/microbes to be resistant to treatment, vaccines and countermeasures
- Enhance the environmental stability of existing pathogens/microbes
- Modify existing pathogens/microbes to be capable of rapid growth in the laboratory
- Enhance the capacity of existing pathogens/microbes for evading detection
- Make an existing pathogen/microbe more infectious and/or lethal
- Increase the transmissibility of an existing pathogen/microbe
- Synthesize existing pathogens/microbes
- Recreate past/eradicated pathogens/microbes

Weaponization and Delivery:
- Enable more effective weaponization of existing pathogens/microbes

Summary Findings:

- Based on respondent scores, synthetic biology will have the greatest impact on the **research and development** stage.
- In the research and development stage, both state and non-state actors are most likely to **make an existing pathogen/microbe more infectious and/or lethal** and least likely to **create novel pathogens/microbes to target population groups.** The likelihood scores for non-state actors were much lower across the board.
- In the acquisition and production stage, state actors are most likely to **synthesize existing pathogens/microbes** and least likely to **enhance the capacity of existing pathogens for evading detection.** Non-state actors are most likely to **make an existing pathogen/microbe more infectious and/or lethal** and least likely to **enhance the capacity of existing pathogens for evading detection.** Overall, the likelihood scores for non-state actors were much lower.

SLIDE 64: WMD Pathways

This slide provides the scores for the final stage of weaponization and delivery (See Q67-68 in the appendix).

- In the weaponization and delivery stage, states are more likely to use synthetic biology **to enable more effective weaponization of existing pathogens/microbes** than non-state actors.

SLIDE 65: Other Enabling Effects

Respondents suggested that we are missing the following enabling effects of synthetic biology for development or use of WMD (See Q69 in the appendix).

Research and Development:

- Development of molecular threat agents (nonliving, non-viral)
- Modify existing pathogens/microbes to change the host range (and/or to target selected subpopulations)

Acquisition and Production:

- Use of synthetic biology to enable industrial-scale toxin production

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[33] As defined by SYNBERC, https://www.synberc.org/what-is-synbio
[34] http://www.merriam-webster.com/dictionary/bioinformatics
[35] As defined by the WYSS Institute, http://wyss.harvard.edu/staticfiles/newsroom/pressreleases/Gene%20drives%20FAQ%20FINAL.pdf
[36] As defined by NIH, https://www.nih.gov/precision-medicine-initiative-cohort-program

Final Conclusions

SLIDE 66: Final Conclusions

Throughout this report, we have provided summary findings for each graph. In this section, we offer a series of final conclusions drawn from the experience of conducting the SME survey.

SLIDE 67: Risk versus Opportunity

Within the context of national security, emerging technologies are primarily viewed through the “risk lens” which leads a desire to control and regulate the technologies to mitigate their risks.

This is problematic for a number of reasons. Emerging technologies offer new solutions for countering WMD. Given their breadth of end-use applications, they serve as important engines for the U.S. economy. Finally, the characteristics of today’s emerging technologies would severely complicate any attempts to control or regulate the technologies.

There are several reasons for the focus on risks over opportunities. In the research for this survey, we found that there are few metrics to evaluate the potential opportunities of a technology. For this reason, we were limited to survey questions that would result in qualitative answers. The sensitivity of efforts to enhance CWMD detection, countermeasures, and response plans may be a factor in the lack of information on potential new solutions.

While the emerging technologies in this survey create new risks, they do not appear to offer tangible ways to prevent WMD development or use. All of the new solutions offered by these technologies would enhance detection, countermeasures and response (left of loss or left of boom). Because CWMD policymakers and operators are trained to think in terms of prevention for countering WMD, we tend to focus on the risk posed by about emerging technologies.

SLIDE 68: State versus Non-State Actors

State actors were consistently assessed higher scores than non-state actors. As expected, non-state actors were assessed low scores across all technology groups with one exception. The scores for the development of drones for use in terrorist operations or attacks were significantly higher than any other set of scores. The data in this survey does not support current hype about non-state actors leveraging CRISPR to develop biological weapons.

Based on the survey, non-state actors are most likely to use advanced robotics and additive manufacturing at the weaponization and delivery stage of their operations, but not necessarily for the delivery of WMD. Non-state actors are least likely to use nanotechnology.

SLIDE 69: Direct versus Indirect Effects

Emerging technologies vary in their impact on WMD development pathways. Additive manufacturing and nanotechnology appear to have indirect effects at all stages of WMD development in the near-term (as the technologies advance, this may change). Given the breadth of their end-use applications, this is not surprising.
In contrast, synthetic biology and advanced robotics have more focused and direct effects on the WMD development pathway. Synthetic biology appears to have the greatest impact on research and development and R&D efforts during the acquisition and production stage. However, synthetic biology does not appear to have significant direct effects on developing ways to disperse or delivery biological weapons (e.g., aerosolization technology), which would be necessary to cause harm on a large scale.

Advanced robotics has focused effects and direct on weaponization and delivery of WMD, in particular due to the accessibility and ease of misuse of UAVs.

Given their broad applicability, the negative effects of additive manufacturing and nanotechnology will be harder to control through regulation given a high opportunity cost of hindering advancement in those fields. In contrast, given their focused and direct affects, it will be easier to justify control measures to mitigate the negative effects of synthetic biology and advanced robotics.

SLIDES 70-71: Old versus New

The nuclear technology scores provided an interesting contrast to the emerging technologies in this study, confirming many of their key characteristics:

- Accessibility to a broader set of actors
- Utility across a broader set of end-use applications
- Ease of use and affordability
- Digital character
- Rapid advancement
- High convergence with other emerging technologies
- Global diffusion

Interestingly, synthetic biology and nanotechnology were assessed higher scores than nuclear technology for magnitude of potential harm. It is possible that SMEs took into account the untapped potential of these emerging technologies. Whereas we know the full extent of harm of nuclear technology, we have less understanding about the potential of synthetic biology and nanotechnology.

SLIDES 72-73: General versus Specific

The assessed scores for the technology groups as a whole were higher than the scores for the specific technologies (UAVs were the single exception). There may be a few factors at play. For the technology groups, respondents assessed the risk of misuse and associated parameters separately for advanced states, developing states, and non-state actors. For specific technologies within each technology group, we did not ask for separate scores by actor type. Another factor could be assessing the untapped potential within the technology groups versus the limited potential of a specific technology.

SLIDE 74: Other Emerging Technologies

We asked respondents if we missed any emerging technologies with enabling effects for WMD (See Q25, Q55 in the appendix). Respondents suggested the following:

- Advanced computing/quantum computing
- Big data
- Dark Web for sharing/exchange of information
- Cyberwarfare
- Electromagnetic warfare/EMP
- High power microwave
- Lasers
- Geoengineering
- Cloaking
- Fermentation
- Aerosolization

Appendix: Survey Questions

This appendix contains the relevant questions about emerging technologies to support the findings in this report. Each question is written as they were administered to survey respondents.

Q13. Overall, how would you rate the **risk of misuse** for each technology group for **advanced nation-states** (1=low, 7=high)?

- Additive Manufacturing
- Advanced Robotics
- Nanotechnology
- Nuclear Energy
- Synthetic Biology

Q14. Overall, how would you rate the **risk of misuse** for each technology group for **developing nation-states** (1=low, 7=high)?

- Additive Manufacturing
- Advanced Robotics
- Nanotechnology
- Nuclear Energy
- Synthetic Biology

Q15. Overall, how would you rate the **risk of misuse** for each technology group for **non-state actors** (1=low, 7=high)?

- Additive Manufacturing
- Advanced Robotics
- Nanotechnology
- Nuclear Energy
- Synthetic Biology

Q16. Overall, how would you rate the **accessibility** for each technology group for **advanced nation-states** (1=low, 7=high)?

- Additive Manufacturing
- Advanced Robotics
- Nanotechnology
- Nuclear Energy
- Synthetic Biology

Q17. Overall, how would you rate the **accessibility** for each technology group for **developing nation-states** (1=low, 7=high)?

- Additive Manufacturing
- Advanced Robotics
- Nanotechnology
- Nuclear Energy
- Synthetic Biology

Q18. Overall, how would you rate the **accessibility** for each technology group for **non-state actors** (1=low, 7=high)?

- Additive Manufacturing
- Advanced Robotics
- Nanotechnology
- Nuclear Energy
- Synthetic Biology

Q19. Overall, how would you rate the **ease of misuse** for each technology group for **advanced nation-states** (1=low, 7=high)?

- Additive Manufacturing
- Advanced Robotics
- Nanotechnology
- Nuclear Energy
- Synthetic Biology

Q20. Overall, how would you rate the **ease of misuse** for each technology group for **developing nation-states** (1=low, 7=high)?

- Additive Manufacturing
- Advanced Robotics
- Nanotechnology
- Nuclear Energy
- Synthetic Biology

Q21. Overall, how would you rate the **ease of misuse** for each technology group for **non-state actors** (1=low, 7=high)?

- Additive Manufacturing
- Advanced Robotics
- Nanotechnology
- Nuclear Energy
- Synthetic Biology

Q22. Overall, how would you rate the **magnitude of potential harm** for each technology group (1=low, 7=high)?

- Additive Manufacturing
- Advanced Robotics
- Nanotechnology
- Nuclear Energy
- Synthetic Biology

Q24. Overall, how would you rate the **imminence of misuse** for each technology group (1=low, 7=high)?

- Additive Manufacturing
- Advanced Robotics
- Nanotechnology
- Nuclear Energy
- Synthetic Biology

Q25. What other technology groups pose a significant risk of misuse and/or having enabling effects for WMD?

Q26. Overall, how would you rate the risk of misuse for **bioprinting** (low=1, high=7)?

- Accessibility
- Ease of Misuse
- Magnitude of Potential Harm
- Imminence of Misuse

Q27. Overall, how would you rate the risk of misuse for **carbon fiber printing** (low=1, high=7)?

- Accessibility
- Ease of Misuse
- Magnitude of Potential Harm
- Imminence of Misuse

Q28. Overall, how would you rate the risk of misuse for **material extrusion** (low=1, high=7)?

- Accessibility
- Ease of Misuse
- Magnitude of Potential Harm
- Imminence of Misuse

Q29. Overall, how would you rate the risk of misuse for **material jetting** (low=1, high=7)?

- Accessibility
- Ease of Misuse
- Magnitude of Potential Harm
- Imminence of Misuse

Q30. Overall, how would you rate the risk of misuse for **microreactor printing** (low=1, high=7)?

- Accessibility
- Ease of Misuse
- Magnitude of Potential Harm
- Imminence of Misuse

Q32. Overall, how would you rate the risk of misuse for **powder bed fusion** (low=1, high=7)?

- Accessibility
- Ease of Misuse
- Magnitude of Potential Harm
- Imminence of Misuse

Q33. Please rank the following emerging technologies for risk of misuse (most=1, least=6).

- Bioprinting
- Carbon Fiber Printing
- Material Extrusion
- Material Jetting
- Microreactor Printing
- Powder Bed Fusion

Q34. Overall, how would you rate the risk of misuse for **autonomous systems** (low=1, high=7)?

- Accessibility
- Ease of Misuse
- Magnitude of Potential Harm
- Imminence of Misuse

Q35. Overall, how would you rate the risk of misuse for **strong artificial intelligence** (low=1, high=7)?

- Accessibility
- Ease of Misuse
- Magnitude of Potential Harm
- Imminence of Misuse

Q36. Overall, how would you rate the risk of misuse for **unmanned aerial vehicles** (low=1, high=7)?

- Accessibility
- Ease of Misuse
- Magnitude of Potential Harm
- Imminence of Misuse

Q37. Overall, how would you rate the risk of misuse for **weak artificial intelligence** (low=1, high=7)?

- Accessibility
- Ease of Misuse
- Magnitude of Potential Harm
- Imminence of Misuse

Q38. Please rank the following emerging technologies for risk of misuse (most=1, least=4).

- Autonomous Systems
- Strong Artificial Intelligence
- Unmanned Aerial Vehicles
- Weak Artificial Intelligence

Q39. Overall, how would you rate the risk of misuse for **carbon nanotubes** (low=1, high=7)?

- Accessibility
- Ease of Misuse
- Magnitude of Potential Harm
- Imminence of Misuse

Q40. Overall, how would you rate the risk of misuse for **nanoelectronics** (low=1, high=7)?

- Accessibility
- Ease of Misuse
- Magnitude of Potential Harm
- Imminence of Misuse

Q41. Overall, how would you rate the risk of misuse for **nanoencapsulation** (low=1, high=7)?

- Accessibility
- Ease of Misuse
- Magnitude of Potential Harm
- Imminence of Misuse

Q42. Overall, how would you rate the risk of misuse for **nanoenergetics** (low=1, high=7)?

- Accessibility
- Ease of Misuse
- Magnitude of Potential Harm
- Imminence of Misuse

Q43. Overall, how would you rate the risk of misuse for **nanomachines** (low=1, high=7)?

- Accessibility
- Ease of Misuse
- Magnitude of Potential Harm
- Imminence of Misuse

Q44. Overall, how would you rate the risk of misuse for **nanomedicine** (low=1, high=7)?

- Accessibility
- Ease of Misuse
- Magnitude of Potential Harm
- Imminence of Misuse

Q45. Please rank the following emerging technologies for risk of misuse (most=1, least=6).

- Carbon nanotubes

- Nanoelectronics
- Nanoencapsulation
- Nanoenergetics
- Nanomachines
- Nanomedicine

Q46. Overall, how would you rate the risk of misuse for **laser enrichment technology** (low=1, high=7)?

- Accessibility
- Ease of Misuse
- Magnitude of Potential Harm
- Imminence of Misuse

Q47. Overall, how would you rate the risk of misuse for **next generation nuclear reactors** (low=1, high=7)?

- Accessibility
- Ease of Misuse
- Magnitude of Potential Harm
- Imminence of Misuse

Q48. Overall, how would you rate the risk of misuse for **nuclear fusion** (low=1, high=7)?

- Accessibility
- Ease of Misuse
- Magnitude of Potential Harm
- Imminence of Misuse

Q49. Please rank the following emerging technologies for risk of misuse (most=1, least=3).

- Laser Enrichment
- Next Generation Nuclear Reactors
- Nuclear Fusion

Q50. Overall, how would you rate the risk of misuse for **bioinformatics** (low=1, high=7)?

- Accessibility
- Ease of Misuse
- Magnitude of Potential Harm
- Imminence of Misuse

Q51. Overall, how would you rate the risk of misuse for **CRISPR/gene editing tools** (low=1, high=7)?

- Accessibility
- Ease of Misuse
- Magnitude of Potential Harm
- Imminence of Misuse

Q52. Overall, how would you rate the risk of misuse for **gene drives** (low=1, high=7)?

- Accessibility
- Ease of Misuse
- Magnitude of Potential Harm
- Imminence of Misuse

Q53. Overall, how would you rate the risk of misuse for **precision medicine** (low=1, high=7)?

- Accessibility
- Ease of Misuse
- Magnitude of Potential Harm
- Imminence of Misuse

Q54. Please rank the following emerging technologies for risk of misuse (most=1, least=4).

- Bioinformatics
- CRISPR/Gene Editing
- Gene Drives
- Precision Medicine

Q55. Have we missed any specific technologies that may have significant enabling effects for WMD? If so, please list them here.

Q56. What is the likelihood that **state actors** will use additive manufacturing to do the following **within the next five years** (1=low, 7=high)?

- Print components for uranium enrichment

- Develop new techniques for enriching uranium
- Print fissile components of a nuclear weapon
- Print non-nuclear components of a nuclear weapon
- Test and evaluate new nuclear weapon designs
- Print missile components
- Print high explosives

Q57. What is the likelihood that **non-state actors** will use additive manufacturing to do the following **within the next five years** (1=low, 7=high)?

- Print components for uranium enrichment
- Develop new techniques for enriching uranium
- Print fissile components of a nuclear weapon
- Print non-nuclear components of a nuclear weapon
- Test and evaluate new nuclear weapon designs
- Print missile components
- Print high explosives

Q58. What is the likelihood that **state actors** will use additive manufacturing to do the following **within the next five years** (1=low, 7=high)?

- Use 3D printers to create novel pathogens/microbes
- Use 3D printers to create known pathogens/microbes
- Print novel chemical compounds
- Print known chemical compounds
- Test and evaluate weapon designs for biological and chemical weapons
- Develop delivery systems for biological and chemical weapons
- Print and assemble drones capable of delivering a biological and chemical weapon

Q59. What is the likelihood that **non-state actors** will use additive manufacturing to do the following **within the next five years** (1=low, 7=high)?

- Use 3D printers to create novel pathogens/microbes
- Use 3D printers to create known pathogens/microbes
- Print novel chemical compounds
- Print known chemical compounds
- Test and evaluate weapon designs for biological and chemical weapons
- Develop delivery systems for biological and chemical weapons
- Print and assemble drones capable of delivering a biological and chemical weapon

Q60. Have we missed any enabling features of additive manufacturing for the development or use of WMD? If so, please list them here.

Q61. What is the likelihood that **state actors** will use advanced robotics to do the following **within the next five years** (1=low, 7=high)?

- Develop drones capable of swarming
- Develop autonomous robots capable of weapon delivery
- Develop drones capable of conducting intelligence, surveillance and reconnaissance mission
- Develop drones capable of targeting individuals for harm/injury
- Develop drones capable of disseminating biological, chemical, or radiological material

Q62. What is the likelihood that **non-state actors** will use advanced robotics to do the following **within the next five years** (1=low, 7=high)?

- Develop drones capable of swarming
- Develop autonomous robots capable of weapon delivery
- Develop drones capable of conducting intelligence, surveillance and reconnaissance mission
- Develop drones capable of targeting individuals for harm/injury
- Develop drones capable of disseminating biological, chemical, or radiological material

Q63. Have we missed any enabling features of advanced robotics for the development or use of WMD? If so, please list them here.

Q64. What is the likelihood that **state actors** will use nanotechnology to do the following **within the next five years** (1=low, 7=high)?

- Develop nanoparticles as a method for delivering drugs and medical treatment
- Develop nanoparticles as a delivery system for harmful pathogens and microbes
- Develop nanoscale chemical particles to induce genetic damage or cause physiological effects
- Develop stronger and lighter weight nanomaterials
- Stabilize harmful pathogens/microbes or chemicals using nanoencapsulation
- Develop nanoenergetics for use in explosive devices

Q65. What is the likelihood that **non-state actors** will use nanotechnology to do the following **within the next five years** (1=low, 7=high)?

- Develop nanoparticles as a method for delivering drugs and medical treatment
- Develop nanoparticles as a delivery system for harmful pathogens and microbes
- Develop nanoscale chemical particles to induce genetic damage or cause physiological effects
- Develop stronger and lighter weight nanomaterials
- Stabilize harmful pathogens/microbes or chemicals using nanoencapsulation
- Develop nanoenergetics for use in explosive devices

Q66. Have we missed any enabling features of nanotechnology for the development or use of WMD? If so, please list them here.

Q67. What is the likelihood that **state actors** will use nanotechnology to do the following **within the next five years** (1=low, 7=high)?

- Create novel pathogens/microbes to harm individuals, agriculture or livestock
- Create novel pathogens/microbes to contaminate food or water
- Create novel pathogens/microbes to harm materiel or commodities
- Create novel pathogens/microbes to target population groups
- Enhance existing pathogens/microbes to be resistant to treatment, vaccines and countermeasures
- Enhance the environmental stability of existing pathogens/microbes
- Modify existing pathogens/microbes to be capable of rapid growth in the laboratory
- Enhance the capacity of existing pathogens/microbes for evading detection
- Make an existing pathogen/microbe more infectious and/or lethal
- Increase the transmissibility of an existing pathogen/microbe
- Synthesize existing pathogens/microbes
- Recreate past/eradicated pathogens/microbes

- Enable more effective weaponization of existing pathogens/microbes

Q68. What is the likelihood that **non-state actors** will use nanotechnology to do the following **within the next five years** (1=low, 7=high)?

- Create novel pathogens/microbes to harm individuals, agriculture or livestock
- Create novel pathogens/microbes to contaminate food or water
- Create novel pathogens/microbes to harm materiel or commodities
- Create novel pathogens/microbes to target population groups
- Enhance existing pathogens/microbes to be resistant to treatment, vaccines and countermeasures
- Enhance the environmental stability of existing pathogens/microbes
- Modify existing pathogens/microbes to be capable of rapid growth in the laboratory
- Enhance the capacity of existing pathogens/microbes for evading detection
- Make an existing pathogen/microbe more infectious and/or lethal
- Increase the transmissibility of an existing pathogen/microbe
- Synthesize existing pathogens/microbes
- Recreate past/eradicated pathogens/microbes
- Enable more effective weaponization of existing pathogens/microbes

Q69. Have we missed any enabling features of synthetic biology for the development or use of WMD? If so, please list them here.

Q70. Does additive manufacturing offer any new opportunities to counter threats posed by WMD? If so, how?

Q71. Does advanced robotics offer any new opportunities to counter threats posed by WMD? If so, how?

Q72. Does nanotechnology offer any new opportunities to counter threats posed by WMD? If so, how?

Q73. Does synthetic biology offer any new opportunities to counter threats posed by WMD? If so, how?

Q74. Overall, how would you rate the **governability** of each technology group?

For governability, please consider that a score of high (7) indicates that a technology is highly susceptible to a broad range of intervention types, and its susceptibility is determined by its maturity, rate of advance, level of convergence, global diffusion and tangibility. A score of low (1) indicates that a technology is not susceptible to most or all types of intervention.

- Additive Manufacturing
- Advanced Robotics
- Nanotechnology
- Nuclear Technology
- Synthetic Biology

Q75. Overall, how would you rate the **maturity** of each technology group (1=basic principles, 2=lab experimentation, 3=proof of concept, 4=prototype, 5-early marketing, 6=limited commercial availability, 7=widespread commercial availability)?

- Additive Manufacturing
- Advanced Robotics
- Nanotechnology
- Nuclear Technology
- Synthetic Biology

Q76. How would you rate the **maturity** of specific technologies related to additive manufacturing?

- Bioprinting
- Carbon Fiber Printing
- Material Extrusion
- Material Jetting
- Microreactor Printing
- Powder Bed Fusion

Q77. How would you rate the **maturity** of specific technologies related to advanced robotics?

- Autonomous Systems
- Strong Artificial Intelligence
- Unmanned Aerial Vehicles
- Weak Artificial Intelligence

Q78. How would you rate the **maturity** of specific technologies related to nanotechnology?

- Carbon nanotubes
- Nanoelectronics
- Nanoencapsulation
- Nanoenergetics
- Nanomachines
- Nanomedicine

Q79. How would you rate the **maturity** of specific technologies related to nuclear energy?

- Laser Enrichment
- Next Generation Nuclear Reactors
- Nuclear Fusion

Q80. How would you rate the **maturity** of specific technologies related to synthetic biology?

- Bioinformatics
- CRISPR/Gene Editing
- Gene Drives
- Precision Medicine

Q81. Overall, how would you assess the **rate of advance** for each technology group (low=1, high=7)?

- Additive Manufacturing
- Advanced Robotics
- Nanotechnology
- Nuclear Technology
- Synthetic Biology

Q82. Overall, how would you describe the **rate of advance** for additive manufacturing?

- Declining
- Plateauing
- Advancing at a Slow Pace
- Advancing at a Steady Rate
- Exponential Growth

Q83. Overall, how would you describe the **rate of advance** for advanced robotics?

- Declining
- Plateauing
- Advancing at a Slow Pace
- Advancing at a Steady Rate
- Exponential Growth

Q84. Overall, how would you describe the **rate of advance** for nanotechnology?

- Declining
- Plateauing
- Advancing at a Slow Pace
- Advancing at a Steady Rate
- Exponential Growth

Q85. Overall, how would you describe the **rate of advance** for nuclear energy?

- Declining
- Plateauing
- Advancing at a Slow Pace
- Advancing at a Steady Rate
- Exponential Growth

Q86. Overall, how would you describe the **rate of advance** for synthetic biology?

- Declining
- Plateauing
- Advancing at a Slow Pace
- Advancing at a Steady Rate
- Exponential Growth

Q87. Overall, how would you assess the level of **convergence** for each technology group (with all other emerging technologies)?

- Additive Manufacturing
- Advanced Robotics
- Nanotechnology
- Nuclear Technology
- Synthetic Biology

Q94. Overall, how would you rate the **global diffusion** for each technology group (1=low, 7=high)?

- Additive Manufacturing
- Advanced Robotics
- Nanotechnology
- Nuclear Technology
- Synthetic Biology

Q95. Overall, how would you rate the **tangibility** for each technology group (1=low, 7=high)?

- Additive Manufacturing
- Advanced Robotics
- Nanotechnology
- Nuclear Technology
- Synthetic Biology

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