GLOBAL SECURITY IMPLICATIONS OF CHEMICAL AND BIOLOGICAL INNOVATION

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Abstract

Profound changes are occurring globally due to rapidly advancing chemical and biological (C/B) innovation. Reduced costs of capabilities, increased availability of materials and knowledge, global connectivity, and complex network interactions are together increasing the risk of significant C/B events—whether intentional or not. Yet, the security risks that arise must be weighed against the tremendous potential of public and private sector innovations to benefit human quality of life globally. In response to these concerns, this study sought to identify the global trends and technological changes that will likely affect the C/B landscape in the next 15 years, as well as the implications of this evolving landscape on global security risks. Our findings suggest that C/B innovations will be a critical and growing consideration for the future of global security—both in terms of governance functions and system effects. The rate of chemical and biological innovation, coupled with transformative developments in complementary technology fields, further indicates: (1) the emergence of dual use applications that create both benefits and security risks; (2) a growing ability to weaponize C/B capabilities by state and non-state actors alike; (3) an increased probability of socially disruptive C/B events; and (4) that the complexity of the global environment will result in unintended consequences. Thus, it is imperative for regulators to explore how to effectively manage future global security challenges that C/B innovations present without constraining research and innovation that serve the global good.

Keywords: Global security, chemical and biological innovation, biotechnology, technology trends

Introduction

Profound changes are occurring globally due to rapidly advancing chemical and biological (C/B) innovation. Reduced costs of capabilities, increased availability of materials and knowledge, global connectivity, and complex network interactions are together increasing the risk of significant C/B events—whether intentional or not. Yet, the security risks that arise must be weighed against the tremendous potential of public and private sector C/B innovations to benefit human quality of life globally. Thus, a governance conundrum arises regarding how to address transformative beneficial research and development that could also drive the proliferation of dual-use products, bioweaponry development, and other unintended consequences.

In response to these concerns, a team of analysts at Sandia National Laboratories underwent a study in 2017 to explore dangers in the future global C/B landscape over the next 15 years. Specifically, this study sought to answer two questions:

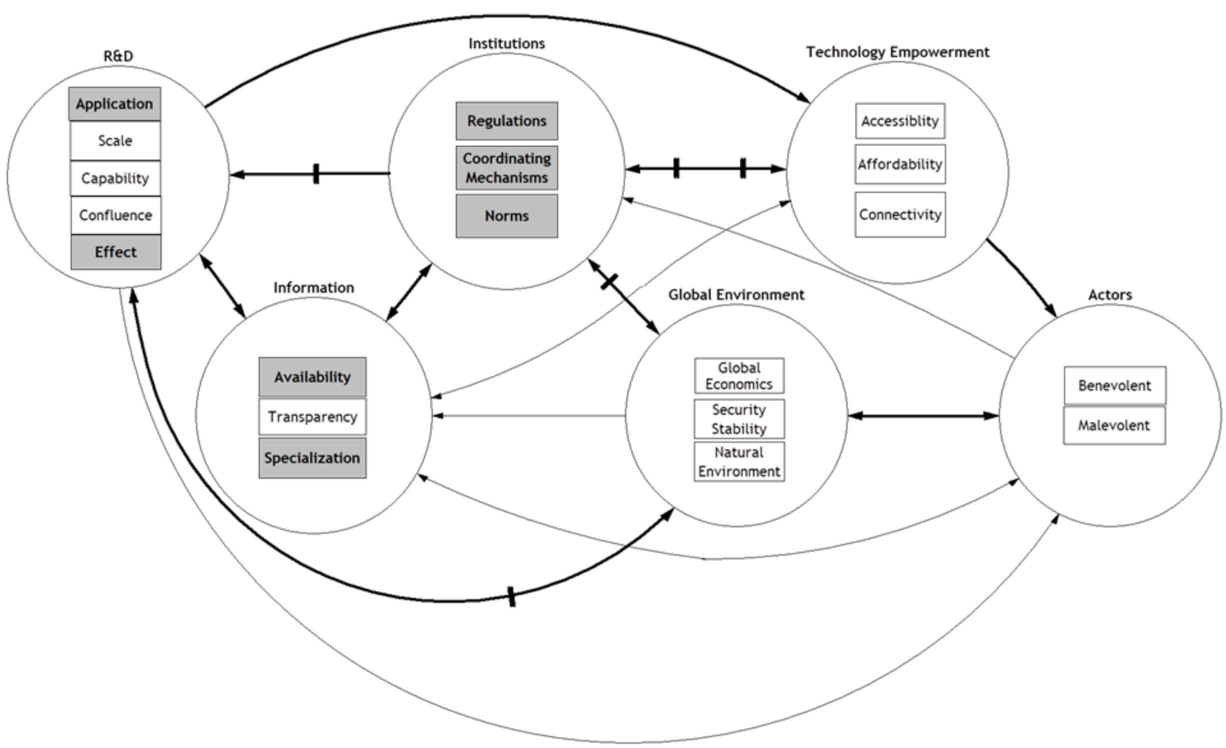
1. What are the global trends and technological changes that will likely affect the C/B landscape in the next 15 years?
2. What are the implications of this evolving landscape on global security risks?

Our findings are discussed in subsequent sections, and they suggest that it will be necessary to effectively manage the risks and complexity of the future C/B landscape. Moreover, the confluences[1] of C/B innovations will require increased resilience[2] across the global security enterprise—meaning policymakers and scientists must develop the capacity to better anticipate and rapidly adapt to emerging security challenges.

Methodological approach

Over the course of a year, our team collected and analysed socio-economic, environmental, and technological data from a series of workshops, subject matter expert interviews, and a review of chemical, biological, security, and foresight literature. Through these engagements the analysis team identified a collection of key technologies and trends that will shape the future of C/B security. We further mapped out key dynamics at play which help drive global security risks for C/B innovation. By analysing the trends and dynamics, we identified a set of global security implications, as well as a set of five hypotheses about future C/B-related global security challenges for further exploration.

Figure 1. *Global Chemical / Biological Security and Innovation System*



Note: Bolded lines indicate those feedback loops considered significantly impacted by C/B innovation. Shaded boxes are those sub-elements that serve as the foundation for the hypotheses outlined in the Conclusions section.

[1] Confluences in this study refers to the merger of two or more previously separate disciplines, research fields, and technologies to create distinct new disciplines, products, or lines of scientific exploration.
[2] Resilience in this context is defined as "the capacity of a system to absorb disturbance and reorganize while undergoing change, so as to still retain essentially the same function, structure, identity, and feedbacks" (Walker et al 2004).

The notion of global security risk--not quantitatively measured in this paper—is central to this study. Building on a standard notion of risk, global security is defined as the amalgamation of protective measures taken by nation states and other entities to ensure mutual survival and safety. Thus, global security risks refer to those viable threats that could disrupt the safety and survival of entities internationally, as well as to threats against the stability of the GSIS.[3]

Our analysis identified key aggregate dynamics and elements shaping the innovation environment, which when critically evaluated begin to reveal the unique security risks C/B innovations present. Leveraging insights from workshop participants, the analysis team built a contextual map of the global C/B security and innovation system (GSIS) as depicted in Figure 1. This map diagrams six significant contextual elements, as well as their sub-elements, and connects them with directional feedback loops. While not a robust causal loop diagram, this contextual mapping provides a foundation for future development of a system dynamics model where the interplay of the elements, sub-elements, and dynamics could be quantitatively tested.

The GSIS map depicted in Figure 1 consists of six high level elements (depicted as circles in the diagram) that combine to form a parsimonious version of the GSIS. The constituent elements and their corresponding definitions are:

- **Research & Development (R&D):** activities that generate knowledge and create new technologies, products, services, and/or systems
- **Institutions:** formal and informal rules and organizations that mediate behaviour in the system
- **Actors:** individuals and entities that act as consumers of security and innovation products in the system
- **Information:** data and knowledge that is produced by and transmissible through the system
- **Technology Empowerment:** extent to which individuals and other non-state entities can leverage highly impactful technologies for their own purposes
- **Global Environment:** contextual environment within which innovation and security operate

Figure 1 depicts each of these elements as containing sub-elements. While not comprehensive, these sub-elements were identified by the analysis team as being significant for the changes occurring in these sub-elements from innovation and the corresponding potential impact to security risk. The elements are then connected through feedback loops that demonstrate directional effects between elements from changes within the element—some of which are unidirectional, and others are bidirectional. Bolded arrows represent those feeds deemed highly significant in terms of impact from innovation on the system. Vertical slashes on the feedback arrows depict time delays in the system with regards to a specific relationship, thereby introducing a gap between when a change takes place in one element and when it introduces an effect in another element.

While visualizing the GSIS elements and their relationships is useful for defining the system of concern, a crucial insight the figure illustrates is the role of time delays. Figure 1 depicts five

[3] In this context the definition is represented by *Risk = Probability X Consequence*. This definition of global security risk should be understood to include the consequences of not pursuing C/B measures that serve to benefit the global good (e.g. vaccines).

points of directional time delays, and four of them are direct inputs to or outputs from Institutions. What this suggests is that an accelerated rate of change in any of the other elements could create challenges for any or all the institutional sub-elements depicted. Thus, time delays must serve as a significant consideration for evaluating the implications of innovation on global C/B security risks.

Results, discussion and implications

On a global basis, C/B innovation is driven by a number of trends. Aggregate trends we identified for C/B technology and innovation include:

- barriers to success in highly scientific fields are diminishing as cost reductions, outsourcing, and knowledge access flourish
- data are being stored at unprecedented rates with increasingly more detail, specificity, and sensitivity
- advancements in genetic sequencing and synthesis, coupled with growth in computing capabilities, are increasingly enabling synthetic biology to program living matter
- increasing processing power, optimization capabilities, and accuracy of modelling and simulation are expanding scientific knowledge fundamental to innovations that may enable C/B dangers
- the lines between chemistry and biology are blurring as synthetic biology is enabling the production of complex chemical molecules at high quantities, purity, and at lower costs
- synthetic biology is vastly expanding upon naturally occurring biologies into *de novo* design spaces with wide disruption potential
- innovations arising from confluences of C/B with non-C/B arena are:
- enabling scientific knowledge acquisition
- increasing the efficiency of processes and systems
- facilitating advanced targeting and delivery
- human modification and augmentation are expanding human capabilities and increasingly seeking to enable effective human function in previously inhospitable environments

Key technology developments: Some of the key developments and capabilities underlying these trends warrant discussion. As the future unfolds, C/B fields and associated disciplines will expand the type and degree of risks. As outlined at a high level in Table 1, several of these disciplines fall at least partially within the broad scientific subfield known as synthetic biology[4], and a few of its most relevant aspects/embodiments are described. While some of the potential

[4] Synthetic Biology “combines the investigative nature of biology with the constructive nature of engineering” to “make living matter fully programmable” (Andrianantoandro et al. 2006; Purnick and Weiss 2009). Synthetic biology includes using genetics to design and synthesize useful organisms, biomolecules, chemistries, materials, cryptographies, and platforms.

highlighted in Table 1's future trajectory column may lie beyond the 15-year timeframe of this study, they are nonetheless future capabilities that policymakers should consider in their C/B security development. Additionally, key enabling advancements in other fields that could strongly influence the direction of C/B dangers are highlighted. The confluence of these disciplines allows for a wide range of beneficial and hazardous applications.

Table 1. *Notable Chemical and Biological Disciplines and Trajectories*

DISCIPLINE	TRAJECTORY
*Genetics** encompasses reading, modifying, and synthesis of genetic material to understand and manipulate genome-to-phenotype correlation.	Genome editing technologies (e.g., CRISPR-Cas) and delivery platforms will likely allow humans to edit the genome at specific locations to affect desired changes with increasing fidelity (Cong et al. 2013; Ma et al. 2017; Cyranoski and Reardon 2017), which may hold strong benefits and/or dangerous potential for humans. This capability also expands beyond human centric uses; naturally occurring organisms with specialized properties can be newly designed to effect significant damage to infrastructure (Tracy 2016).
*Bioinformatics** combines computer science, statistics, mathematics, and engineering to analyze and interpret biological data. This field is necessary for genome-to-phenotype correlation, and is a sub-set of the application of data analytics to biology.	As computational power and the data available for analysis increase, this area will deepen the relational understanding between coding (DNA, RNA, proteins) and expression. The increased correlative power will enable the broader area of synthetic biology.
*Chemical Synthesis** is the production of desired chemicals either through natural physiological processes or through controlled reactions. Traditionally chemical synthesis has been relegated to the field of synthetic chemistry, however the production of stereochemically pure small molecules for industrial needs (medical, agriculture, material, etc.) has been increasingly met through the techniques of synthetic biology (Carothers, Goler, and Keasling 2009; Smanski et al. 2016).	Advances in genetics, control over catalytic reactions, and high-throughput system assembly will enable production of hundreds of thousands of complex chemical molecules at higher quantities, purity, and at lower cost (Carothers, Goler, and Keasling 2009; Smanski et al. 2016). The intended and unintended consequences of this development range from impacts to food production, to contamination of medical fluids, to the development of *de novo* or existing chemical warfare precursors or final products through nontraditional less easily monitored methods.
*Biocircuitry** involves arranging synthesized biology into configurations that allow for penetration into traditionally inorganic spheres of computing, communication, electromagnetic spectrum expression, etc. This fields is attempting to develop biological 'electronics' such as biological voltage production and transmission (Pearlman 2016*,* Widom et al. 2011), as well as biologically based computation, storage, and cryptography (Church, Gao, and Kosuri 2012).	Given biocircuitry's inherent, augmented, and *de novo* designed capabilities, new biological organisms may be developed to disrupt the electrical integrity of systems. These self-replicating "electric viruses" could infect the control systems of civilian or defense applications and could be very difficult to detect or disinfect. These engineered biologic systems may also become the foundation of communication systems, computers, and information storage.

DISCIPLINE	TRAJECTORY
Tissue Engineering involves developing methods to encourage tissue growth on (biodegradable) lattices, 3-D printing new organs (printed directly using scaffolding), arrange via self-assemble by controlling ambient environment, or start with the smallest structural and functional component and let it grow, and altering genetics to achieve “unnatural” properties.	If challenges can be overcome in achieving the desired 3D shapes, mechanical and structural properties, bioactivity, degradation properties, and infrastructure (blood vessels or nerves) needed to maintain health and bioactivity of the printed material, then tissue and organ capabilities (e.g., night vision, resistance to radiation, increased pain tolerance, etc.) could be enhanced beyond natural levels (Murphy and Atala 2014; Guvendiren et al. 2016; Wang et al. 2016, Zhang 2015).
Wearables and Implantables are augmenting technologies that expand naturally occurring capabilities or can monitor functionality of natural systems.	Despite current limitations on biocompatibility (Jarchum 2017; Tingley 2013), devices worn on the body will enhance human capabilities including enhancing physical strength (Cornwall 2015), providing information directly to the eyes (Levy 2017) and greater sensing, monitoring and control over human vitals (Kao et al. 2016). Eventually, mind-mind (Rao et al. 2014) and mind-machine interfaces may enable humans to wirelessly communicate with each other and with their devices.
Biomimicry involves non-biological/materials-based solutions conceptualized from discoveries of biological systems, properties, and phenomena (e.g., nano-bots mimicking organisms (Huang et al. 2016), neural network algorithms, genetic optimization algorithms, folding of organelles or proteins (Colapinto 2014)).	As deeper scientific understanding of complex biological systems is found, inspiration for in vivo delivery mechanisms, machine learning techniques, self-assembly, and other areas are expected. (Huang et al. 2016).
Natural Pathogens are disease causing bacteria, virus, and microorganisms that evolve over time and when subject to differing environmental conditions.	Comprehensive knowledge of existing pathogens is lacking, and a global effort to discover zoonotic viruses of pandemic potential has found nearly 1,000 new viruses (Doucleff and Greenhalgh 2017). In the future, not only will the environment have changed but potentially human genetic make-up will be altered; hence susceptibility to new and existing diseases will rise.

Note: * denotes Synthetic Biology subfield.

Advancements in any, or all, of the following fields can strongly influence the development of the sub-fields above.

Artificial Intelligence: Combining the capabilities of artificial intelligence with biological and chemical arena results in multi-dimensional impacts, such as *de novo* and highly effective design options (e.g. toxins, chemicals, pathogens, etc.) that are potentially disruptive and hazardous as much as they are beneficial (e.g. drugs, vaccines, etc.). Artificial intelligence could also dramatically increase fundamental knowledge in biologic systems by enhancing the efficiency and effectiveness of bioinformatics for instance.

Computing: As processing power increases, the ability to efficiently use optimization and search algorithms will also increase. Modelling and simulation capabilities will increase further refining knowledge and hence the set of possible solutions to a given challenge. Combining increased processing power with simulation capabilities will lead to new breakthroughs in many scientific fields directly enabling the innovation space encompassing the C/B arena.

Cyber: As more individuals, entities, and information transition to the internet, so does the potential for sharing, hacking, and selling. The web, and especially the dark web, offers a mechanism for nefarious actors to share sensitive information and to sell potentially dangerous materials. Understanding how and what to regulate (information, materials, methodologies, sequences, etc.) is not straightforward due to the dual-use capabilities of many of the innovations, and even with the knowledge of what to regulate cyber capabilities dramatically enhance alternative mechanisms to circumvent these regulations.

Data Analytics: Data will continue to be stored in vast amounts with increasingly more detail and specificity. Ownership of this data, access to this data, and security of this data will elevate in importance as population based genomics will enable more advanced genome-to-phenotype correlation, new protein design, and more powerful and personalized treatment modalities. Proxy identifiers (e.g. increased Sudafed purchases) will be increasingly important in confirming, anticipating, and localizing outbreaks. Unique anonymized datasets will be cross-correlated to unveil identification of individuals, more complete genetic sequences, and other intentionally concealed or compartmentalized data.

Materials Science: Biological materials offer the potential for properties that are difficult to achieve with synthetic chemistry, including the ability to rapidly grow, self-repair, expand the strength and fracture toughness range, and adapt to the environment. Basic materials science combined with synthetic biology can increase yield, decrease cost, and expand the characteristics of available materials. Non-traditional application of these materials (e.g. as the outer coating of buildings) also potentially introduces new vulnerabilities to pathogens or toxins.

Advanced Manufacturing: Advances in additive manufacturing to enable faster production times, multiple inks within the same apparatus, as well as cheaper and smaller footprints will facilitate breakthroughs that will impact the C/B arena. Point of use printing could offer many responses to an outbreak: healthy replacement organs (Murphy and Atala 2014), needed countermeasures from drugs to equipment (Mearian 2016), or transmission reduction measures like keeping people home by printing food sources from basic constituent material (Dance 2017).

Internet of Things: The ubiquitous connectedness of everyday objects to cyber structures that are storing data allow for an unprecedented opportunity to correlate behaviour to neuro-cognitive models. The specific knowledge of peoples' patterns, locations, and habits can be used for advanced targeting.

Medicine: Understanding of genetic diseases, pathogens, cellular function through to hierarchical organ function, and the influence of toxins and materials in the environment on human health will continue to increase. The honing of medical practices to the individual person based on their genetics and environment will continue. This increased knowledge, simultaneously at the population and personal scales, will offer increased treatments as well as new pathways for disruption.

Neuroscience: Capabilities to both understand and control neurological processes of thought, emotion, and behaviour will continue to increase (DiEuliis and Giordano 2017). Agents that affect the neural system are not confined solely to toxins, and as this field increases in capabilities, so will the nefarious employment of its' developments. Affecting the cognitive and emotional states of decision makers, the general populous, or key leaders offers a dangerous employment of this science and certainly falls within the emerging C/B dangers.

Nanotechnology: The development of nanodevices, nanoparticles, nanoscale phenomena, and nanotools for medical and biological purposes combines the field of nanotechnology with the C/B arena. Advanced delivery mechanisms for drugs, monitoring of cellular functions, regenerative medicine, and manipulation of molecular processes are all bolstered in this confluence.

Based upon the current trends, trajectories, and dynamics in the C/B landscape, the analysis team extracted security implications of these changes to international security. While future C/B risks will overall consist of intentional events (including state bioweapons, bioterror, and bio crime) and unintentional events (including accidents, natural outbreaks, and unintended consequences and use), the GSIS dynamics in Figure 1 imply the probability of both event types are growing. As a result, significant governance and systems implications emerge.

Governance implications: Figure 1 revealed how time delays between R&D and regulations create and expand system vulnerabilities. These delays, however, are by no means new as the C/B community has a history of imposing self-regulation. A prime example of this is the Asilomar gathering of approximately 140 academics to address the potential risks of using recombinant DNA (Berg 2008). For some time, this level of regulation, in conjunction with some public-sector regulations, was adequate to address new developments. However, there is now a significant and growing gap in policies able to address the ever-evolving environment, and there are significant challenges for state entities to regulate and maintain relevancy within the space.

For some, the biotech community's history of self-regulation may call into question the relevancy and role of state-based regulation and entities and instead favour increased activity by various non-state actor groups. For instance, a rising number of non-governmental organizations (NGOs) that have their expressed their own regulatory priorities and have the resources to execute them. In some cases, these NGOs, while benevolent in intention, have begun to take on roles traditionally defined as state functions, such as the Bill and Melinda Gates Foundation offering to fund the Biological Weapons Convention (BWC).

Yet, regardless of who ultimately regulates the biotechnology space, the ability to fully understand and utilize new information gained through biotechnology innovations is still lagging behind the vast amount of information available. As biological innovations continue to advance and diversify, there are significant doubts on the ability of regulation to keep pace and therefore whether regulation should even be pursued (Kusnezov and Jones, 2017). If traditional public regulation is not feasible, alternative frameworks will have to be created with engagement from state and non-state actor representation. The alternative is a likely increased risk or accidental and/or malicious biological events that will have global ramifications. Therefore, greater engagement and agility to respond to the continued biotechnological advances should be a priority for all regulatory entities.

Global system implications: Beyond governance, several implications emerged from the analysis regarding the behaviour and dynamics of the global C/B security system. These implications related to the inherently complex and adaptive nature of this system and what that means for the pursuit of security.

Global C/B security is a problem to be managed, not solved: Within the security R&D realm, discussions and ambition frequently centre around developing "solutions" to global security problems. However, from a security perspective, the landscape revealed in this study suggest that C/B risks from innovation is a "wicked problem"—one that does not lend itself to a future solution but must instead be managed to maintain global security through greater resilience. Even so the prospect of effective resilience-based C/B security management is challenged by the broader overall complexity emerging in the global system. Connections between a set of actions and their full range of effects become increasingly difficult anticipate as the number of potential connections between actors and activities increase. The line of sight between cause and effect becomes blurred and only the most local or direct consequences can be definitively identified. This growing complexity enhances the challenge to science of understanding unintended consequences to natural systems and organisms in the absence of sufficient baselines.

C/B security concerns move beyond human focus: Interdependency between species, balance in resources, and exogenous factors collectively shaped the biological systems present today, and current scientific knowledge is insufficient to understand all the dynamics-including the absence of baselines regarding much of the natural world. Although we have altered ecosystems in the past (non-native species introduction, selective breeding, etc.), evolving capabilities to genetically engineer exotic / chimerical organisms for specific outcomes stimulates the underlying dynamics in novel ways. These engineered biological systems will eventually adapt, reproduce, and grow independently of the initial engineered outcome as they are influenced by the same forces of natural selection (and exogenous factors) that rejected over 99% of all species that have ever existed (Novacek 2014). Many of the advancements in the C/B arena rely on this manipulation, thus fundamentally expanding the types of imminent C/B dangers beyond traditional bio security with a human focus.

Technology and discipline confluences amplify C/B risk and complexity: Going forward, the C/B risks of greatest significance may be those produced by confluences of technologies and systems and not by specific technologies and capabilities. Combining C/B disciplines with associated fields may produce unforeseen opportunities and capabilities that serve as game changers from a security perspective. Moreover, the widespread ability in the future to directly manipulate organisms—flora, fauna, and human— through genetic modification may increase the susceptibility to existing and previously mitigated pathogens. Indeed, the range of C/B innovations and their convergence may put wide ranges of organisms, systems, materials, processes, and behaviours beyond physical human conditions at risk. Such a C/B threat landscape would likely compel a reconsideration of the human-centric consequence bias of security scope and functions—thereby evolving from an agent-based threat perspective to one focused on capabilities as dual use and unintended consequences become greater risks than intentional acts

Conclusions

The above implications of led our analysis team to explore several of the sub-elements of the global C/B security system. Within the GSIS mapping, analytical interest arose in the sub elements of R&D applications and effects, informational availability and specialization, and institutionalized regulations and coordination mechanisms (as depicted with shaded boxes in Figure 1) due to their perceived potential to dramatically disrupt the GSIS. Trends within these sub-elements, in conjunction with the broader system dynamics yielded five hypotheses for global C/B security risks:

- *H1: Insufficient global assertion and consolidation of visions and leadership increases future C/B risks*

- *H2: Global incentive structures and policymaking priorities that tend to encourage reactive measures increase future C/B risks*
- *H3: Human-centric C/B security consequence bias that overlooks other organisms, materials, and systems increases future C/B risks*
- *H4: Hyper specialization of professions and research that limit perspective on complex dynamics of C/B innovation increases future C/B risks*
- *H5: Insufficient C/B baselines to identify and understand innovation's unintended consequences to natural systems and organisms increases future C/B security risks*

Forthcoming efforts by our team will test these hypotheses using robust modelling and testing. Yet, C/B innovations will be a critical and growing consideration for the future of global security. The rate of C/B innovation, coupled with transformative developments in complementary technology fields, indicates: (1) the emergence of dual use applications that create both benefits and security risks; (2) a growing ability to weaponize C/B capabilities by state and non-state actors alike; (3) an increased probability of socially disruptive C/B events; and (4) that the complexity of the global environment will result in unintended consequences. Thus, it is imperative for nation-states to pursue a posture of resilience in the face of global security challenges that C/B innovations present. And in the near term, nation-states can begin accounting for system effects and explore alternative governance models (e.g. public-private partnership models) that anticipate and mitigate future C/B security risks without constraining research and innovation that serve the global good.

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References

Andrianantoandro, Ernesto, Subhayu Basu, David K. Karig, and Ron Weiss. 2006. "Synthetic Biology: New Engineering Rules for an Emerging Discipline." Molecular Systems Biology 2 (1): 2006.0028. doi:10.1038/msb4100073.

Berg, P., 2008. Asilomar 1975: DNA modification secured," Nature 455: 290–291.

Carothers, James M, Jonathan A Goler, and Jay D Keasling. 2009. "Chemical Synthesis Using Synthetic Biology." Current Opinion in Biotechnology, Protein technologies / Systems and synthetic biology, 20 (4): 498–503. doi:10.1016/j.copbio.2009.08.001.

Church, George M., Yuan Gao, and Sriram Kosuri. 2012. "Next-Generation Digital Information Storage in DNA." Science, August, 1226355. doi:10.1126/science.1226355.

Colapinto, J., 2014. Material Question. The New Yorker.

Cong, Le, F. Ann Ran, David Cox, Shuailiang Lin, Robert Barretto, Naomi Habib, Patrick D. Hsu, et al. 2013. "Multiplex Genome Engineering Using CRISPR/Cas Systems." Science 339 (6121): 819–23. doi:10.1126/science.1231143.

Cornwall, Warren. 2015. "Feature: Can We Build an 'Iron Man' Suit That Gives Soldiers a Robotic Boost?" Science, October 15. http://www.sciencemag.org/news/2015/10/feature-can-we-build-iron-man-suit-gives-soldiers-robotic-boost.

Cyranoski, David, and Sara Reardon. 2017. "Chinese Scientists Genetically Modify Human Embryos." Nature News. Accessed June 21. doi:10.1038/nature.2015.17378.

Dance, Amber. 2017. "Engineering the Animal out of Animal Products." Nature Biotechnology 35 (8): 704–7. doi:10.1038/nbt.3933.

DiEuliis, Diane, and James Giordano. 2017. "Why Gene Editors Like CRISPR/Cas May Be a Game-Changer for Neuroweapons." Health Security 15 (3): 296–302. doi:10.1089/hs.2016.0120.

Doucleff, Michaeleen, and Jane Greenhalgh. 2017. "Why Killer Viruses Are On The Rise." All Things Considered. Naitonal Public Radio. http://www.npr.org/sections/goatsandsoda/2017/02/14/511227050/why-killer-viruses-are-on-the-rise.

Gao, B., Yang, Q., Zhao, X., Jin, G., Ma, Y., Xu, F., 2016. 4D Bioprinting for Biomedical Applications. Trends in Biotechnology 34, 746–756. doi:10.1016/j.tibtech.2016.03.004

Guvendiren, Murat, Joseph Molde, Rosane M.D. Soares, and Joachim Kohn. 2016. "Designing Biomaterials for 3D Printing." ACS Biomaterials Science & Engineering 2 (10): 1679–93. doi:10.1021/acsbiomaterials.6b00121.

Huang, Hen-Wei, Mahmut Selman Sakar, Andrew J. Petruska, Salvador Pané, and Bradley J. Nelson. 2016. "Soft Micromachines with Programmable Motility and Morphology." Nature Communications 7 (July): ncomms12263. doi:10.1038/ncomms12263.

Jarchum, Irene. 2017. "Turning Silver Dust into Electronics." Nature Biotechnology 35 (8): 723–723. doi:10.1038/nbt.3939.

Krishnamurthy, M., M. Kundu, Kartik Bane, Amit D. Lad, Prashant Kumar Singh, Gourab Chatterjee, G. Ravindra Kumar, and Krishanu Ray. 2015. "Enhanced X-Ray Emission from Nano-Particle Doped Bacteria." Optics Express 23 (14): 17909–22. doi:10.1364/OE.23.017909.

Kusnezov, Dimitri, and Wendell B. Jones, 2017. "Are Some Technologies Beyond Regulatory Regimes?" arXiv.org, September 3. https://arxiv.org/abs/1707.06668

Levy, Steven. 2017. "Google Glass 2.0 Is a Startling Second Act | Backchannel." WIRED, July 18. https://www.wired.com/story/google-glass-2-is-here/.

Ma, Hong, Nuria Marti-Gutierrez, Sang-Wook Park, Jun Wu, Yeonmi Lee, Keiichiro Suzuki, Amy Koski, et al. 2017. "Correction of a Pathogenic Gene Mutation in Human Embryos." Nature 548 (7668): 413–19. doi:10.1038/nature23305.

Mearian, Lucas. 2016. "This Is the First 3D-Printed Drug to Win FDA Approval." Computerworld. March 28. http://www.computerworld.com/article/3048823/3d-printing/this-is-the-first-3d-printed-drug-to-win-fda-approval.html.

Murphy, Sean V., and Anthony Atala. 2014. "3D Bioprinting of Tissues and Organs." Nature Biotechnology 32 (8): 773–85. doi:10.1038/nbt.2958.

Novacek, Michael J. 2014. "Prehistory's Brilliant Future." The New York Times, November 8. https://www.nytimes.com/2014/11/09/opinion/sunday/prehistorys-brilliant-future.html.

Pearlman, Alex. 2016. "Lightbulb Made of Modified E. Coli Fuses Biology and Electronics." New Scientist, October 28. https://www.newscientist.com/article/2110839-lightbulb-made-of-modified-e-coli-fuses-biology-and-electronics/.

Purnick, Priscilla E. M., and Ron Weiss. 2009. "The Second Wave of Synthetic Biology: From Modules to Systems." Nature Reviews Molecular Cell Biology 10 (6): nrm2698. doi:10.1038/nrm2698.

Rao, Rajesh P. N., Andrea Stocco, Matthew Bryan, Devapratim Sarma, Tiffany M. Youngquist, Joseph Wu, and Chantel S. Prat. 2014. "A Direct Brain-to-Brain Interface in Humans." PLOS ONE 9 (11): e111332. doi:10.1371/journal.pone.0111332.

Smanski, Michael J., Hui Zhou, Jan Claesen, Ben Shen, Michael Fischbach, and Christopher A. Voigt. 2016. "Synthetic Biology to Access and Expand Nature's Chemical Diversity." Nature Reviews. Microbiology 14 (3): 135–49. doi:10.1038/nrmicro.2015.24.

Tingley, Kim. 2013. "The Body Electric." The New Yorker, November 18. https://www.newyorker.com/magazine/2013/11/25/the-body-electric.

Tracy, David. 2016. "Tiny Bacteria Are Eating America's Fighter Jets." Foxtrot Alpha. September 26. http://foxtrotalpha.jalopnik.com/tiny-bacteria-ar-eating-americas-fighter-jets-1786906441.

Walker, Brian, C. S. Holling, Stephen R. Carpenter, and Ann Kinzig, 2004. "Resilience, Adaptability and Transformability in Social-ecological Systems," Ecology and Society 9 (2): 5.

Wang, Xiaojian, Shanqing Xu, Shiwei Zhou, Wei Xu, Martin Leary, Peter Choong, M. Qian, Milan Brandt, and Yi Min Xie. 2016. "Topological Design and Additive Manufacturing of Porous Metals for Bone Scaffolds and Orthopaedic Implants: A Review." Biomaterials 83 (Supplement C): 127–41. doi:10.1016/j.biomaterials.2016.01.012.

Widom, A., J. Swain, Y. N. Srivastava, and S. Sivasubramanian. 2011. "Electromagnetic Signals from Bacterial DNA." ArXiv:1104.3113 [Physics], April. http://arxiv.org/abs/1104.3113.

Zhang, Sarah. 2015. "Cat Eyes and Other Radical Ideas to Re-Engineer Humans for the Future." Gizmodo, May 15. https://gizmodo.com/cat-eyes-and-other-radical-ideas-to-re-engineer-humans-1704511039.