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Documenting Cloud Labs and Examining How Remotely Operated Automated Laboratories Could Enable Bad Actors

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About This Paper

As artificial intelligence (AI) and biotechnology converge, it is important to examine the technologies and organizations at this intersection. Research laboratories that allow for remote execution of experiments and rely heavily on automation, known as *cloud labs*, can be manifestations of this convergence, especially when they incorporate AI-powered technologies and approaches.

In this paper, we provide an overview of cloud lab organizations identified using online and database resources. We then discuss how automated laboratories, such as cloud labs, could enable bad actors in developing and proliferating chemical and biological weapons. This discussion may be of interest to cloud lab organizations and stakeholders in science automation who have responsibilities to inform policymakers about the current state of cloud lab organizations and potential vulnerabilities of the cloud lab model to facilitate the safe and secure development of scientific cloud labs.

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Summary

There is growing interest in the intersection of biotechnology, automation, and artificial intelligence (AI). *Cloud labs*, which are facilities that allow for fully remote, on-demand laboratory experimentation that is highly automated and could include the use of AI, embody this intersection. Cloud labs could promote standardized protocols and data management, contributing to improved reproducibility and open science across numerous topics, such as drug discovery and materials chemistry. They offer the potential for significant advantages, including increased accessibility, scalability, operational flexibility, and the facilitation of collaborative research across geographical boundaries. However, the automation and remote capabilities that define cloud labs also could introduce specific risks, particularly in the context of biosecurity. The decreased reliance on human intervention as AI becomes more integrated into cloud lab systems provides an additional potential vulnerability. The potential for misuse by malicious actors to develop harmful agents used in chemical or biological weapons (CBWs) through these platforms is a notable concern.

In this paper, we used online and database resources to document cloud lab organizations around the world. Our list contains 15 cloud lab organizations located in the United States, Canada, the United Kingdom, Singapore, and the People's Republic of China. We provide specific details about some of the organizations, such as facility size, the number of scientific instruments, location, and the type of science they focus on. However, we are unable to obtain data for all categories for each cloud lab because of a lack of readily accessible, publicly available data. We also discuss how cloud labs could enable bad actors in developing and proliferating CBWs. Although our list of cloud labs is not exhaustive, we show that numerous cloud labs exist around the world and that there are opportunities to reduce the potential for cloud labs to be misused for the creation of CBW agents.

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Chapter 1. Introduction

The National Academies of Sciences, Engineering, and Medicine (NASEM) Artificial Intelligence and Automated Laboratories for Biotechnology workshop in April 2024 showcased cloud labs as an innovation in which biotechnology, automation, and artificial intelligence (AI) converge.[1] The term *cloud labs* entered the modern lexicon in the form of cloud computing, but, in recent years, the experimental sciences have been staking their claim on the term as well. Multiple sets of criteria have been suggested as the characteristics that set cloud labs apart from other organizations. For this paper, we identify cloud laboratories, or simply *cloud labs*, using the definition from the Nucleic Acid Synthesis Screening Framework:

> [a] highly automated research laboratory possessing a diversity of analytical and synthesis capabilities across the life sciences that can be remotely operated by specifying experimental protocols via software.[2]

Cloud labs represent a significant shift in scientific research because they enable researchers to program and conduct experiments remotely. This can democratize access to advanced research tools by increased accessibility. It also offers the promise of accelerating scientific research beyond current human capabilities.[3]

Although cloud labs require the use of on-site human operators, experimental design and higher-level research planning can be done remotely. An example is Emerald Cloud Lab (ECL), a prominent company in the cloud lab industry, which has staff who handle the equipment but any scientist can submit remotely to have experiments completed at the facility, with no travel required.[4] Cloud labs offer several possible advantages, such as increased accessibility, scalability, and flexibility in conducting experiments.[5] Cost may also play a significant role, from reduced costs of starting a lab through cost-sharing to rapid increases in drug discovery lowering drug costs.[6] Researchers can set up experiments, monitor progress, and analyze results without

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[1] NASEM, "Artificial Intelligence and Automated Laboratories for Biotechnology: Leveraging Opportunities and Mitigating Risks: Proceedings of a Workshop—in Brief," 2024.

[2] National Science and Technology Council, Executive Office of the President, "Framework for Nucleic Acid Synthesis Screening," revised September 2024.

[3] D. Sebastian Arias and Rebecca E. Taylor, "Scientific Discovery at the Press of a Button: Navigating Emerging Cloud Laboratory Technology," *Advanced Materials Technologies*, Vol. 9, No. 16, August 21, 2024.

[4] Daniil A. Boiko, Robert MacKnight, Ben Kline, and Gabe Gomes, "Autonomous Chemical Research with Large Language Models," *Nature*, Vol. 624, No. 7992, December 21, 2023.

[5] Arias and Taylor, 2024.

[6] Arias and Taylor, 2024; NASEM, 2024.

being physically present in the lab. This technology enables collaboration among researchers from different locations, streamlines data management, and optimizes laboratory equipment use.[7]

Cloud labs can be roughly divided into two categories based on a lab's level of autonomy: researcher-driven or self-driving (see Figure 1). A *researcher-driven cloud lab* refers to a virtual laboratory environment in which scientists actively control and conduct experiments remotely using cloud-based tools and resources. Scientists use the cloud lab platform as a tool to facilitate their research activities and experiments, but they retain control over the experimental design and decisionmaking processes. These labs are the more mature of the two categories, have existed for longer, and rely on preexisting laboratory automations. Conversely, a *self-driving cloud lab* (SDL) operates with a higher degree of automation and autonomy,[8] and experiments are conducted and managed by AI and advanced algorithms.[9] Several open-access SDL software packages exist, including ChemOS and ARES OS.[10] The SDL coordinates lab equipment operation and therefore replaces the physical presence of scientists in the lab. In an SDL, the system is designed to autonomously execute experiments, analyze data, and make decisions based on predefined parameters and algorithms.[11] Researchers play a more supervisory role in overseeing the overall process and ensuring that the system operates effectively, although, as in all cloud labs, on-site operators may be present to handle manual tasks, such as moving materials and glassware or refilling reagents. Because it is the newer and less mature of the two categories, less is known about the benefits and challenges of using an SDL in lieu of a researcher-driven (or traditional) cloud lab. For example, further research could examine how consistent the results are among different SDLs and what standardization can be implemented.[12]

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[7] Yaser A. Al Naam, Salah Elsafi, Majed H. Al Jahdali, Randa S. Al Shaman, Bader H. Al-Qurouni, and Eidan M. Al Zahrani, "The Impact of Total Automaton [sic] on the Clinical Laboratory Workforce: A Case Study," *Journal of Healthcare Leadership*, Vol. 14, May 9, 2022; Chase Armer, Florent Letronne, and Erika DeBenedictis, "Support Academic Access to Automated Cloud Labs to Improve Reproducibility," *PLOS Biology*, Vol. 12, No. 1, January 3, 2023; Mathew M. Jessop-Fabre and Nikolaus Sonnenschein, "Improving Reproducibility in Synthetic Biology," *Frontiers in Bioengineering and Biotechnology*, Vol. 7, February 10, 2019.

[8] Jiaru Bai, Sebastian Mosbach, Connor J. Taylor, Dogancan Karan, Kok Foong Lee, Simon D. Rihm, Jethro Akroyd, Alexei A. Lapkin, and Markus Kraft, "A Dynamic Knowledge Graph Approach to Distributed Self-Driving Laboratories," *Nature Communications*, Vol. 15, January 23, 2024.

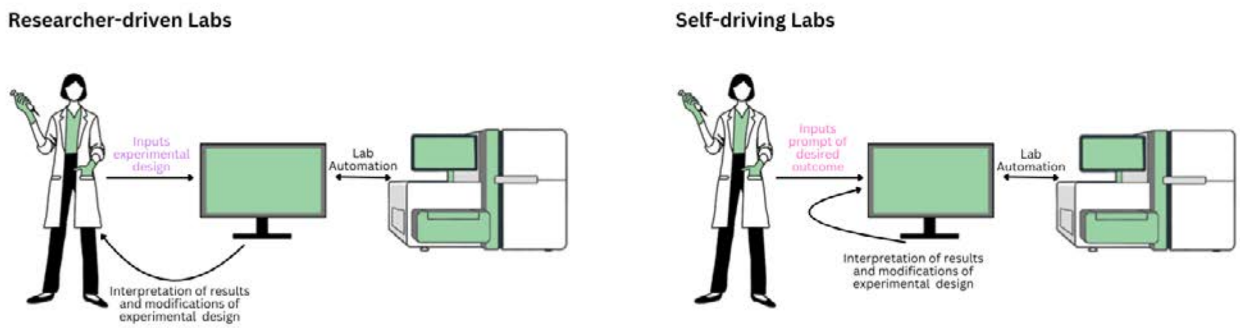
[9] Milad Abolhasani and Eugenia Kumacheva, "The Rise of Self-Driving Labs in Chemical and Materials Sciences," *Nature Synthesis*, Vol. 2, No. 6, June 2023.

[10] Loïc M. Roch, Florian Häse, Christoph Kreisbeck, Teresa Tamayo-Mendoza, Lars P. E. Yunker, Jason E. Hein, and Alán Aspuru-Guzik, "ChemOS: An Orchestration Software to Democratize Autonomous Discovery," *PLOS ONE*, Vol. 15, April 26, 2020; Whitney Wetsig, "Open-Source Software Enables Scientists to Expedite Research," Air Force Research Laboratory, September 15, 2021.

[11] Florian Häse, Loïc M. Roch, and Alán Aspuru-Guzik, "Next-Generation Experimentation with Self-Driving Laboratories," *Trends in Chemistry*, Vol. 1, No. 3, June 2019.

[12] Joshua Steier and Rushil Bakhshi, "Progress or Peril? The Brave New World of Self-Driving Science Labs," *The Hill*, September 17, 2023.

Figure 1. Basic Overview of the Differences Between Researcher-Driven and Self-Driving Laboratories



Multiple cloud lab facilities exist around the world and offer several potential advantages for the scientific enterprise. These include the potential for enhanced reproducibility through standardized protocols and data management, as well as potential opportunities for fostering open science by facilitating collaboration and data-sharing.[13] Parallel workflows consisting of multiple projects that may look at different research questions also allow for the possibility of efficient experimentation within labs with fewer personnel. This allows for a potential increase in throughput and scalability of research output in general. Cloud labs also offer access to advanced lab resources and technologies that researchers may not otherwise be able to access. Finally, cloud labs could become a crucial tool in scientific research, aiding in integrating large datasets, refining measurements, guiding experiments, exploring theoretical spaces, and (particularly with SDLs) creating reliable models for autonomous discovery.[14] Cloud lab services can be a potential force multiplier for scientific research in this regard. That said, critics of SDLs and the use of AI agents in labs (such as Coscientist, an AI agent built by the Gomes lab at Carnegie Mellon University [CMU] to interface with ECL[15]) have noted that researchers using these facilities may have data that could contain unknown flaws or assumptions.[16] It is important with these cloud lab facilities that accurate measurements of uncertainty and error are collected to confirm that there

[13] Steier and Bakhshi, 2023.

[14] Hanchen Wang, Tianfan Fu, Yuanqi Du, Wenhao Gao, Kexin Huang, Ziming Liu, Payal Chandak, Shengchao Liu, Peter Van Katwyk, Andreea Deac, et al., "Scientific Discovery in the Age of Artificial Intelligence," *Nature*, Vol. 620, No. 7972, August 3, 2023.

[15] Boiko et al., 2023.

[16] Boiko et al., 2023.

are no algorithmic biases that could skew data in a way that potentially would not occur if the experiment were run solely by a human.[17]

Despite the opportunities that cloud labs can bring to science, unchecked capabilities could be a source for proximal and future biological risk. Some experts in the biosecurity field have raised concerns that cloud labs and the addition of AI in the lab space present several vulnerabilities.[18] These vulnerabilities could be exploited by bad actors to research and develop harmful biological material in an automated manner without direct actor involvement in laboratory research activities.[19] Cloud lab companies themselves have noted the potential data security risk.[20] This concern was the focus of one of the discussions in the NASEM workshop. Participants emphasized the need for a shared understanding of the biological risks and the development of tools to mitigate them.[21]

Although there is a growing body of information broadly discussing cloud labs and the increasing use of AI in the lab space, there is little detailed information available on what the current cloud lab landscape looks like. In Chapter 2, we start to address this gap by identifying 15 cloud lab organizations from across the globe and attempt to outline key attributes for each (e.g., facility size, instrument number, fields of research). Neither the list of labs nor the list of their attributes is comprehensive because of the lack of information available on these labs. In Chapter 3, we explore how cloud labs could enable bad actors, including through the integration of large language models (LLMs) with cloud labs. In Chapter 4, we summarize the knowledge gaps we found and provide avenues for future research.

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[17] Steier and Bakhshi, 2023.

[18] Cassidy Nelson and Sophie Rose, *Understanding AI-Facilitated Biological Weapon Development*, Centre for Long-Term Resilience, October 18, 2023.

[19] Filippa Lentzos and Cédric Invernizzi, "Laboratories in the Cloud," *Bulletin of the Atomic Scientists*, July 2, 2019.

[20] Automata, "What Are Cloud Labs in Life Science?" *Lab Automation Blog*, July 11, 2023.

[21] NASEM, 2024.

Chapter 2. Notable Cloud Lab Organizations

There is a lack of information regarding the number and types of cloud lab organizations that exist in the world, which can lead to confusion about or underestimation of their spread, capabilities, and growth. Understanding the trajectory of cloud lab development also helps assess the risk of cloud lab misuse. In this chapter, we describe how we used database and internet searches to identify some notable cloud labs and their capabilities. Many of the cloud lab organizations that we document have existed for several years and are in well-resourced countries, yet there is a scarcity of directly accessible, public information on their capabilities and operations.

To identify potential cloud lab organizations, we first examined results from online database searches, using ECL as the root organization for the search. We selected ECL because of its role as a prominent cloud lab, believing that it would be linked to other cloud lab organizations.[22] We then used web searches to expand the scope of our search.[23] We conducted the bulk of our searches from April through September 2024.[24]

The resulting organizations from both the database and web searches were then compiled into a list and subjected to verification according to the definition of a cloud lab introduced in Chapter 1. We then documented the following information for each identified cloud lab organization:

1. location of the organization's headquarters (country)
2. year founded or launched

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[22] Using the PitchBook and Owler business information research platforms, we tracked ECL competitors to two levels from the root search. Each organization name that resulted from the initial *ECL* search term in both PitchBook and Owler was compiled and entered as a new search term within the database. All results in the first-level search and the first five results in the second-level search were documented.

[23] We used web searches to identify cloud labs for scientific research in a non-database-dependent manner. For our targeted web search, we used the following search terms: *scientific research cloud laboratory* and *biological research cloud laboratory*. We included country-specific web searches using the following search terms: *scientific research cloud laboratory [country name]* and *biological research cloud laboratory [country name]* for the top five countries in the Nature Index 2024 Research Leaders list (China, United States, Germany, United Kingdom, and Japan) (Nature Index, "2024 Research Leaders: Leading Countries/Territories," webpage, undated). We also conducted web searches using Mandarin Chinese ("科研云实验室" and "生物研究云实验室," which translate to *scientific research cloud laboratory* and *biological research cloud laboratory*, respectively). All results for organizations from the first page were recorded, removing any repeated results for the same organization and including all sponsored and featured results. News or academic publications were not included unless organizations were directly mentioned in the title. Finally, we conducted an untargeted web search using a variety of cloud lab, automation, and scientific keywords and listed all cloud labs found within articles.

[24] Although we originally identified 14 cloud labs during the April to September 2024 period, one additional cloud lab, the Sustainable Technology and Analytical Research Laboratory at Republic Polytechnic in Singapore, was identified during an untargeted web search in February 2025.

3. scientific discipline
4. general focus area
5. size of the facility
6. number of scientific instruments.

Using the approach outlined previously, we identified 15 example cloud lab organizations around the world. Although these labs are heavily concentrated in the United States, cloud lab organizations also exist in the United Kingdom, Canada, Singapore, and the People's Republic of China (PRC) (see Table 1). These organizations are not all nascent—the majority were founded before 2019, with two founded in 2010. There is also a consensus in the type of science being conducted. From our analysis, 11 cloud lab organizations conduct research in both chemical and biological disciplines, two focus on chemical research, and two focus on biological research. Within these disciplines, the cloud labs that we identified focus on a diverse array of topics, including drug discovery, synthetic biology, biomanufacturing, materials science, chemistry, and organoids.

The cloud labs also vary in terms of infrastructure. According to available data, the smallest facility that we identified is 1,000 ft^2, and the largest is larger than 100,000 ft^2. In addition, we found that three facilities all reportedly have around 200 unique pieces of scientific instrumentation. Although the size of the cloud lab and the unique count of instruments contained within may not correspond directly to its total research capacity, they provide an estimation of what the organization and facility could potentially achieve in total research output. Unique counts of scientific instruments do not reveal how many individual pieces of equipment are present, and facility measurements do not reveal the true laboratory space dedicated to scientific research and production rather than space for non-laboratory use, such as offices. Our data collection effort also revealed one major limitation of our work and the field in general. Metrics on cloud labs can be hard to obtain through publicly accessible sources. Most of the cloud labs in our list are of unknown size and contain an unknown number of scientific instruments. Any expansion projects underway or modifications to initial press releases could change details about the labs, space, and equipment. Future research efforts could include independently confirming and updating these details, such as through interviews or site visits, as well as identifying new cloud lab organizations. Although this was out of the scope of our current effort, confirmation of such details could allow for more-accurate documentation and assessment of cloud lab capabilities.

In the following sections, we provide an overview of three cloud labs, specifying their locations and organizational roots along with details about the facilities. These labs were selected because of the amount of publicly available information; however, even in these cases, the information is scarce and often obtained from company statements.

Table 1. Example Cloud Lab Organizations That Exist Around the World

Name	Country	Year Founded or Launched	Scientific Discipline	Focus Area	Facility Size (ft^2)[a]	Number of Instruments[b]
ECL (Austin, Texas)[c]	U.S.	2010	C/B	General science applications	105,000	230+
Strateos[d]	U.S.	2019	C/B	Drug discovery, synthetic biology	14,000	200
ECL/CMU Cloud Lab (Pittsburgh, Pennsylvania)[e]	U.S.	2021	C/B	General science applications	20,000	200+
Culture Biosciences[f]	U.S.	2018	B	Biomanufacturing	N/A	N/A
Recursion[g]	U.S.	2013	C/B	Drug discovery	N/A	N/A
DAMP Lab[h]	U.S.	2017	C/B	General science applications	N/A	N/A
Kebotix[i]	U.S.	2017	C	Materials	1,000	N/A
Acceleration Consortium[j]	Canada	2021	C/B	Drug discovery, chemistry, materials	N/A	N/A
Arctoris[k]	United Kingdom	2016	C/B	Drug discovery	~23,000	N/A
LabGenius[l]	United Kingdom	2012	B	Drug discovery	4,000	N/A
Digital Innovation Facility[m]	United Kingdom	2010	C	AI scientist development	16,000	N/A
XtalPi[n]	PRC	2014	C/B	Materials, drug discovery	100,000	N/A
镁伽 (Mega/Megarobo)[o]	PRC	2016	C/B	Synthetic biology, drug discovery, organoids	N/A	N/A
Advanced Biofoundry Shenzhen (ABS)[p]	PRC	2020	C/B	Synthetic biology	~19,560	N/A
Sustainable Technology and Analytical Research Laboratory[q]	Singapore	2024	C/B	Agriculture, food technology	3,000	N/A

NOTE: The year founded or launched does not denote exactly when the cloud lab organizations had infrastructure or fully operational facilities. This list is not exhaustive. B = biological; C = chemical; N/A = not available.

[a] Facility sizes may include non-laboratory space.

[b] Some organizations specify instrument number and others specify the number of unique instruments; see the main text for more information.

[c] ECL, "Emerald Cloud Lab to Relocate State of the Art Facility from South San Francisco to Austin," PR Newswire, February 28, 2023.

[d] Strateos is the result of a merger between Transcriptic and 3Scan. See Strateos, homepage, undated.

[e] CMU, "AI for Science," webpage, undated; CMU, "Carnegie Mellon University and Emerald Cloud Lab to Build World's First University Cloud Lab," press release, August 30, 2021.

Name	Country	Year Founded or Launched	Scientific Discipline	Focus Area	Facility Size (ft^2)[a]	Number of Instruments[b]

[f] Culture Biosciences, "About Us," webpage, undated-a; Culture Biosciences, "How It Works," webpage, undated-b; Ginkgo Bioworks, "Introducing Ginkgo's Technology Network," press release, February 28, 2024.
[g] Recursion, homepage, undated-a; Recursion, "LOWE," webpage, undated-b; Alex Knapp, "Recursion Announces New Generative AI Platform to Speed Up Drug Discovery," *Forbes*, January 8, 2024.
[h] Boston University Biological Design Center: DAMP Lab, homepage, undated; Andrew Thurston, "What Happened to the Robots in BU's COVID-19 Testing Lab? They're Getting a New Mission," *The Brink*, November 15, 2022.
[i] Kebotix, "About Us," webpage, undated; Kebotix, "Kebotix Expands with Second Research Lab," press release, July 30, 2020; Kebotix, "Kebotix Selected as Industry Partner for New $15-Million Institute Funded by National Science Foundation," press release, September 28, 2021; Kebotix, "Kebotix Taps Green Chemistry Pioneer John Warner to Bolster Platform Company's Breakthrough AI/ML Capabilities," press release, June 27, 2023.
[j] Tabassum Siddiqui, "U of T Receives $200-Million Grant to Support Acceleration Consortium's 'Self-Driving Labs' Research," press release, April 28, 2023; University of British Columbia, "UBC a Partner on Four New Initiatives Funded by the Canada First Research Excellence Fund," April 28, 2023; University of Toronto Acceleration Consortium, homepage, undated-a; University of Toronto Acceleration Consortium, "Our Vision," webpage, undated-b.
[k] Arctoris, "Arctoris Secures £3.2M," press release, June 12, 2020.
[l] James Field, "LabGenius' £35 Million Series B," Medium, May 21, 2024; Jeremy Kahn, "This Startup Is Using Robots and A.I. to Design New Drugs," *Fortune*, October 29, 2020; Amit Katwala, "AI Is Building Highly Effective Antibodies That Humans Can't Even Imagine," *Wired*, August 9, 2023.
[m] "£12.7m Digital Innovation Hub Opens in Liverpool," Liverpool Business News, May 23, 2022; University of Liverpool Digital Innovation Facility, "About Us," webpage, undated-a; University of Liverpool Digital Innovation Facility, "Autonomous Chemistry Laboratory," webpage, undated-b.
[n] ABB Robotics, "ABB Robotics Partners with XtalPi to Build Intelligent Automated Laboratories," press release, December 13, 2023; Google Cloud, "XtalPi: Accelerating Drug Discovery and Development to Offer More Timely and Affordable Medical Treatments," webpage, undated; XtalPi, "Laboratory Automation: Building an Efficient and Intelligent R&D System," webpage, undated; XtalPi, "Fierce Medtech Names XtalPi as One of Its 'Fierce 15' Med Tech Companies of 2021," press release, March 7, 2022.
[o] Megarobo, homepage, undated.
[p] Shenzhen Institute of Advanced Technology, "Advanced Biofoundry Shenzhen," webpage, June 1, 2020.
[q] Ang Qing, "Republic Poly Opens First Cloud-Based Lab for Agritech in a S'pore Institute of Higher Learning," *Straits Times*, November 25, 2024.

Emerald Cloud Lab and Carnegie Mellon University Cloud Lab

Currently, the largest and most well-established cloud lab is ECL in the United States. ECL was founded in 2010 with $100 million invested in the technical development of its own platform over ten years.[25] Although ECL formerly had a South San Francisco, California, location, it is now spread over two locations that we organize in this paper as separate cloud lab organizations. The ECL facility in Austin, Texas, covers more than 105,000 ft^2 and contains more than 230 types of scientific instruments.[26] In 2021, ECL partnered with CMU in Pittsburgh, Pennsylvania, to build the CMU Cloud Lab. The CMU Cloud Lab cost $40 million to construct, covers 20,000 ft^2, and houses more than 200 pieces of equipment.[27]

Although there is a lack of public data on the research capacity of cloud labs, company statements offer an overview of potential operational advantages.[28] ECL compares its services with those of traditional contract research organizations (CROs), which provide research in a fee-for-service model, and other research settings.[29] Although we were not able to find figures that show distinctions of the ECL Austin campus or CMU Cloud Lab facilities, ECL reports that it can process 155,400 analytical samples per year at the highest capacity level, which considers the number of simultaneous experiments that can be run in parallel, compared with 22,000 for CROs. ECL estimates that the time to first publication of quality data is three months in a traditional academic lab but decreases to 24 hours with the use of ECL's cloud lab services. In addition, ECL claims that the time to publish a single paper decreases from 1.96 years in a traditional lab to one year with help from a cloud lab. ECL claims that experiments in the cloud lab start within 24 hours of being submitted, enabling easy and quick access to instruments. Additionally, it states that organizations that use cloud labs show "documented productivity improvements in the 300% to 700% range" and that its system provides "push-button reproducibility" and maintains the accessibility of data by capturing them digitally and automatically.[30] Overall, the ECL facility in Austin and the CMU Cloud Lab are two of the most well-characterized and well-reported cloud lab organizations that articulate the potential for instrumentation accessibility and efficiency in executing experiments at cloud labs.

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[25] CMU, 2021.

[26] ECL, 2023.

[27] CMU, undated; CMU, 2021.

[28] Much of the information on ECL's research capacity is directly sourced from company statements and, to our knowledge, has not been independently confirmed.

[29] ECL, "Efficiency," webpage, undated.

[30] ECL, undated.

Advanced Biofoundry Shenzhen

The PRC is home to several cloud labs, including one in Shenzhen that is focused on synthetic biology research. In 2018, Guangming District (光明区) was formally established in the southeastern city of Shenzhen, a major hub for scientific and technological development within the PRC.[31] Within Guangming, the Guangming Science City occupies 99 km^2 (about 38 mi^2) and houses the PRC's first cloud lab, ABS. Construction of the ABS lab was led by the Shenzhen Institute of Advanced Technology, along with support from BGI and Shenzhen's Second People's Hospital, and it is part of the Guangming Life Science Park.[32] ABS's plan was to focus on synthetic biology in a transformative approach using the cloud lab format and to be open for use by academics and industry, much like its counterparts in the West. Using publicly available documents, we estimate the ABS cloud lab facility to be approximately 19,560 ft^2.[33] This is similar to the size of the CMU Cloud Lab facility in the United States. However, these details do not indicate the experimental capacity of the facility and exact nature of experiments conducted at ABS. According to the same news article, ABS, which is either part of or also known as the Infrastructure for SynBio, and the nearby brain science research building contain more than 1,800 pieces of equipment and support 100 researchers in total. However, we were not able to find information detailing the specific types of equipment or the current research capacity specifically for the cloud lab itself.

[31] Guangming Government, "About Guangming," webpage, undated.

[32] Shenzhen Institute of Advanced Technology, 2020.

[33] See the appendix for our approach to estimating the size.

Chapter 3. How Cloud Labs Might Enable Threat Actors

With the implementation of LLMs as tools interfacing with cloud labs, researchers may become better able to translate experimental ideas into experiments within simulated laboratory environments for the users' needs and subsequently in real-world laboratories.[34] Cloud labs allow for shared analytical systems with LLMs to decide how to design and conduct experiments and modify their outcomes in subsequent phases.[35] Although this interface may enhance the efficiency and scale of scientific discovery, the presence of autonomous AI agents (the AI that runs and designs the experiments in SDLs) could lower the barriers to nonexpert actors and increase the risks associated with cloud labs.

Cloud labs could expand access to more forms of scientific experimentation to more individuals and groups.[36] Although this may have many beneficial effects for science and society, it may also enable nefarious actors. In this chapter, we first explore how this expansion affects research. We then provide an overview of how cloud labs can be an enabling technology, examine the characteristics of threat actor groups that might limit their abilities, and discuss how cloud labs might expand or inhibit access to groups with those capabilities compared with other research organizations.

How Self-Driving Cloud Labs and Their Autonomous Artificial Intelligence Agents Influence Research

ChemCrow and Coscientist are semiautonomous AI agents that demonstrate that LLM-based agents can use domain-specific tools. ChemCrow interprets natural language instructions, such as "synthesize ibuprofen."[37] Coscientist, which is based on multiple LLMs and can design, plan, and perform experiments, has demonstrated the ability to execute high-level commands in a cloud lab, write code for robotic liquid handlers from low-level instructions, work on complex scientific tasks that depend on the simultaneous use of multiple hardware modules, and solve

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[34] Jason Wallace, "Cloud Labs + AI: The New Digital Workflow," *Emerald Cloud Lab Blog*, May 18, 2023.

[35] Rita Cardoso, Kristian Kinscher, Tobias Ruof, Ahsan Saeed, Ulf Schrader, and Julius Seitter, "From Bench to Bedside: Transforming R&D Labs Through Automation," McKinsey & Company Life Sciences, March 8, 2023.

[36] Nataliia V. Valko, Nataliya O. Kushnir, and Viacheslav V. Osadchyi, "Cloud Technologies for STEM Education," *CEUR Workshop Proceedings*, Vol. 2634, December 20, 2019.

[37] Andres M. Bran, Sam Cox, Oliver Schilter, Carlo Baldassari, Andrew D. White, and Philippe Schwaller, "ChemCrow: Augmenting Large-Language Models with Chemistry Tools," arXiv, arXiv:2304.05376, October 2, 2023; Sarah R. Carter, Nicole E. Wheeler, Sabrina Chwalek, Christopher R. Isaac, and Jaime Yassif, *The Convergence of Artificial Intelligence and the Life Sciences: Safeguarding Technology, Rethinking Governance, and Preventing Catastrophe*, Nuclear Threat Initiative, October 2023.

optimization problems using experimental data.[38] Although autonomous AI agents may enhance the efficiency and scale of scientific research, their ability to interface with cloud labs, which carry out experiments with less involvement from scientists, could allow them to assist actors in fleshing out experimental plans and obtaining dangerous materials that may not be on any screening list. SDLs, including those that are cloud labs, are part of a nascent but growing field. Thus, risks stemming from autonomous AI agents that implement research operations at SDLs may change as this technology matures.

Cloud Labs as an Enabling Technology

The actual impact of cloud labs on risk will depend on the trajectory that the technology takes, as well as the policies and policy implementations that are adopted by governments, industry bodies, and individual labs. There may be ways in which cloud labs could reduce risks, such as by centralizing experimentation and offering an avenue for oversight; however, these opportunities raise the question of how to best leverage them ethically in a way that does not interfere with researcher independence and privacy.

The question of whether cloud lab providers could enable actors to produce agents used in chemical or biological weapons (CBWs) that they otherwise could not or would not have produced is a nuanced one. There are many chemical and biological agents, and they differ greatly in terms of the resources required to successfully produce and deploy them. Using the term *actors* to denote both individuals and groups, including large and well-resourced terrorist organizations, there are many possible scenarios in which a rise in the operational capacity and ubiquity of cloud lab service providers around the world might help enable such actors to acquire a CBW agent.[39] The two characteristics unique to cloud labs—remote access and increased automation—are potential vulnerabilities that might be exploited.[40] Without appropriate controls, cloud labs that are focused on scientific research might be used to facilitate the early stages of a CBW development program. However, the overall process of perpetrating large-scale harm with a CBW agent contains many steps.

Furthermore, if a given actor could produce a CBW agent but it would take a high percentage of their time and resources, or it would take a long time to develop a working product and be able to attack, then they might elect not to produce such an agent. However, if cloud lab organizations alter the landscape such that this development would take less time and fewer resources, the same actor might then choose to pursue chemical terrorism or bioterrorism. Similarly, if a terrorist organization that had the resources to try to develop only one CBW agent in a non–cloud lab paradigm would have the resources in a cloud lab paradigm to try developing

[38] Boiko et al., 2023.

[39] See the next section for an explanation of why we focus on non-state actors.

[40] To our knowledge, there have been no publicly documented biosafety or biosecurity incidents at cloud labs.

several CBW agents at once, this would increase the chance of the organization developing at least one functional CBW agent.

Actor Attributes

We frame this section from the angle of a non-state actor instead of a state actor, with the assumption that state actors would have the necessary resources to conduct their own CBW research, whereas a non-state actor may be more likely to lack such resources and thus potentially see cloud labs as a viable avenue for researching and acquiring dangerous agents. Non-state actors have a wide variety of relevant actor attributes, such as group size, financial resources, access to scientific equipment, time constraints, expertise in each relevant scientific or technical domain (including tacit knowledge), connections, location, creativity, ideology, and willingness to get caught or incur harm to self or to members of the group.[41] Actors may also vary in terms of ability to execute in accordance with their goals (for example, an individual foiling their own plot by bragging about it or a group failing to realize an outcome because of poor internal coordination). The combination of these attributes determines what an actor can achieve. For example, a group lacking domain expertise might be able to make up for it if they have the financial means to pay unwitting external experts. The peak of what bad actors can achieve depends not only on their attributes but also on the state of the world. Some key characteristics of cloud labs may change the research landscape in ways that could make chemical or biological terrorism in reach for actors with more-common combinations of attributes.

Aspects of Cloud Labs Compared with Contract Research Organizations That Enable or Inhibit Bad Actors

It is not straightforward to make a statement on the CBW risks of cloud labs relative to other organizations, such as traditional CROs. This is due to the lack of a perfectly clear and widely agreed-on definition of what constitutes a cloud lab outside the one provided in Chapter 1, as well as the increasing blur between cloud labs and other research organizations. For example, whereas ECL customers perform their own automation engineering, Strateos's 2022 operating model had all automation engineering being performed by professionals. This difference in operating models led some experts to term Strateos a "robotic CRO" rather than "a company that provide[d] access to 'programmable experiments' broadly."[42] Given that there is so much nuance to organizations' technical and commercial setups, it may be beneficial to investigate how each

[41] W. Seth Carus, "Bioterrorism and Biocrimes: The Illicit Use of Biological Agents Since 1900," working paper, National Defense University, revised February 2001.

[42] Chase Armer, S. Goals, T. Kalil, and E. DeBenedictis, "Barriers to Academic Use of Commercial Cloud Labs," *Online Journal of Robotics and Automation Technology*, Vol. 1, No. 3, July 28, 2022, p. 3.

of the proposed characteristics of cloud labs could contribute to vulnerabilities or enable threat actors,[43] then assess the vulnerabilities and risks presented by organizations on a case-by-case basis. Here, we provide a preliminary exploration of how characteristics might contribute to risk.

The extent to which a cloud lab increases accessibility depends on implementation details, including its pricing model. Proponents of cloud labs claim that with "an annual subscription that often costs less than a single laboratory instrument, scientists can . . . [use] more than 200 unique pieces of instrumentation."[44] However, it has been argued that pricing models that have been developed with industry customers in mind are prohibitive to potential academic customers.[45] Individual cloud labs may vary significantly in how automated and accessible they are. The cloud lab ecosystem as a whole has achieved only a certain degree of automation and accessibility, but it seems likely to offer more in the future.

Cloud labs are not the first labs to feature automation or fee-for-service availability, although they are likely the first to combine fee-for-service availability with such extensive automation and fine-grained customer control of experiments. There are private labs and traditional, non-cloud-lab CROs (cloud labs themselves may be a type of CRO, depending on their operating model). CROs vary in terms of their level of automation. Some CROs (often called *niche traditional CROs*) focus on a narrow range of experiments and procedures. It has been argued that cloud labs, conversely, will benefit from being more of a one-stop shop in terms of comprehensive experimentation and sample preparation.[46] This could magnify CBW risk. Although it may, in principle, be possible for a bad actor to interface with many different traditional CROs to piece together all the necessary steps of a design, build, test, and learn cycle, having all the necessary elements in one place could make sending the order to a cloud lab a more practical alternative. More work is needed to define terminology to easily convey how automated a given cloud lab is or how broad its experimental offerings are. Doing so would enable a comparison of the breadth of experiments available at cloud labs with those available at full-service traditional CROs.

Using cloud lab facilities and tools, actors may require less of their own scientific equipment and subject-matter expertise. An actor will not have to worry about injuring oneself during the research and development process if this is performed by a cloud lab. The ability of autonomous agents and cloud lab robots to execute many steps may also lower the need for coordination and execution ability, and the one-stop-shop nature of cloud labs could decrease the need for connections to many separate traditional CROs. The extent to which cloud labs might lessen financial burden will likely change over time and will depend on the particulars of cloud lab

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[43] Tony Blackburn, "5 Criteria of a True Cloud Laboratory," Drug Discovery & Development, February 25, 2022a.

[44] Blackburn, 2022a.

[45] Armer et al., 2022.

[46] Tony Blackburn, "What Are the Criteria of a True Cloud Laboratory?" Drug Discovery & Development, March 16, 2022b.

policies. For example, if a cloud lab requires a pay-per-period service as opposed to a pay-per-experiment service, that may be prohibitive to a greater number of actors.

Two types of time can be relevant to bad actors: the number of person-hours that must be devoted to a project and the time from project start to completion. The automation and parallelization offered by cloud labs may lead to reductions in both. Reducing the number of person-hours necessary might enable small groups. It may also free up groups to work on a greater number of nefarious projects. Reducing the time to project completion could facilitate weapon development during a brief period of rash decisionmaking that could have faded with time. It could also give authorities less time to detect and foil schemes. This could be a concern if sufficient oversight of cloud lab organizations is not realized and if channels for reporting suspicious activities to authorities are not leveraged.

Finally, cloud labs offer actors the ability to pay for geographically distant production of biological materials in a way that might be (now or in the future) easier for the actors to access than working with multiple traditional CROs. Geographically distant production could potentially lower the burden of some steps in the CBW risk chain, such as storage, transport, and deployment. It could appeal to non-domestic terrorist groups that want to create a CBW on domestic soil.

Chapter 4. Conclusion

Despite the growing interest in the policy implications of the intersection between AI and biotechnology, very little information is available on one of its growing areas: cloud labs. However, cloud labs could potentially be exploited by bad actors to enable experimentation and acquisition of CBW agents. Thus, documenting cloud labs and highlighting how they could enable bad actors could contribute to further research and actions toward mitigating possible cloud lab risks. In this paper, we used a combination of web and database searches to identify 15 cloud lab organizations. Although our search is not exhaustive and may not capture all cloud lab organizations, it provides a starting point for future work. These cloud labs are generally focused on biological and chemical research topics, such as drug discovery and synthetic biology. Although we provide detail on the facility size and the number of instruments that these labs contain, the information is not readily available for a majority of organizations. Thus, conclusions about research capacity and potential for future growth are difficult to draw without a large margin of error. The available data about cloud labs are highly variable; some labs are more open than others with details about their instruments, size, and scale. Data on the budgets of these cloud lab facilities, their average user numbers, the size of their staff (and specifically for SDLs, how often that staff intervenes in an experiment), and the speed and efficacy of creating chemical and biological products would be helpful for identifying potential vulnerabilities, assessing risks, and proposing mitigations.

Our list of cloud labs could be the starting point for efforts to construct a more detailed picture of the status of the labs and organizations. For example, cloud labs could be privately run or affiliated with academia, cater to different customer types, or differ in the degree to which humans are involved. More information could help accurately identify and classify types of cloud labs. We welcome others to build on our work.

Additionally, we have discussed concerns that may arise during the operation of cloud labs and how cloud labs could enable misuse by threat actors to create CBW agents. As the model for scientific cloud lab research continues to grow, increased awareness of security concerns related to automated, remote research could help prevent misuse while capitalizing on their potential benefits. Cloud labs are becoming more numerous, and there is an opportunity now to help reduce their potential to be misused for the creation of CBW agents. Future work can explore what types of mitigations are likely to be effective and how such mitigations could be implemented.

Appendix. Estimation of Advanced Biofoundry Shenzhen Facility Size

A contract to Kebei Technology for the buildings that occupy Science Park, where ABS is housed, details 19,985 m^2 (215,119 ft^2) of laboratory space;[47] however, a bid notification from Shenzhen Das Intellitech for a computing platform project worth more than 245 million Chinese yuan for the same park reveals the physical space that the ABS cloud lab potentially occupies.[48] According to Shenzhen Das Intellitech, the fourth and fifth floors cover a total of 3,634 m^2 (39,116 ft^2), or 1,817 m^2 (19,558 ft^2) per floor, and a news article indicates that the cloud lab within ABS is located on the fourth floor of a 14-floor building.[49] Taken together, the true physical space for the ABS cloud lab is likely 1,817 m^2 (approximately 19,560 ft^2).

[47] Kebei Technology, "Shenzhen Bright Science City," webpage, undated.

[48] Shenzhen Das Intellitech, "Das Intellitech Wins Bid for Guangming Life Science Big Data Center Project!" August 25, 2023.

[49] Shenzhen Government, "Guangming Science City: Tech Hub Rises from Former Farmland," September 7, 2023.

Abbreviations

ABS	Advanced Biofoundry Shenzhen
AI	artificial intelligence
CBW	chemical or biological weapon
CMU	Carnegie Mellon University
CRO	contract research organization
ECL	Emerald Cloud Lab
LLM	large language model
NASEM	National Academies of Sciences, Engineering, and Medicine
PRC	People's Republic of China
SDL	self-driving cloud lab

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