Summary Report of the National Summit on the Science and Technology of Epidemiological Modeling and Prediction

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and

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A. Organization of This Report

The White House Office of Science and Technology Policy (OSTP) asked the Science and Technology Policy Institute (STPI) to support the National Summit on the Science and Technology of Epidemiological Modeling and Prediction (Summit), which was held in a virtual format on November 12–13, 2020. The goal of the Summit—which was co-organized by the National Science Foundation (NSF), Centers for Disease Control and Prevention (CDC), Intelligence Advanced Research Projects Activity (IARPA), and OSTP—was to stimulate discussion across multiple relevant disciplines and stakeholder groups regarding a national research and development (R&D) roadmap for epidemiological modeling and prediction.

The order of the summaries follows the order of the Summit's agenda. The Summit began with a topical overview from the OSTP Director, perspectives from each of the Summit's co-organizers, and a keynote presentation. The Summit's next three sessions focused on model capabilities, data, and modeling strategies and output generation, respectively. Each session included introductory presentations, breakout discussions, and breakout reports. This report includes highlights from every component of each session and concludes with a summary of common themes that emerged throughout the Summit and how these insights can benefit the Nation going forward.

B. Summit Introduction

To maximize America's ability to respond to infectious disease outbreaks and threats posed by the intentional or accidental release of biological agents, researchers, policy makers, and many others are working to improve national capacity and capability in epidemiological modeling and prediction. As a result of this work, advances in epidemiological modeling and prediction are occurring across the science and technology (S&T) enterprise, including within industry, academia, non-profit foundations, and government agencies. Collectively, these efforts produce actionable knowledge that can strengthen our Nation's safety, security, and economic prosperity.

NSF, CDC, and IARPA, in coordination with OSTP, organized a Summit to support these efforts and to help our Nation address future challenges more effectively. The Summit brought together researchers and end user practitioners from multiple disciplines, across all sectors of the S&T ecosystem, to discuss challenges and opportunities.

Held virtually on November 12–13, 2020, the Summit stimulated discussion around a new national R&D roadmap for epidemiological modeling and prediction. Throughout the Summit, participants expressed individual views regarding ways of (a) maximizing America's ability to respond to infectious disease outbreaks and threats posed by the intentional or accidental release of biological agents; (b) improving national capacity and capability in epidemiological modeling and prediction; and (c) identifying actions for a national R&D roadmap for epidemiological modeling and prediction. Appendix A contains the complete Summit agenda.

C. Overview and Perspectives of the Summit

1. Overview

Kelvin Droegemeier, Director, OSTP: Dr. Kelvin Droegemeier noted that he learned during discussions with experts in the early stages of the SARS-CoV-2 pandemic that coordination of modeling efforts could be improved, and that data usability is a key issue. Specifically, epidemiological data come from a wide array of public and private sources, are not generally collected on a continuous basis across all need areas, locations, and organizations in consistent formats, have varying levels of reliability and accuracy, and are associated with issues regarding privacy, security, and ownership. Academia has been supporting the Federal Government pandemic response effort by running models and providing associated output, but these efforts typically are not funded, with the exception of existing investigator grants for which funding was redirected from research to response support. Dr. Droegemeier also identified a need for a persistent infrastructure for infectious disease prediction, not unlike that currently in place for weather surveillance and forecasting, given that diseases are ever present even though pandemics are, fortunately, rare.

Dr. Droegemeier stated that the ultimate goal is to create a whole-of-Nation strategy that incorporates public and private sectors, data and security issues, real-time monitoring and surveillance, and continuous prediction to maximize our Nation’s ability to identify and respond to infectious disease outbreaks. This strategy will generate useful outcomes, such as R&D model development and operational prediction capabilities, and will encompass distribution, communications, and outreach. Dr. Droegemeier closed by informing attendees that the Summit was focused on the science and technology of epidemiology and modeling and prediction—not on policy.

Michael Schmoyer, Assistant Director for Health Security Threats, OSTP: In his remarks, Dr. Michael Schmoyer, OSTP, thanked Summit attendees for participating and gave a brief overview of the meeting agenda.

2. Co-Organizer Perspectives

Representatives from the agencies co-organizing the Summit—CDC, IARPA, and NSF—shared their views on the utility of models and challenges facing their optimal use. The speakers offered examples of how epidemiological modeling contributes to the mission of their agencies, ongoing challenges associated with data, and a desire to help stakeholders work together more effectively.

Dr. Brian Moyer, Director of the National Center for Health Statistics, CDC: Dr. Moyer emphasized that multidisciplinary dialogues are critical to improving epidemiological modeling and implementing recommendations ascertained from model results. He then discussed how emerging data sources require new methods of data curation and new models to best incorporate those resources. In particular, Dr. Moyer observed that access to real-time electronic health records (EHR) represents a new frontier. In the same way that real-time credit card transaction data enabled *nowcasting* in the realm of gross domestic product (GDP) modeling, EHR access might allow rapid responses to emerging crises. To conclude, Dr. Moyer discussed recent Federal efforts to support advances in epidemiological modeling to enable transformative change in decision-making processes. Specifically, he highlighted the recent Federal Data Strategy[1] that illustrates the government's commitment to the greater use of data in policy making.

Dr. Kristen Jordan, Program Manager, IARPA: Dr. Jordan discussed why infectious diseases are a risk to national security. She noted that after the 9/11 terrorist attacks, biological warfare connoted the deliberate use of disease as a weapon. The SARS-CoV-1 and Ebola outbreaks demonstrated that even naturally occurring pathogens pose a threat to national security. Dr. Jordan discussed IARPA's multi-disciplinary programs in modeling and prediction, including the Aggregative Contingent Estimation[2] and Open Source Indicators[3] programs, which focus on probabilistic forecasting for geopolitical events and provide an early warning system for societal events, including disease outbreaks, respectively. Finally, Dr. Jordan noted key questions to the Summit participants: How do we invest in the state-of-the-art modeling and predictive analytics? What do we want to get out of our models, and how does that shape how we design those models?

Dr. Arthur Lupia, Assistant Director, NSF: Dr. Lupia discussed the power of models within epidemiology and reiterated that models help close gaps between "our observations and our aspirations." He also discussed the utility of models in analyzing large-dimensional spaces and huge numbers of scenarios. Further, he suggested that models can uncover causal links between factors that would not otherwise be apparent. He emphasized that models must produce rigorous, precise, and explainable outcomes in order to be usable by decision makers. Dr. Lupia then discussed how NSF tries to help by supporting research in all fields of science and engineering, and emphasized the importance of social and behavioral sciences within that effort.

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[1] https://strategy.data.gov/assets/docs/2020-federal-data-strategy-action-plan.pdf

[2] https://www.iarpa.gov/index.php/research-programs/ace

[3] https://www.iarpa.gov/index.php/research-programs/osi

D. Keynote: "Real-time Pandemic Preparedness and Response: State of the Art and New Opportunities"

Dr. Madhav Marathe is a Professor of Computer Science and Distinguished Professor in Biocomplexity at the University of Virginia. Dr. Madhav Marathe is also a Division Director of Network Systems Science and Advanced Computing in the Biocomplexity Institute.

Dr. Madhav Marathe discussed advances in computational epidemiology, challenges in building and applying large-scale models, the use of artificial intelligence (AI) and high-performance computing for epidemiological modeling and decision support, and considerations for developing future strategies.

Dr. Marathe identified specific data- and modeling-related challenges in building and applying large-scale models. He noted that, in some cases, large amounts of data are not available or challenges exist in integrating and synthesizing datasets. A need also exists for models to capture heterogeneity and have multiscale capabilities. In addition, Dr. Marathe noted that models of human immune systems and viral phylodynamics are needed. Reducing uncertainty, such as when modeling human behavior or the impacts of human behavior, would also be helpful.

To enhance the Nation's future modeling capacity, Dr. Marathe recommended additional timing and location detection mechanisms, improved ability to anticipate public reactions, and the development of actionable and targeted interventions. Dr. Marathe also highlighted potential benefits of better distribution of real-time data collections, increased computational and data resources, and clearer communication about how to use model outputs. By taking these actions and coordinating more effectively with decision makers, the Nation can produce more pervasive, personalized, and precise analytics that can inform essential actions.

E. Model Capabilities

This panel identified needs and challenges associated with epidemiological modeling capabilities, as well as research and development opportunities that could accelerate the field. Participants also explored existing modeling cross-sector partnerships and described potentially relevant emerging technologies that could be leveraged during breakout sessions.

1. Panel Session 1 – Model Capabilities

Dr. John Drake, University of Georgia: *Dr. John Drake is a Distinguished Research Professor, Associate Dean for Academic Affairs, and the Director of the Center for Ecology of Infectious Diseases at the University of Georgia Odum School of Ecology. His research focuses on population dynamics, epidemiology, and computational ecology* *including forecasting tipping points in emerging and reemerging infectious diseases, and studying global patterns, predictors, and their consequences in mammalian zoonotic diseases.*

Dr. Drake's research team developed parametric and semiparametric SARS-CoV-2 models to predict how human behavior would affect SARS-CoV-2 spread. Specifically, he used models to predict disease spread under the scenario of a return to normal human movement, if social distancing were maintained, and if social distancing were increased. Dr. Drake showed how different behaviors correlated with increased or decreased case counts, such as how an increase in social distancing could reduce SARS-CoV-2 case numbers. He also identified modeling constraints that SARS-CoV-2 research revealed, specifically difficulties with integrating data from multiple scales, translating human behavior into transmission models, and obtaining data from State, county, and municipal sources.

Dr. Drake also highlighted the need for an infectious disease intelligence system, inspired by weather systems, wherein phased, action-based approaches are utilized. Specifically, a multi-tier system of statements concerning infectious disease risk should include watch, warning, and emergency response phases in analogy to the severe weather terminology used by the National Weather Service. To support such a system, data sharing in real time would be necessary, along with standard practices in data sharing, storage, and cleaning.

Dr. Michelle Hawkins, National Oceanic and Atmospheric Administration (NOAA): *Michelle Hawkins is Chief of the Severe Fire, Public, and Winter Weather Services Branch of the National Weather Service and an experienced atmospheric scientist.*

Dr. Hawkins provided an overview of NOAA, a Federal agency that is charged with understanding and predicting changes in climate, weather, oceans, and coastal activities. NOAA has been working to sustain engagement with user communities. NOAA is also collaborating with social, behavioral, and economic scientists to understand end user needs, risk and impact, and how to better communicate probabilistic information. Dr. Hawkins noted that advances in technology, such as use of cloud services, AI, and supercomputing, are essential to advancing prediction. Working collaboratively across Federal agencies, and State and local governments, is also required to advance modeling capabilities. Future opportunities include improving predictions in the seasonal-to-subseasonal timeframe, making use of an Earth system science approach, improving data assimilation, leveraging AI and cloud solutions, and improving understanding and linkage to the work of social sciences.

Dr. Aaron King, University of Michigan: *Dr. Aaron King is the Nelson G. Hairston Collegiate Professor of Ecology, Evolutionary Biology, and Complex Systems at the University of Michigan. His research focuses on the dynamics of ecological,* *epidemiological, and evolutionary systems and on powerful methods for inferring the properties of such systems from data.*

Dr. King warned that efforts to develop complicated models that aimed to represent an epidemiological system faithfully in all its complexity are doomed to fail. Rather, he suggested that models should be viewed as instruments such as lenses, focusing the information latent in data to resolve outstanding uncertainties. As such, some of the most critical issues surround questions of model identifiability (i.e., whether the data contain sufficient information to estimate model structure and parameters). In particular, the key challenges are in constructing models that can be estimated on the basis of available data and collecting the new data needed to estimate crucial model parameters. Dr. King illustrated this by describing how pandemics predictably unfold in phases, with different modeling needs and challenges in each phase.

In the early, exponential phase, uncertainties are many and large and the data are few and biased. There is a need, therefore, for investment in unbiased population surveillance, even at the expense of some clinical effort. Genomic surveillance can be an important supplement to more traditional epidemiological incidence time series data in this phase, the latter alone being of extremely limited utility.

In the middle phase, when heterogeneities in transmission begin to manifest themselves and the epidemic must be controlled by limiting transmission, models need to inform adaptive outbreak management. In this phase, key non-identifiabilities are associated with human behavioral changes and their relationship to transmission and public health policy. Sewage testing, serological surveys, and monitoring for asymptomatic infections are indispensable during this middle phase, as are data on the movement of individuals at regional and intra-urban scales.

In the late phase—when vaccines and/or effective control or treatment strategies exist—the most useful role of models, in guiding the optimization of resource allocation, is very different. Finally, with an eye to the next pandemic, Dr. King identified the need to build, integrate, streamline, and maintain infrastructure in the form of national epidemiological, serological, and genomic surveillance databases, which will support model development and deployment in all pandemic phases.

Dr. James Stock, Harvard University: *Dr. James Stock is a Harold Hitchings Burbank Professor of Political Economy at the Harvard Kennedy School. His research areas are empirical macroeconomics, monetary policy, econometric methods, and energy and environmental policy.*

Dr. Stock noted that data in a pandemic need to be captured and applied quickly, which runs counter to the longer-term focus of many economics studies. He then described how infections affect, and are affected by, consumer behavior. Better maintenance of weekly economic data, increasing interdisciplinary work between economists and epidemiologists, and increasing watch and warning data would help improve economic modeling during a disease outbreak. Standardization of datasets also would facilitate utilization and collaboration between economists and epidemiologists.

2. Breakout Session 1 – Model Capabilities

Participants identified emerging technologies that could improve U.S. epidemiological modeling as well as partnership opportunities that would fill unmet needs. Conversations focused on current R&D opportunities, existing partnerships, and frontier opportunities and non-traditional approaches to epidemiological predictions. Several themes emerged from the discussion.

Data standardization is critical for model development and use. Participants noted that large swaths of data exist both in the public and private sector, but those data are not accessible and usable in ways that are conducive to epidemiological modeling. Developing standards for data generation, storage, and management can increase the usability and interoperability of data and contribute to generation of new epidemiological models and tools that would increase U.S. modeling and forecasting abilities.

Barriers to accessing public health data prevent optimal model development and verification. Specifically, participants noted that many public health districts do not share health data due to privacy concerns, and that navigating data acquisition is difficult under the current framework. Participants suggested that mechanisms be established to provide health districts and health providers ways to share data that are usable for research purposes while maintaining privacy. Participants experienced similar challenges in accessing and operationalizing potentially useful private sector data, such as from Facebook and Google.

The Nation needs a coordinating hub to manage modeling efforts. This hub would include a centralized data management and data storage component as well as an organization of existing models. It would serve as a repository for existing public health and health services data and could facilitate data standardization mechanisms across fields. Through activities including conferences and similar events, the hub would coordinate modeling efforts across academia and public services and integrate modeling efforts across sectors. Participants recommended the U.S. Government establish this coordinating hub and provide incentives for researchers to participate.

To develop more useful models and related tools, end users should be engaged at earlier stages of design. Such engagement would help model developers understand how models are (and are not) being used, which would inform the development of new models. Learning about end users' needs clarifies the types of models and model outputs that best inform essential actions.

Participants noted that to instill trust and enable nuanced decision making based on models, long-term relationships between subject matter experts and decision makers are necessary. Decision makers will trust and have a better understanding of the limits and uses of models if they are able to examine model output regularly, not only in times of crisis. Participants suggested continuing to maintain the many relationships established before and during the SARS-CoV-2 pandemic to ensure they remain a continuing priority.

Many participants also commented on the need to better define the goals and timeframe for prediction both among model users and developers. Participants discussed "How much lead time should predictions provide?" and noted that it is often more expensive to build models that can produce faster responses. Monitoring frequent spillover events[4] may not be feasible; however, surveillance of pathogens with limited human transmission may be within reach. One suggestion for pathogen monitoring was a global serological observatory to monitor novel circulating viruses in animal reservoirs that have the potential to transmit to humans.

Coordination with other fields is critical to modeling success. Participants noted that other disciplines may provide insight for how to better create and leverage AI and machine learning (ML) applied to epidemiology. Examples include integrating lessons learned from meteorological and ecological predictions, and predictions created for other diseases. Several participants noted the importance of including social scientists in epidemiological modeling and prediction to better understand how societal and real-life factors feed into model capability. Social scientists could help modelers understand how human behavior changes over time and identify effective ways to communicate model capabilities to end users. Furthermore, social scientists could help develop scenario-based models that would help modelers understand how model output contributes to human decision making. Coordination with social scientists also was suggested to improve communication of model output, especially with regard to uncertainty quantification. Increased understanding of model capabilities and uncertainties would help users better understand risks and uncertainties associated with model forecasts.

Another discussion centered on the need to more effectively coordinate models across different fields of science. For instance, coordinating epidemiological and economic models may help better inform options for mitigating the spread of a disease in the context of potential costs of associated actions.

AI uses and limits for epidemiological modeling should be defined. Participants discussed the persistence of uncertainty related to the definition of AI. Participants expressed the need for clarity regarding specific applications for which AI is being proposed. Up until this point in the pandemic, AI has been used primarily for short-term predictions, though it has far greater potential in infectious disease modeling.

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[4] Spillover events are events during which humans are infected by pathogens from animal reservoirs.

The use of AI and ML should be carefully considered. A robust conversation considered the most appropriate and effective ways to utilize AI and ML in epidemiological modeling and prediction. AI and ML excel at taking complex data and extracting correlations for use in short-term predictions where changes in dependent variables are smooth, and with parameters that are easily defined. It becomes more difficult to leverage AI if it is used to make longer-term predictions that involve a larger number of unknowns, or to evaluate complex causal hypotheses, such as those involving behavior change. Whether or not sufficient data exists to apply AI and ML also varies wildly across applications of AI and ML, and participants felt that the use of AI and ML is generally perceived as being a uniform method with uniform data and computational requirements, which is not the case. Therefore, AI should be used with caution when making diagnoses due to the large number of assumptions made when developing and training the associated models.

F. Data

This session examined data needs, challenges associated with data usage, research opportunities, and partnership opportunities in data production and distribution. Advances in each of these areas can increase the Nation's capacity to understand, and more effectively react to, a wide range of epidemiological phenomena.

1. Panel Session 2 – Data

Dr. Pavel Pevzner, University of California-San Diego: *Dr. Pavel Pevzner is the Ronald R. Taylor Chair and Distinguished Professor of Computer Science and Engineering at University of California, San Diego and Director of the National Institutes of Health Center for Computational Mass Spectrometry. His research focuses on computational technologies that allow scientists to solve biological problems including genome sequencing, immunoproteogenomics, antibiotic sequencing, and comparative genomics.*

Dr. Pevzner discussed tracking the spread of infectious diseases using genomic and immunological data from viruses and humans, respectively. He noted that the rapid assessment of pathogen genomic data, and how it could be changing, is useful during disease outbreaks to support public health planning. Specifically, these data can help identify transmission hotspots, calculate basic reproduction numbers, and determine whether the virus is becoming more or less transmissible over time. Dr. Pevzner discussed opportunities presented by viral genomic sequencing to prepare for infectious disease outbreaks. For example, biochemical and structure-function analysis of the ACE2 receptor and the SARS-CoV-2 spike protein predict that it can infect over 80 species of mammals. When SARS-CoV-2 infects these animals, it creates the possibility of further recombination events with other coronaviruses native to those species. The resulting virus can then reenter humans with novel epitopes.

Dr. Pevzner also spoke about the popular SPAdes genome assembler developed by his group. Since SPAdes and other assemblers have limitations in assembling viral genomes, a specialized coronaSPAdes assembler was developed that exploits the SARS-CoV-2 genome structure to improve the assembly and to address various viral sequencing artifacts, such as sample contamination. Dr. Pevzner suggested that, moving forward, the key to genomic preparedness is establishing a genomic surveillance effort that can identify more pathogens hosted by vertebrates before they spread to humans. Human immunological data also are needed to assess the success of vaccination efforts. Dr. Pevzner underscored that collaboration between biodiversity researchers, genomic experts, and bioinformaticians will be critical for the success of such efforts.

Dr. Jean-Paul Chretien, Defense Advanced Research Projects Agency (DARPA): *Dr. Jean-Paul Chretien is a DARPA program manager whose interests include disease and injury prevention, operational medicine, and biothreat countermeasures. Prior to joining DARPA, he led the Pandemic Warning Team at the Defense Intelligence Agency's National Center for Medical Intelligence.*

Dr. Chretien indicated that, with SARS-CoV-2, modeling has been used to work backwards and understand the origin of the virus and how it progressed to infect humans and spread. He suggested potential exists to improve clinical severity modeling based on host biomarkers, which can subsequently be used to anticipate medical requirements and allocation of resources. Dr. Chretien indicated that, currently, an urgent need exists for fast, accurate, and easily deployable detection technologies to keep pace with potential outbreaks. As a result, a new DARPA program, Detect It with Gene Editing Technologies (DIGET),[5] is working to develop a diagnostic test for organisms that is multiplex, will provide results in minutes, and can be used at the point of need without special instrumentation. Dr. Chretien closed by encouraging the modeling community to engage with DARPA and support infectious disease modeling and prediction.

Dr. Blythe Adamson, University of Washington and Flatiron Health: *Dr. Adamson is a health economist and pharmacoepidemiologist serving as principal quantitative scientist at Flatiron Health. She is also an Affiliate Professor at the University of Washington in the Comparative Health Outcomes, Policy & Economics Institute and a SARS-CoV-2 Advisor at Testing for America.*

Dr. Adamson stressed that policy makers need more information than case counts or deaths to properly address the questions they face. For example, knowing how long a patient stays on a ventilator is crucial for predicting ventilator needs and direct resource

[5] https://www.darpa.mil/news-events/2019-11-15

allocation. Longitudinal person-level data could allow the rapid estimation of real-world treatment effectiveness in fighting novel pathogens. She stressed that utilizing data from EHRs would help address this problem, and that the community needs to find ways to invest in and partner with industry groups that curate EHRs for business reasons. She underscored the critical need for partnerships of trusted academic and government researchers for using EHR data effectively, and that investments need to be made to efficiently extract data from EHRs at scale. Dr. Adamson indicated that industry already has developed software for this purpose, including the use of natural language processing and ML methods. She closed by highlighting that the unstructured data from EHRs are valuable, and advanced analytic methods could help researchers extract and gain insight from these data.

Dr. Roni Rosenfeld, Carnegie Mellon: *Dr. Roni Rosenfeld is a Professor and Head of Machine Learning at Carnegie Mellon University's School of Computer Science. He also leads the Delphi Research Group, which is dedicated to developing the theory and practice of epidemic tracking and forecasting.*

Dr. Rosenfeld presented data for epidemic forecasting, discussing what has been learned, what is needed, and how the field should advance. Reflecting from his perspective working for the DELPHI group[6] at Carnegie Mellon, Dr. Rosenfeld noted that a better understanding of the current state of epidemiological disease is necessary to improve forecasting abilities. To achieve this, his group prioritizes acquisition of data sources—such as from SafeGraph mobility, Facebook, and Google—that will provide situational awareness of disease states in real time. He indicated that very specific data, such as case count and deaths, do not help make inferences about the disease and pandemic behaviors on a population level. Population level data are less specific, but nonetheless essential to prediction. Based on his experience working on SARS-CoV-2 with the DELPHI group, Dr. Rosenfeld reiterated the utility of properly combined proxy signals in saving time during disease forecasting efforts. Dr. Rosenfeld also identified the untapped potential for using EHRs to generate models and recommended the generation of a national data repository to house and regulate EHR access, potentially though a tiered system similar to biosafety levels in laboratories.

2. Breakout Session 2 – Data

In this session, participants shared ideas and information to help improve identification of and access to data needed to develop and validate epidemiological models. Groups explored identification of data sources, barriers to acquisition of data, and how to operationalize data processing. Participants also discussed data verification and model

[6] https://delphi.cmu.edu/

validation and noted areas of opportunity for research and development related to these topics. Several themes emerged from the discussions.

Multiple mechanisms exist to verify and validate models. Participants described models as being a potentially powerful way to draw connections between events and make predictive forecasts. Models were characterized as successful if they could be used to make a useful decision. Participants noted that evaluating models for accuracy is difficult because evaluations often require comparisons to "ground truths" that are frequently changing. For this reason, short-term models are often easier to validate. Model ensembles were noted as being capable of producing increased accuracy.

Epidemiological data reporting should be standardized. A primary challenge identified by the group was that epidemiological data currently are not reported in a consistent manner (formats, regularity, content), making it difficult to incorporate available data into models. For example, some data providers do not report whether clinical cases stem from disease tests, non-clinical testing sites, or contact-tracing reports. Without this context, case data that are not strictly equivalent end up being grouped in a manner that can introduce bias and uncertainty in model results. In addition, the types of auxiliary information or metadata needed—and how to report it—are not well communicated to the municipalities and health departments that provide fundamental data.

To address the challenge of inconsistent reporting of epidemiological data, the groups discussed creating standards for content, metadata, and format—all of which combined would increase data value over their entire use path from data reporting through modeling and analysis to communicating with policy makers and the public. In addition, the group discussed the potential value of developing off-the-shelf reporting tools that incorporate best practices. Such resources would reduce the burden on providers in gathering important information and ensure it is reported in a standard format. New methods to better prepare data pipelines and efforts to develop machine-readable tools to help automate data collection and cleaning also could help in updating and maintaining datasets in real time during emerging situations.

Increased coordination and collaboration are necessary to optimize model output. Participants also noted that a sustained effort to identify and maintain high-quality public health and disease surveillance data is needed. Because high-quality data are a requirement for the production of reproducible modeling studies, a need exists for U.S. leadership in coordinating and managing data sources, including quality control. Data standards were identified as being necessary to promote increased model accuracy. One participant noted that standards involving the minimal amount and "correctness" of the data used during model development and testing could reduce model uncertainties, especially during high-pressure modeling scenarios.

A centralized data repository that implements data standards could facilitate increased data access and quality. Of particular interest is the need to coordinate and provide access to public health and healthcare data to create, train, and refine models. For example, one participant noted that large volumes of data detailing yearly influenza epidemics, including vaccination, testing, and hospitalization information, already exist. If made more easily accessible in a centralized location, these data could be used to develop more accurate influenza models and forecasting capabilities that could apply to other diseases.

Participants discussed the value of strategies to mitigate data gaps by developing taxonomies of research questions and quantifying biases introduced by missing data. The group acknowledged it is not possible to create a master dataset to meet every possible research or policy need. In part, this is because researchers do not know what data will be needed, or where to get it, before an epidemic begins.

Additionally, the consideration of how models change if new data are introduced was recognized to be an important part of building robust models. Some participants noted that during high-pressure situations, such as during an epidemic, increased data production and accessibility could improve modeling capabilities. One participant noted that the Defense Production Act could be used to obtain privately held, modeling-relevant data, including testing, case, and hospitalization information. Outreach and coordination with other fields, such as election polling, also could help identify appropriate standards and best practices.

Data privacy rules are a key challenge of epidemiological data. One group noted that difficulties exist with de-identifying datasets from small geographic areas in ways that preserve enough detail to contribute to epidemiological modeling. Participants suggested that streamlined access to U.S. Census data, which utilizes differential privacy, could be one solution to this problem. Participants also expressed support for more federated learning from proprietary data, such that models can be trained on datasets that are protected or privately held without needing to more broadly share the data.

Participants noted difficulties in accessing data from the private sector, though it has been somewhat easier during this pandemic. However, researchers expect it to become more challenging again in the future. These data are valuable to private companies and the companies often are not incentivized to share. Because patients own their own data, one group discussed the idea of creating markets where individuals might be willing to share or sell their information and incentivizing them to do so. For example, standing subject pools currently exist, but they are relatively small and may not be entirely generalizable. To be successful, this concept would need to be implemented on much larger scale; a national infrastructure to collect and aggregate these data was suggested.

Creating long-term data-sharing relationships, including via public-private partnerships, is essential for developing model output that is actionable and will help maintain national readiness. Academic partnerships with healthcare institutions, such as nursing homes, were suggested to help test and validate models and forecasting tools. Additional partnerships and coordination between model users and developers are needed to increase modeling capabilities. Specifically, participants noted that coordination with individuals using models to make decisions could inform the generation and granularity of model output. For example, hospitals need approximately 4–6 weeks of notice to staff their facilities in response to an epidemic. Currently many models produce 1–2 week forecast time horizons, a time scale that has limited utility for hospital systems. Partnerships between hospitals and modelers could address this issue and increase the efficiency and utility of forecasting efforts. Additionally, communication between model users and developers would provide the opportunity to optimize model outputs as new data and needs arise. This collaboration could also help users understand model caveats, limitations, and accuracy levels. The National Weather Service's test beds, which bring end users together with model developers and data providers, should be explored as a possible framework for creating the aforementioned partnerships.

Lastly, participants discussed the consequences of returning from the current crisis-level effort to understand and combat the SARS-CoV-2 pandemic back to "peacetime" conditions. Much of the data used now have not been available in non-pandemic situations. Participants inquired as to whether it is possible to maintain these data sources for the long term. Challenges of maintaining access to data streams include data privacy concerns, the distribution of data ownership, and who pays to maintain access. On these matters, participants expressed the importance of learning from recent experiences and not losing this knowledge before it can be employed to inform future crisis response.

G. Modeling Strategies and Output Generation

This session focused on how to improve modeling strategies and the public value of the output that they generate. Panelists and participants discussed current and future R&D and partnership opportunities in these domains.

1. Panel Session 3 – Modeling Strategies and Output Generation

Dr. Caitlin Rivers, Johns Hopkins Center for Health Security: *Dr. Caitlin Rivers is a senior Scholar at the Johns Hopkins Center for Health Security and an Assistant Professor in the Department of Environmental Health at the Johns Hopkins Bloomberg School of Public Health. Her research focuses on improving public health preparedness and response, particularly by improving capabilities for infectious disease modeling to support public health decision making.*

Dr. Rivers discussed interviews she conducted in 2018 and 2019, prior to the SARS-CoV-2 pandemic, to better understand how people do and do not use models. She discovered many barriers to making models more usable. She noted a lack of formal coordination and communication between relevant agencies, organizations, and researchers. In practice, she indicated, connections are built on personal relationships and collaboration is less widespread. As such, she noted that many modelers in academia need support mechanisms to coordinate with government entities. Dr. Rivers also described poorly aligned incentives among stakeholders. Decision makers need usable information, while academics are often rewarded for producing scholarly publications. In some parts of the world, cultural factors depress model usage. This is particularly true when historically marginalized communities are skeptical about researcher motives. Additionally, financial constraints create barriers for research modelers as few programs have funding allocated for infectious disease modeling and tend not to support operational activities. For these reasons, supporting and training students is difficult and a need exists for bringing new people into the field. Lastly, Dr. Rivers indicated that accessing privately held data is also a challenge in a public health crisis.

Dr. Alessandro Vespignani, Northeastern University: *Dr. Alessandro Vespignani is a Sternberg Family Distinguished Professor at Northeastern University Khoury College of Computer Science and the Director of the Network Science Institute. His research interests include the characterization and modeling of complex networks, modeling the spatial spread of epidemics, resilience of complex networks, and collective behavior of techno-social systems.*

Dr. Vespignani's team works on multiscale modeling approaches to infectious diseases. These efforts contribute to the CDC modeling network for seasonal and pandemic flu, SARS-CoV-2 global spread, test and trace modeling, and the SARS-CoV-2 forecasting hub. He spoke about how, as an approach, actionable modeling is effective when there exists a focus on understanding datasets, rather than a sole focus on forecasting. He discussed how model heterogeneity could be better communicated as models have different needs, uses, and limitations. Lastly, Dr. Vespignani discussed how uncertainty in models, including biases and incompleteness, needs to be better communicated to the public and to decision makers.

Dr. Dominique Brossard, University of Wisconsin-Madison: *Dr. Dominique Brossard is a professor and chair of the Department of Life Sciences Communication at the University of Wisconsin-Madison. Her research focuses on the intersection between science, media, and policy.*

Dr. Brossard's work focuses on the psychology of risk and risk communication. Through discussion groups with public officials, she identified the necessity for local decision makers to be transparent with communities in order to foster trust. She underscored that the purpose of modeling is to develop actionable knowledge and to be useful in decision making, not just to produce information. In addition, Dr. Brossard indicated that the manner in which information is represented, and how uncertainty is portrayed, remains an issue. She explained the focus should not just be on output, but on users to ensure the safety, security, and economic prosperity of the communities the models are informing. Lastly, Dr. Brossard emphasized the importance of engaging model users and decision makers when developing modeling tools.

Dr. Liberty Vittert, Washington University in St. Louis: *Dr. Liberty Vittert is a Professor of Practice in Data Analytics at the Olin Business School at the Washington University in St. Louis. One of her many research interests is understanding and communicating risk statistics in the field of public health.*

Dr. Vittert provided several examples of how information from models is communicated to the public. One of the examples she highlighted was the power of visual representations to communicate uncertainty. Dr. Vittert explained that effective communication should consider the nature of the audience and how the numbers presented will be interpreted. In many cases, she indicated that numbers and output from models have an emotional interpretive component. Dr. Vittert suggested that this emotional component be recognized and accommodated when communicating model output.

2. Breakout Session 3 – Modeling Strategies and Output Generation

In this session, participants offered ideas to improve the public value of epidemiological models. Participants discussed approaches and best practices to quantify model uncertainty, concatenate multiple model outputs, and use model ensembles. Others discussed computational resources, such as computational tools and data platforms, and identified where additional resources could be used to improve modeling capabilities. Several themes emerged from the discussions.

Multi-sector partnerships could overcome institutional challenges associated with model development. Participants noted a need to establish wider-reaching partnerships, such as creating a coordinating body within the Federal Government, to connect model stakeholders from various sectors. A proposed method of coordination involved a hybrid model that would involve both the public and the academic sector in close-knit relationships, similar to NOAA's Cooperative Institutes or CDC's Prevention Effectiveness Fellowship. The model would leverage the talent and technical expertise from the academic sector to bolster the efforts of the public sector. Participants also noted that any cross-sector partnerships must carefully balance the benefits gained through cooperation; for instance, a relationship with the academic sector must provide sufficient opportunity to retain the dynamic aspect of research in addition to industry-led initiatives. Other aspects of improving coordination include ensuring partnerships across sectors are persistent, as temporary partnerships limit the ability of modelers to nimbly respond to rapidly emerging needs. Additionally, participants noted that partnership-building efforts should have a broad reach, as this can create stronger synergy between government agencies and engender a whole-of-government approach to strategic coordination. Such an effort would increase the impact in terms of both scope and magnitude.

Participants noted that lack of access to public health and healthcare data impedes model development. One participant noted that although this need has been recognized for many years, large costs of data storage and maintenance have prevented realization of this goal. Additionally, data generation costs are notably high as health practitioners have to spend large amounts of time inputting patient data into healthcare systems in lieu of spending time with patients. Finally, many health datasets are stored in silos and not interoperable, further generating barriers to utilizing health data. A number of participants recommended increasing partnerships with clinical physicians and research scientists to stimulate data generation and to navigate data silos.

Communication between modeling experts and model users is necessary to build trust and increase understanding of appropriate model uses. Participants discussed uncertainty as it pertains to the outcomes drawn from the models and how to properly communicate uncertainty to non-technical stakeholders. They noted that, due to the fragile trust sometimes placed in models by decision makers, it is vital to make the uncertainty quantification as transparent and understandable as possible. Individual participants recommended that collaborations between modelers and decision makers be used to facilitate this relationship. Additionally, participants proposed translators—individuals who specialize in communicating modeling results to non-technical audiences—be used to harmonize the transfer of information between modelers and decision makers. Standardizing modeling terminology across disciplines and increased use of visual communication tools were also suggested to facilitate this collaboration.

Participants expressed a critical need for modelers to engage the ultimate end users of the information when developing products from model output. They stressed that a dialogue in this arena is one of the most important aspects of ensuring that models generate actionable information. Developing products from output and clearly communicating the purpose of the information—and the associated caveats—is important. Participants suggested that communicating model results as a comparison to, or in the context of a known—such as economic impacts, for example—could be an effective way to help policy makers understand model output.

All participants expressed that conveying model-generated information in ways that have greater utility for decision makers and greater value to the public requires a bottom-up approach to communications, involving engagement and dialogue with end users. To this end, there exists a need to better understand how limits of human attentive capacity, including the impact of stress, influence how model-generated information is interpreted and used. In addition, more work is needed to understand how charts, visualizations, and lists can convey risk to audiences.

The participants shared an interest in quantifying sources of uncertainty and harmonizing outputs of several models. While the preceding panel was generally enthusiastic about the possibilities of using ML methods to improve epidemiological modeling, participants also shared concerns about the relatively understudied nature of many ML methods. Many participants recommended a thorough examination of ML-associated methods and uncertainties to determine appropriate application to epidemiological modeling and prediction. In circumstances for which models produce competing outcomes, participants noted the importance of being able to communicate key model differences so their output differences could be used in meaningful ways. Additionally, some participants stated that the ability to harmonize models is key to understanding sources of uncertainty. Participants also highlighted the importance of communicating the effect of using emergency model predictions to inform public decisions. For example, when responsive action is taken, model predictions can be misinterpreted as incorrect in public hindsight. Many participants saw this problem as primarily operational in nature; increasing the accessibility and transparency of models that produce such predictions can assist decision makers in utilizing modeling and requesting funds to support its use.

To maintain the current modeling and tool development momentum, mechanisms to sustain epidemic modeling efforts are needed. Participants identified a need for increased funding for disease modeling and forecasting that could be used to build computing facilities across the Nation. Access to computing resources is unevenly distributed across the United States. Participants noted that although some institutions—such as the University of Texas, Austin—have robust computational centers, many institutions have sub-optimal resources for computational researchers. Participants indicated that time limits on shared equipment create barriers to efficiently completing their work and that financial costs associated with equipment use generate financial constraints. Participants also identified an increased need for computing power due to the increased volumes and granularity of data being generated during SARS-CoV-2 contact tracing.

A number of participants suggested a coordinating center to support sustainability in the epidemiological modeling field. The coordinating center could support not only the management of federally funded models, algorithms, and tools, but also coordinate communication across research groups and fields. Participants noted that the coordinating center could establish research test beds to bring together a variety of stakeholders and engage numerous users. The coordinating center also was suggested as a means to generate a community in which researchers could engage.

Many participants noted that a barrier to sustainability in the field was the lack of value academic institutions placed on modeling and tool development during the tenure process. As such, participants stated that the tenure process is overly weighted towards publications. Instead, participants recommended that mechanisms to certify or verify the impact of modeling on public service be generated to communicate the value of their efforts to tenure committees. NSF or non-profit professional organizations were identified as potential organizations to champion this process.

Additional researchers with modeling expertise and coding capabilities are needed to fill labor gaps. This increased need in the technical workforce was attributed to faster computational resources (increased computing power) and accelerated model development time. Participants also identified a need for assistance from graphic designers to more effectively communicate the outputs of their work.

H. Plenary Discussion of Summary Points from Breakout Sessions

Summit Discussion: In the final plenary discussion, several individuals commented that previous efforts to convene modelers, public health practitioners, and policy makers did not yield long-term change and lacked follow-on efforts. Additionally, participants called for sustained institutional oversight and coordination of those efforts. Dr. Droegemeier acknowledged the need for continued engagement among government officials, modelers, and researchers to steadily improve the capacity of the United States to forecast and respond to public health crises. He agreed with the sentiment shared by participants that OSTP should serve as a coordinator for these multidisciplinary efforts.

One participant noted a problem not previously addressed: agencies often run into a mandate issue during times of crisis. Agencies' responsibilities are narrowly defined to avoid overlap and ensure any activity is in service of each agency's goals, but the inflexibility of those responsibilities makes it hard to support collaborative efforts during emergencies. The recent pandemic, and modeling efforts in particular, have shown the importance of allowing more agencies to work on health-related issues.

Finally, participants noted that with sustained coordinated efforts, the country would have the capabilities and previous research necessary to respond to future crises. Individuals commented that at this point in the pandemic, the focus should not just be on using models to address the evolving issue of SARS-CoV-2. Instead, multidisciplinary efforts must use the lessons learned from responding to SARS-CoV-2 to better prepare the country for emergency research and response in the future.

Dr. Kelvin Droegemeier, OSTP: Dr. Droegemeier offered the first summary of the event, overviewing the main needs he identified based on Summit discussions. First, he acknowledged the need for a nationally coordinated framework for modeling, akin to those used for by the Nation's meteorological services enterprise. Second, Dr. Droegemeier noted that data quality, access, and ease of use were critical to ensure further progress could be made in improving models. He also stressed that more emphasis is needed on actionable modeling, along with communication of risk and uncertainty, which should be included in the framework moving forward. Finally, he highlighted the need to embed epidemiological modeling research with operational practitioners.

Dr. Michael Schmoyer, OSTP: Dr. Schmoyer identified OSTP and the National Science and Technology Council (NSTC) as appropriate actors for coordinating future modeling efforts. He drew attention to predictions and modeling as a cross-cutting element of several NSTC subcommittee efforts. He closed by highlighting ongoing efforts of the Executive Office that promoted epidemiological modeling efforts, including *Advancing America's Global Leadership in Science and Technology—Trump Administration Highlights (2017–2020)*.

I. Final Comments from Co-Organizers and Path Forward

Dr. Arthur Lupia, NSF

Dr. Lupia thanked all participants, and reviewed the goals of the Summit. Dr. Lupia then summarized some of the common needs that participants identified during the meeting, which included the use of a national framework to support data standards and tool coordination, and to consider the end user during model development. Additionally, Dr. Lupia highlighted the need of the modeling community to be future-focused to ensure that the Nation is better prepared to manage future health crises.

Dr. Brian Moyer, CDC

Dr. Moyer emphasized the need to improve data accessibility and interoperability. He identified the need for a central data repository or platform for researchers to access EHRs. That platform, he said, should serve as a data stockpile for any researcher in the United States to access relevant information when developing or implementing an epidemiological model.

Dr. Kristen Jordan, IARPA

Dr. Jordan closed with an analogy to her military experience: just as she requires constant training in chemical and biological warfare to stay prepared to respond to an event, so too must researchers and the government engage in persistent activity for disease modeling and forecasting. Dr. Jordan proposed that researchers focus on identifying early indicators for potential pandemics that would allow the Nation to deploy resources rapidly and efficiently to mitigate emerging health threats. Finally, she noted the importance of technology investment in order to make complex modeling possible.

Dr. Kelvin Droegemeier, OSTP

Dr. Droegemeier offered a final thank you to all participants, and discussed how modeling is a priority.

Appendix A. Summit Agenda

This appendix contains the agenda for the Epidemiological Modeling Summit on November 12–13, 2020.

Day 1

9:00 AM **Welcome/Overview/Goals of the Summit**

- Kelvin Droegemeier, Office of Science and Technology Policy
- Michael Schmoyer, Office of Science and Technology Policy

9:30 AM **Co-Organizer Perspectives on the Summit**

- Brian Moyer, Centers for Disease Control and Prevention
- Skip Lupia, National Science Foundation
- Kristen Jordan, Intelligence Advanced Research Projects Activity

10:00 AM **Keynote: "Real-time Pandemic Preparedness and Response: State of the Art and New Opportunities"**

- Madhav Marathe, University of Virginia

10:30 AM **BREAK**

10:45 AM **Panel Session #1: Model Capabilities (needs/challenges, R&D opportunities, partnerships, emerging technologies)**

This panel provides views and engages the audience on key topics that will set the stage for the subsequent breakout session.

Moderator:

- Skip Lupia, National Science Foundation

Panelists:

- John Drake, University of Georgia
- Michelle Hawkins, National Oceanic and Atmospheric Administration
- Aaron King, University of Michigan
- James Stock, Harvard University

11:45 PM **Lunch**

12:30 PM **Action Team Breakouts on Model Capabilities**

Moderator:

- Skip Lupia, National Science Foundation

Facilitators:

- Team A: Aaron King, University of Michigan
- Team B: James Stock, Harvard University
- Team C: John Drake, University of Georgia

1:15 PM **Breakout Reports**

2:00 PM **Break**

2:15 PM **Panel Session #2: Data (needs/challenges, R&D opportunities, partnerships)**

This panel provides views and engages the audience on key topics that will set the stage for the subsequent breakout session.

Moderator:

- Brian Moyer, Centers for Disease Control and Prevention

Panelists:

- Pavel Pevzner, University of California-San Diego
- Jean-Paul Chretien, DARPA
- Blythe Adamson, University of Washington and Flatiron Health
- Roni Rosenfeld, Carnegie Mellon

3:15 PM **Action Team Breakouts on Data**

Moderator:

- Brian Moyer, Centers for Disease Control and Prevention

Facilitators:

- Team A: Pavel Pevzner, University of California-San Diego/Jean-Paul Chretien, DARPA
- Team B: Blythe Adamson, University of Washington and Flatiron Health
- Team C: Roni Rosenfeld, Carnegie Mellon

4:00 PM **Break**

4:15 PM **Breakout Reports**

5:00 PM **Adjourn for the Day**

Day 2

9:00 AM **Panel Session #3: Modeling Strategies and Output Generation (needs/challenges, R&D opportunities, partnerships)**

This panel provides views and engages the audience on key topics that will set the stage for the subsequent breakout session.

Moderator:

- Kristen Jordan, Intelligence Advanced Research Projects Activity

Panelists:

- Caitlyn Rivers, Johns Hopkins Center for Health Security
- Alessandro Vespignani, Northwestern University
- Dominique Brossard, University of Wisconsin-Madison
- Liberty Vittert, Washington University-St. Louis

10:00 AM **Action Team Breakouts on Modeling Strategies and Output Generation**

Moderator:

- Kristen Jordan, Intelligence Advanced Research Projects Activity

Facilitators:

- Team A: Caitlyn Rivers, Johns Hopkins Center for Health Security/Alessandro Vespignani, Northwestern University
- Team B: Dominique Brossard, University of Wisconsin-Madison
- Team C: Liberty Vittert, Washington University-St. Louis

10:45 AM **Break**

11:00 AM **Breakout Reports**

11:45 AM **Lunch**

12:15 PM **Plenary Discussion of Summary Points from Breakout Sessions**

- Kelvin Droegemeier, Office of Science and Technology Policy
- Michael Schmoyer, Office of Science and Technology Policy

1:00 PM **Final Comments from Co-Organizers and Path Forward**

Agency leads will reflect on points made during the Summit.

- Brian Moyer, Centers for Disease Control and Prevention
- Skip Lupia, National Science Foundation
- Kristen Jordan, Intelligence Advanced Research Projects Activity
- Kelvin Droegemeier, Office of Science and Technology Policy

1:30 PM **Adjourn Summit**

- Skip Lupia, National Science Foundation