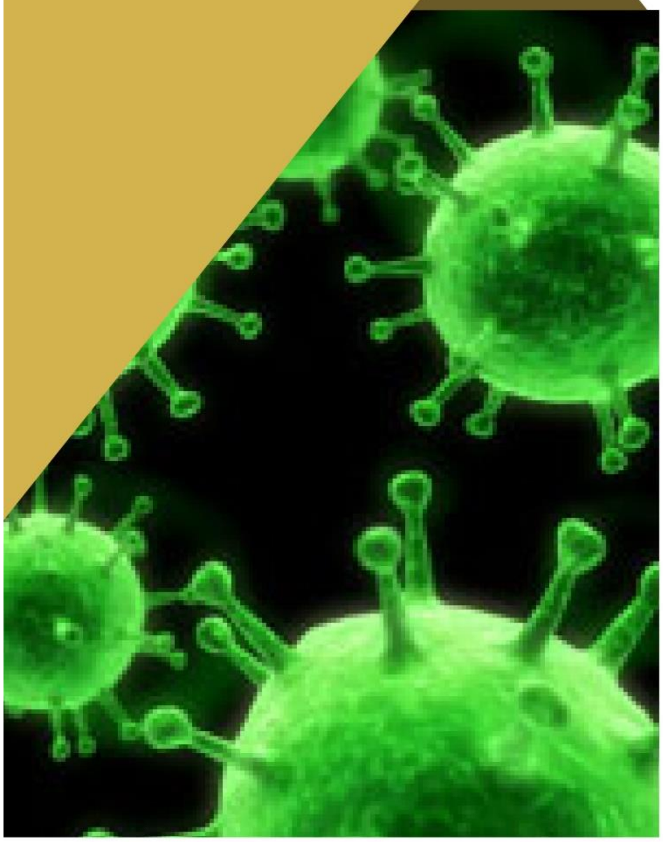
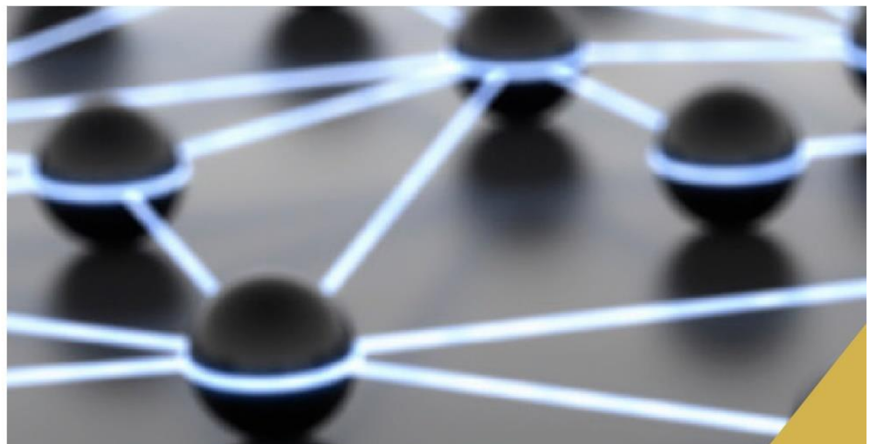
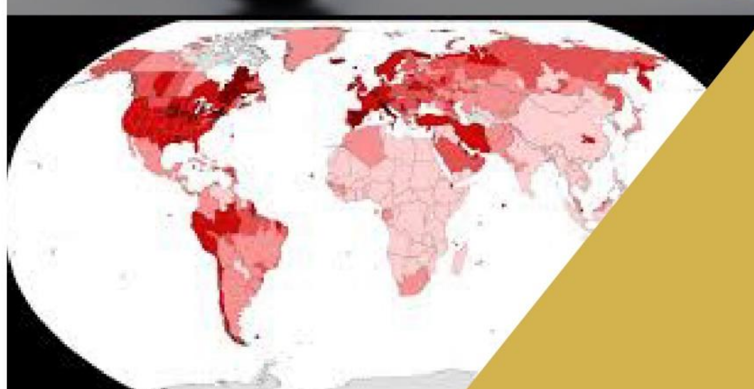
NSF PREDICTIVE INTELLIGENCE FOR PANDEMIC PREVENTION (PIPP)

Workshop on Predicting Pandemic Emergence







Workshop Summary Report
June 2021

THE UNIVERSITY OF TENNESSEE KNOXVILLE · Massachusetts Institute of Technology · Duke UNIVERSITY · BOSTON UNIVERSITY

Acknowledgements

Many thanks to everyone who contributed and participated in the "Predicting Pandemic Emergence" workshop held virtually on February 25 – 26, 2021. This report was prepared with the input from over 80 scientists, engineers, and other stakeholders, and represents the synthesis of results and discussion from the February 2021 virtual Workshop on Predicting Pandemic Emergence. Any opinions, conclusions, or recommendations expressed in this material are those of the authors and do not reflect the views of the United States Government.

Special thanks are extended to those listed below and to active discussants who participated in the breakout sessions (a complete list is provided in *Appendix B: Workshop Participants*).

Plenary Speakers:
Rashid Bashir (University of Illinois), Yana Bromberg (Rutgers University), Gerardo Chowell (Georgia State University), Utkan Demirci (Stanford University), James Holland Jones (Stanford University), Eric Lofgren (Washington State University), Martina Morris (University of Washington), Alex Olshevsky (Boston University), Sadie Ryan (University of Florida), Themis Sapsis (MIT), Venu Veeravalli (University of Illinois)

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From the Organizers

The global Covid-19 pandemic has resulted in unprecedented challenges that cross social, cultural, and national boundaries. Unfortunately, it will not be humanity's last pandemic. While the response of citizens, medical professionals, scientists, and policy makers at local and national levels has given us countless examples of heroic behavior, the response to Covid-19 has also highlighted serious vulnerabilities in national and global pandemic preparedness.

At present, pandemic preparedness is best described as a constellation of fields within two major divisions: basic scientific research and applied public health. Within the research community, scientists are typically focused on methods relevant to the most recent clear pandemic threat (e.g., HIV, influenza, Zika virus, Ebola, Covid-19), and work is largely governed by a simplification-for-solvability paradigm, in part due to a natural tendency toward reductionism, the time scale of funding cycles, and the need for periodic deliverables.

Pandemic science will likely continue to be a constellation of fields. The origin, spread, and control of pathogens raises questions in a broad array of disciplines including epidemiology, biology, ecology, bioinformatics, network science, engineering, biophysics, fluid dynamics, public health, statistics, and data sciences. What is clearly needed is increased communication between these fields and integrative models that continually draw upon each field's findings to address all stages of pandemic emergence. The rise of any pathogen to global prevalence results from a series of probabilistic events: mutation to pathogenicity, zoonotic crossover, mode of and ease of transmission, susceptibility, disease duration and lethality, human migration, early detection, ease of intervention, etc. Increased understanding of the factors that influence these probabilities, and their joint likelihood will better predict the emergence of pathogens and point towards the best opportunities for intervention and control.

Pandemic science is a multi-level problem requiring multi-level solutions. Foremost among these is increased communication between disparate fields. This can be facilitated in several ways:

- Dedicated research centers and institutions
- Workshops and conferences focused on multi-level integration
- Incentivizing collaboration within and across academic and research institutions
- Special issues or field specific journals
- Adoption of a unified nomenclature
- Development of standards for data collection, curating, and sharing

Increased communication will help to achieve near term results (next decade) focused on early detection, rapid treatment, and control. This will require investment in:

- Active, continued, worldwide biological monitoring aimed at quickly detecting new emergent infections
- Delineating contact spaces with wild and agricultural animals to better understand risk and prevent zoonotic crossover
- Increased ability to identify disease-specific relevant heterogeneities in susceptibility and risk across population groups (age, comorbidities, etc.)
- Data-grounded models for disease progression that incorporate the array of transmission modalities (airborne, physical contact, insect vector, environmental)

- Effective rapid vaccine templates for wide classes of potential pathogens
- New data-grounded models for epidemic spread, linked to risk profiles that allow for more targeted interventions rather than a blunt-force “lockdown” approach
- Integration of behavioral health sciences to better understand and counteract policy resistance
- Increased outreach to build public trust of medical and pandemic science

Multilevel problems such as pandemic preparedness require individuals and institutions, who through intention and design are interdisciplinary, to draw together findings from the numerous relevant fields into predictive conceptual, qualitative, and quantitative models that identify risk and potential leverage points for intervention. Through increased communication and the adoption of communication norms, collective understanding of the origin and dynamics of pandemics will deepen. Continued attention to and investment into these issues, and the issues raised in the companion workshops on pandemic preparedness will undoubtedly strengthen our ability to predict and respond to the next emerging pandemic.

List of Acronyms

BIO	National Science Foundation Research Directorate for Biology
CCICADA	Command, Control, and Interoperability Center for Advanced Data Analysis
CDC	Centers for Disease Control and Prevention
CISE	National Science Foundation Research Directorate for Computer Information Science and Engineering
DARPA	Defense Advanced Research Projects Agency
DHS	Department of Homeland Security
DOD	Department of Defense
ENG	National Science Foundation Research Directorate for Engineering
EPA	Environmental Protection Agency
LAMP	Loop-mediated amplification
NIH	National Institutes of Health
NIMBioS	National Institute for Mathematical and Biological Synthesis
NSF	National Science Foundation
OISE	Office of International Science and Engineering
PIPP	Predictive Intelligence for Pandemic Prevention
QCD	Quickest Change Detection
SBE	National Science Foundation Research Directorate for Social, Behavior, and Economic Sciences
USFWS	United States Fish and Wildlife Service
USDA	United States Department of Agriculture

Executive Summary

The National Science Foundation (NSF) held a virtual Workshop on Predicting Pandemic Emergence, on February 25 – 26, 2021, as a part of its series on Predictive Intelligence for Pandemic Prevention (PIPP). The workshop brought together more than 80 leading experts, representing NSF research directorates for Biology (BIO), Computer Information Science and Engineering (CISE), Engineering (ENG), Social, Behavioral and Economic Sciences (SBE), and the Office of International Science and Engineering (OISE), to discuss the identification of pre-emergence, emergence dynamics, and the predictions of rare events in multi-scale, complex and dynamical systems, and how to integrate the approaches taken by each community into a more effective, unified science of pandemic prediction. Particular focus was given to identifying challenges and opportunities at the intersection of different scales (e.g., molecular, physiological, and environmental).

The workshop aimed to:

- Formulate a new science base on pandemic preparedness
- Identify scientific gaps that need to be addressed
- Discuss how to design solutions to fill those gaps in ways that anticipate multidisciplinary use
- Construct integrative and multidisciplinary frameworks to enable deeper insights into the fundamental processes of pandemic emergence and translate those insights into practical tools for preventing and/or mitigating pandemic threats

With these goals in mind, workshop participants developed concrete recommendations for how critical and diverse fields can move forward together to increase global safety, guarding against future pandemics.

This workshop report summarizes the plenary presentations, panel discussions, and breakout group sessions that took place during the event. The results presented here are a glimpse of the viewpoints expressed by the participants and do not necessarily reflect those of the broader pandemic research community.

Throughout the workshop, discussions focused on exploring barriers to interdisciplinary collaboration and technical research challenges. A number of common themes emerged, described below and summarized in graphical form in Figure ES-1 and Figure ES-2:

Barriers to Interdisciplinary Collaboration

People: Organizing an interdisciplinary team that works and communicates effectively is a daunting challenge. Not only should there be a balance of disciplinary and inter-disciplinary researchers, but a consistent terminology must also be established to better foster effective collaboration. Developing research questions that cross disciplines and are interesting to everyone, and establishing avenues to find the right partners, were both cited as primary challenges.

Communication: Differences in terminology between research fields present significant challenges to interdisciplinary collaboration. The same words often don't mean the same thing across disciplines. Methods to develop common parlance and understanding among disparate research fields need to be established to quickly overcome challenges in communication. Equally important is effective communication to non-research stakeholders, including policymakers, clinicians, and the general public.

Researchers must also provide timely, actionable information for policymakers and clinicians and provide clear, consistent, and concise information to and guidance for the general public.

Institutional Structures of Research: The current structure of academia and research institutions was identified as one of the largest obstacles to interdisciplinary collaboration. As it stands, deepening the knowledge in a specific field is highly prioritized (the result of hiring and promotion policies), over interdisciplinary work, leading to siloing within the research community. Moreover, the reactionary "boom-bust" cycle of funding, where topics are funded based on changing national priorities, was noted as being particularly detrimental to building the meaningful collaborative relationships and sustained research efforts required for tackling multi-dimensional, multi-scale problems.

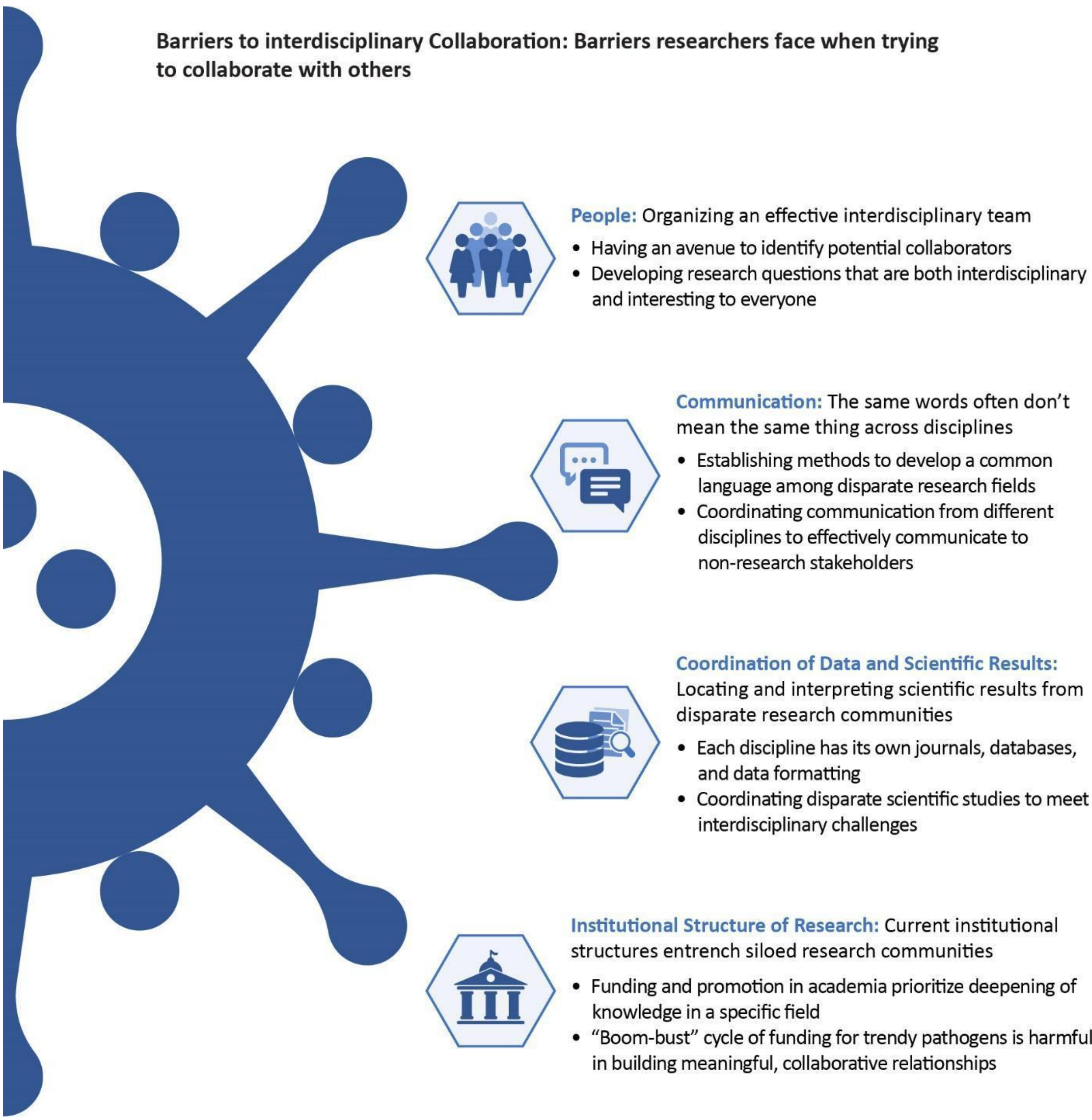

Figure ES-1: Summary of Barriers to Interdisciplinary Collaboration

Coordination of Data and Scientific Results: Each research discipline has its own journals, databases, data format, and terminology such that finding and interpreting desired scientific results and data present significant challenges.

Technical Research Challenges

Modeling: A robust, pandemic prediction model will integrate interactions across relevant scales, couple mechanistic and statistical approaches, and assemble input from numerous research disciplines. Consistent naming conventions, data access and retrieval protocols, and common code syntax will be necessary for seamless integration of contributions from disparate fields. Integrating human behavioral data was cited as the top priority for developing accurate pandemic prediction models. To accomplish this, social-behavioral sciences must be fully integrated, from the outset, into pandemic research. In addition, establishing cleaner, consistent data streams and data standardization can help drive development of dynamic, adaptive models and effective machine learning techniques.

Foundational Science: Deeper fundamental understanding of the interactions of emerging pathogens at all scales (molecular, physiological, and environmental) to determine pre-indicators of pandemics was cited to be one of the highest priorities in pandemic prediction. Discussions particularly focused on the lack of knowledge in pathogen evolution in the animal hosts and the mechanisms, drivers, and predictors of cross-species spillover. Further research areas to explore include virus-host interactions, effects of environmental factors such as population density and climate change on pandemic emergence, drivers of variant origination, and viral network dynamics.

Data Access and Quality: Limited data access, poor quality, and the lack of standard formats are some of the most often encountered barriers across disciplines. Standardized data collection and storage, and more open, comprehensive databases will foster scientific discovery and encourage interdisciplinary collaboration.

Epidemiology and Viral Surveillance: Whether through active or passive sample collection methods, viral surveillance was raised as a potential method to collect better data for predictive models. With significantly larger data sets, epidemiologists can better track emerging pathogens, monitor outbreaks as they emerge, and evaluate intervention efficacy. However, deployment of such a system on the population-level would require robust privacy and security measures to alleviate any concerns of data misuse and malpractice. A robust, widespread surveillance system can provide researchers, clinicians, and policymakers with a comprehensive, centralized data repository to inform research and management decisions.

Integration Across Scales: Developing a holistic framework that integrates expertise across scales and disciplines may be the best method to develop comprehensive predictive models for pandemic emergence. This framework will allow research teams from disparate fields to contribute to unifying models and help bridge gaps in understanding by incorporating expertise from many scales. Succinctly integrating each contribution and identifying and addressing the challenges that exist when connecting models from different scales will be paramount to developing integrative models.

Research to Action: Throughout the current SARS-CoV-2 pandemic, there have been significant challenges in translating research findings and data into actionable information for policymakers and public health officials. Part of the difficulty derives from the timeline that each stakeholder requires. Scientists desire longer timeframes for data collection and theory developments, while policymakers prefer short timeframes to communicate actionable information to the public. The communication barrier between these stakeholders presents an additional challenge. What may be important or interesting for a researcher may not be important or useful for a policymaker. Effective, robust lines of communication between the two must be established to provide clear and concise translation of research findings into actionable policy.

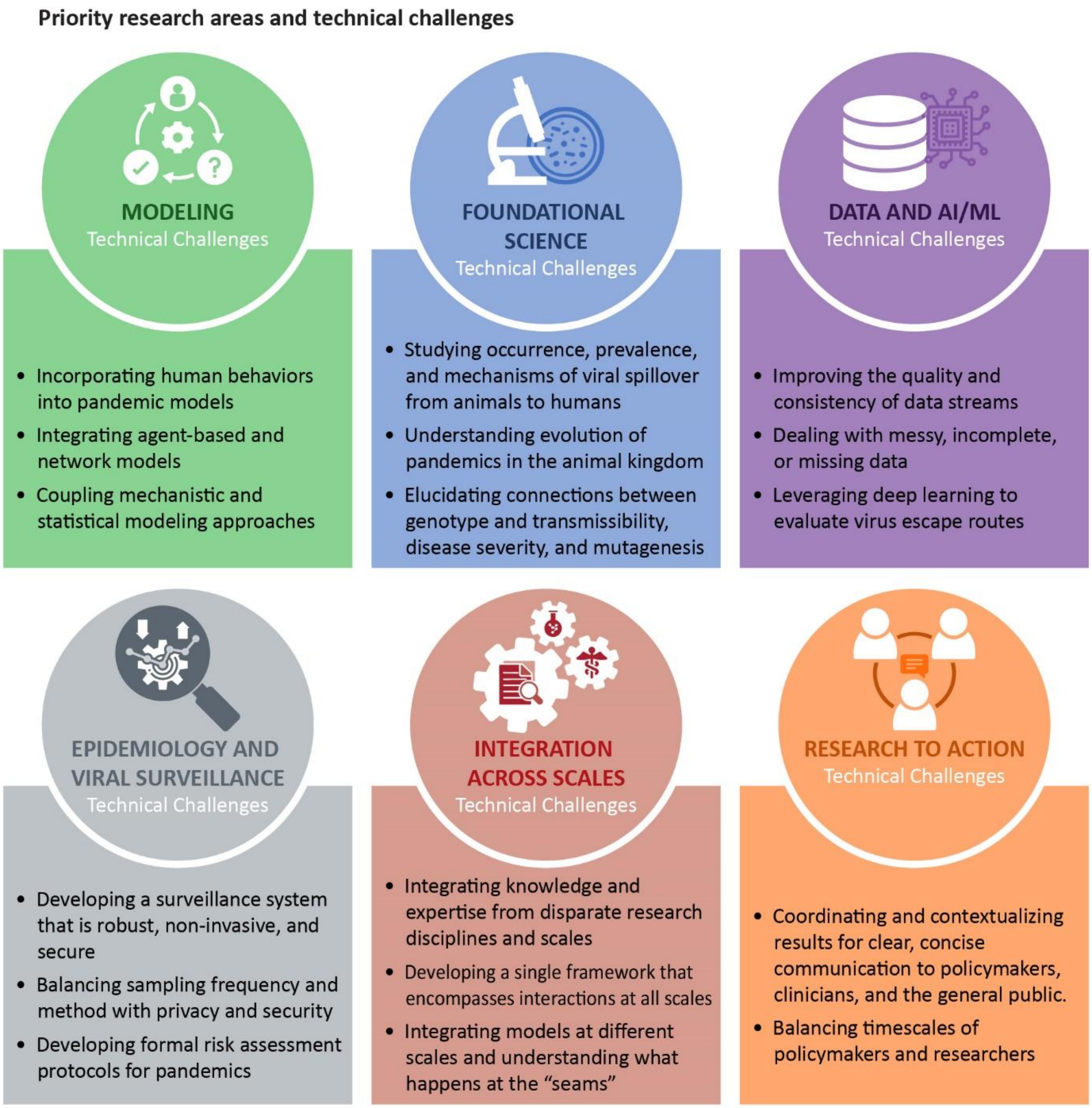

Figure ES-2: Priority research areas and associated technical challenges

Conclusions and Actionable Recommendations

Addressing the areas described herein will not only provide deeper foundational understanding of pandemic emergence, but will also foster effective interdisciplinary collaboration to tackle complex problems and provide a framework for communication with policymakers, clinicians, and the public. The academic legacy of siloed research will not be sufficient to detect the emergence or minimize the effects of future pandemics. A more collaborative research environment, including shifts in the structure of academic incentives, diverse funding distribution, and robust lines of communication between various stakeholders, must be nurtured to establish a public health infrastructure, and ultimately a society that is more resilient and prepared for future pandemics.

High impact recommendations to reduce barriers to interdisciplinary collaboration and tackle technical challenges associated with predicting pandemic emergence include:

- Improve foundational knowledge of the biological mechanisms and environmental drivers of viral transmission, mutagenesis, zoonosis, and prevalence
- Increase integration of SBE in BIO, CISE, and ENG research efforts to incorporate the much-needed human behavioral element in developing theories and models
- Re-imagine academic incentive and funding structures in research to promote interdisciplinary collaboration
- Establish a collaborative, discipline-blind, real-time repository of results and data accessible by all, incorporating consistent standards for reporting codification and scope
- Adopt consistent methods and language between disparate research disciplines
- Establish an initiative, similar to OneHealth, for pandemic preparedness and prediction
- Develop robust data management protocols to align data formatting, notation, and access across disparate research fields
- Create joint funding opportunities or institutes with NIH or other agencies to attract and integrate a wider array of stakeholders with a focus on long-term interdisciplinary research
- Ensure ongoing funding into foundational problems rather than chasing the most recent instances of outbreaks with pandemic potential
- Organize a recurring workshop or journal editions on the topic of pandemic preparedness to nurture a collaborative research community

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1. Background and Workshop Proceedings

Workshop Motivation and Purpose

Pandemics have threatened human civilization since it's foundation. Methods of predicting and preventing pandemics remain one of the most pressing challenges in human society. The SARS-CoV-2 pandemic has illustrated, to all of us, the immense human and economic toll of pandemics. Although there have been many pandemics since human civilization began, these events are rare enough that there hasn't been the necessary scientific rigor to study them in appropriate depth. A pandemic, in and of itself, is a very complex phenomena where diverse actions, environments, and attitudes all intertwine to determine its occurrence, severity, and outcome. Events and actions at many different scales all combine through an incidental "perfect storm" to create a pandemic.

A pandemic is fundamentally a multi-disciplinary and multi-scale problem, with deep knowledge required to understand pathogen infection mechanisms at the molecular level, immune response at the physiological level, zoonotic transmission of emerging pathogens at the environmental level, and pathogen transmission at the population level. Equally important is understanding of the specific interconnections between each of these levels. Building predictive models and tools can certainly help identify and mitigate emerging pathogens with pandemic potential. But on a more fundamental level, improved science must be developed to better prepare the global community for the next pandemic.

Holistic and multi-disciplinary research solutions are needed, solutions that transcend traditional scientific models with siloed research programs. With this goal in mind, the National Science Foundation (NSF), in coordination with the Directorates for Biological Sciences (BIO); Computer Information Science and Engineering (CISE); Engineering (ENG); Social, Behavioral, and Economic Sciences (SBE); and the Office of International Science and Engineering (OISE) organized a series of four workshops on the topic of Predictive Intelligence for Pandemic Prevention (PIPP) to bring together a diverse research community to identify the most pressing challenges and barriers for pandemic prediction and prevention. The four workshops within the series looked at different aspects of PIPP to provide NSF and the greater research community a holistic vision of the challenges and opportunities needed in this space.

Workshop Overview

On February 25^{th}-26^{th}, the NSF hosted the Workshop on Predicting Pandemic Emergence, the third of four in the workshop series. This workshop focused on identification of pre-emergence and the predictions of rare events in multi-scale, complex, and dynamical systems. The workshop brought together disparate scholarly communities in mathematics, engineering, computer science, biology, ecology, and social science to discuss how to integrate the approaches taken by each community into a more effective, unified science of pandemic prediction.

The workshop consisted of two plenary sessions and extended breakout sessions that prioritized cross-disciplinary and brainstorming activities (workshop agenda shown in *Appendix A: Agenda*). This "flipped" format was designed to more effectively cross-pollinate ideas across the various research fields and expertise, identify and address challenges at the interfaces of the disparate communities, and identify synergies and collaboration opportunities. Invited plenary speakers were asked to record and upload talks, on an external collaboration platform, regarding their work and how it relates to pandemic science. Invited plenary speakers and active participants viewed the videos before the workshop.

During the first plenary session Sethuraman Panchanathan (Director of the NSF), Katharina Dittmar (NSF Program Director), and the workshop organizers provided opening remarks. The invited plenary speakers then delivered five-minute mini-talks on synergies and opportunities they identified while viewing the other presentations. This was followed by a panel discussion amongst all the plenary speakers to discuss more deeply the topics of interest and answer audience questions. During the afternoon, there were two breakout sessions focused on brainstorming and discussing research challenges and opportunities in smaller groups.

The plenary session on Day 2 focused on the report-outs of the Day 1 breakout sessions, followed by a final panel discussion among all the plenary speakers. The third, and final, breakout session focused on how the workshop influenced the participants' thinking and viewpoints. The final discussion focused on culminating thoughts and next steps as a newly formed research community.

Plenary Presentations

Summarized below are the mini talks delivered during the plenary sessions on Day 1. As noted above, each invited plenary speaker uploaded a longer talk to a collaboration platform and delivered shorter remarks on synergies and opportunities after viewing other speakers' talks. These other speaker presentations have been uploaded to a community YouTube page for general viewing and are not summarized here.

Rashid Bashir, Distinguished Professor, University of Illinois – Urbana-Champaign

Dr. Rashid Bashir briefly discussed the development of loop-mediated isothermal amplification (LAMP)-based point of care sensors for rapid COVID-19 detection. This technology allows for faster analysis than RT-PCR-based techniques and was demonstrated with both nasal swabs and saliva tests. Dr. Bashir then described University of Illinois's campus-wide testing effort which successfully developed algorithms to identify at-risk populations; created saliva-based tests that are fast and scalable; deployed an app that provides exposure notifications to its users; and ultimately implemented it on the state level. Dr. Bashir concluded his talk by identifying synergies with the other plenary speakers.

Yana Bromberg, Associate Professor, Rutgers University

Dr. Yana Bromberg highlighted four key aspects of how she views pandemic prevention: the biological aspect dealing with detection of new virus streams and the direction and drivers of viral evolution; the medical aspect dealing with patient treatment development, pathogen testing protocols, and dissemination of medical supplies; the control aspect dealing with forecasting events, infection spread, cost-benefit analysis of preventative action, and vaccine distribution; and the human aspect dealing with education of the general public on pathogen spread and pandemic understanding. Dr. Bromberg raised several questions for the active participants to consider, ranging from how best to map the environments of viral spread to how best to educate the general public of the threat pandemics pose to our society.

Gerardo Chowell, Professor, Georgia State University

Dr. Gerardo Chowell discussed challenges in data sourcing and quality mathematical epidemiologists face when developing pandemic models. With an emerging pandemic, many disparate data sources, including demographics, social behaviors, and mobility, need to be integrated to create an accurate, coherent model. However, in reality, the fragmentation of these data sources and the noisiness of data limit utilization. Dr. Chowell closed by providing areas of improvement for the future. These include training emerging researchers to develop a common language for research-specific jargon; deeper understanding of transmission environments; developing advanced technologies for future pandemics; and a more integrated approach to pandemic prediction.

Utkan Demirci, Professor, Stanford University

Dr. Utkan Demirci discussed the importance of point of care tools for tracking pathogens. He highlighted the need for technologies that can directly measure viral genomic material due to the current limitation of antibody/antigen testing that won't show a positive result for 4-6 days after infection. Dr. Demirci noted that emerging pathogens may be more prevalent in the future and point of care tools will be a simple, cost-effective tool to monitor these pathogens and potentially predict future outbreaks.

James Holland Jones, Associate Professor, Stanford University

Dr. James Holland Jones highlighted the difficulties in predicting and controlling pandemic outcomes due to the unpredictability of human behaviors. He noted that when faced with uncertainty, due to an information poor environment, like the beginning of a pandemic, humans naturally rely on social heuristics, which may not lead to the best outcomes. Even if we develop the most sophisticated models of viral transmission and pandemic forecasting, if a portion of the population denies the existence of a pandemic, the models won't provide accurate predictions. Because of this, Dr. Jones strongly advocates for incorporating human behavior in infectious disease theories; the development of tools for dealing with information poor situations to better prepare us for the next pandemic; and full incorporation, from the start, of social-behavioral sciences in interdisciplinary pandemic research.

Eric Lofgren, Assistant Professor, Washington State University

Dr. Eric Lofgren discussed the weaknesses of the current hospital environment and the synergies he saw while viewing the other plenary presentations. Health care systems can often amplify and disseminate infectious pathogens due to a higher concentration of infected individuals within an enclosed space. There is typically a delay between when a pathogen arrives at a hospital and when the hospital first detects it resulting in increased attack rate, slow response time, and micro-epidemics at hospitals. Dr. Lofgren described several examples of intersections of his own work with the other plenary speakers including, framing a hospital setting as a third layer of mixing in epidemics; the importance of data streams being collected ahead of time; structure of network models and the how these structures arise; how the population views risk; and change or anomaly detection in hospital data during pandemics.

Martina Morris, Professor Emerita, University of Washington

Dr. Martina Morris provided an overview of various modeling frameworks to establish a common language for the disparate fields represented at the workshop. Deterministic compartmental models, agent-based models, and network models can all be used for pandemic modeling and prediction, each with their strengths and weaknesses. Within these modeling frameworks, statistical, based on data, and mechanistic, based on first principles, models can be used for each. Generally, there are three levels of the network structure, macro describes the global flows, meso describes movement and flows at the community level, and micro describes flows at the individual level. Finally, Dr. Morris concluded with describing what she thought was critically needed including, statistically integrated epidemic models, pro-active data collection that is made to feed into models, and efficient algorithms.

Alex Olshevsky, Assistant Professor, Boston University

Dr. Alex Olshevsky summarized his work on using geographic spatiality to understand pandemic spread and determining intervention efficacy. Using a geographical framework for interactions between infected and susceptible individuals in SIR models can be more useful than the traditional assumption of uniform interaction because human interaction occurrence is better described by geographical proximity. Developing a network model under this framework allows for model-agnostic patterns to develop and helps researchers come to conclusions without deep understanding of the network. The primary weakness of this modeling technique is that the model is qualitative. Integration of more data sources is needed for these models to provide actionable data. Dr. Olshevsky highlighted that although coefficients of these network models may look similar at first, they can greatly diverge over time, illustrating the difficulty of predicting pandemic course from network data alone.

Sadie Ryan, Associate Professor, University of Florida

Dr. Sadie Ryan described her work on creating risk maps of various pathogens. By integrating population density maps, future climate risk maps, and mechanistic models of pathogens, high fidelity risk maps can be developed to identify future transmission likelihood across the globe. Dr. Ryan highlighted that these maps are very useful tools in communicating actionable information to policymakers. She concluded by identifying the two overarching themes of the plenary talks, interactions at multiple scales and type of transmission and noted how each of the plenary speakers fit into these themes.

Themis Sapsis, Associate Professor, Massachusetts Institute of Technology

Dr. Themis Sapsis described his work on prediction of extreme events and the similarities he saw with pandemic prediction. He noted that pandemic prediction is similar to prediction of extreme events because they consist of high dimensional space, incorporate large networks, are sensitive to small perturbations, and consist of a critical threshold where an event has a strong likelihood of occurring. Additionally, he noted targeted, smart data is more important than big data and that active learning algorithms alone are not sufficient for large network models. Because of this, Dr. Sapsis stressed the need for deeper theoretical understanding of viral transmission to aid in developing more accurate models that rely less on data.

Venu Veeravalli, Distinguished Professor, University of Illinois – Urbana-Champaign

Dr. Venu Veeravalli discussed quickest change detection (QCD) for predicting and monitoring pandemics. QCD can be used to provide real-time feedback during data collection and can be useful for monitoring data online. Using this technique, researchers were able to effectively predict a second wave of the pandemic. Dr. Veeravalli noted future work will focus on identifying the best parameters (pre-indicators) to monitor such that QCD can accurately detect the emergence of a coming pandemic.

Nina Fefferman, Professor, University of Tennessee – Knoxville

Dr. Nina Fefferman provided a general discussion of the gaps and opportunities in pandemic prediction that weren't discussed by the plenary speakers. This included the basic definition of what a pandemic is and what constitutes a pandemic; how to best exploit dynamic situations to make informed decisions; and thinking about how human behaviors may affect surveillance efforts and how normal behaviors may signal pandemic emergence. Dr. Fefferman then presented three categories organizing the topics of the plenary presentations to best leverage synergies and collaboration, these are: specific research problems, methodologies to tackle these problems, and factors needed for real-world viability of solutions.

Yannis Paschalidis, Professor, Boston University

Dr. Yannis Paschalidis discussed developing predictive pandemic analytics for COVID-19 outcomes using demographic data. His work was able to predict, with fairly high accuracy, patient outcomes. They are now looking to develop risk models that combine omics data, physiological variables, network epidemic models, and different pathogens. The challenges in developing these predictive models include integration of many features into the model, outliers in datasets, and the lack of historical data. Finally, Dr. Paschalidis and his team are developing models that incorporate prescriptive control measures that can simulate how specific actions can dampen pandemic emergence.

James Moody, Distinguished Professor, Duke University

Dr. James Moody discussed the topics that he would like to learn more about as the workshop moved forward. They fell into three categories, data, models, and dissemination. Dr. Moody noted that messy data is the norm, especially with societal data, and that the key is to effectively use noisy, non-ideal data. Data sharing and distribution will be paramount for a holistic approach. From the modeling aspect, Dr. Moody stressed that simple models can be surprisingly effective in many scenarios, including complex systems. Finally, it is critical to have effective dissemination of information to build public knowledge and effectively communicate to policymakers.

Lydia Bourouiba, Associate Professor, Massachusetts Institute of Technology

Dr. Lydia Bourouiba discussed the key challenges in pandemic prediction. Proper data collection, treatment, storage, and sharing/access is paramount in predicting and identifying emerging pandemics. Tackling model validation when models are so complex and data is so heterogeneous is a huge challenge. Foundational knowledge gaps in biology and physics, including, multi-scale host dynamics, animal spillover, and model integration, must be addressed for robust model development with predictive capabilities.

Panel Discussion Day 1

Much of the panel discussion on Day 1 focused on model validation. There was general agreement that an external data set, that wasn't used in developing the model, is required for validation. Model calibration and model validation are often conflated but are two distinct activities. Model calibration modifies input parameters to match observed statistics, while model validation ensures the output matches observed statistics. Once a model is calibrated to a data set, it cannot be validated against it. It was also noted that having performance metrics can help validate models. However, because models are so application dependent, models validated for a specific purpose or research question could be invalid in other scenarios. The research community's lack of model validation was cited as a challenge.

The discussion then turned towards the challenges in identifying pre-indicators for emerging pandemics. Because of its multi-scale, multi-dimensional nature, identifying the right indicators and whether they will give an appropriate response is difficult. One suggestion was to evaluate high throughput environments for certain disease markers. Previous epidemics and pandemic-potential pathogens have all come from zoonotic origin, so heightened surveillance in pathogen spillover environments, including wet markets in Asia and human-livestock-wildlife interfaces, can help identify pandemic emergence. However, with most widespread surveillance efforts, this may be unpopular and politically unviable.

Panel Discussion Day 2

The panel discussion on Day 2 opened with identifying perspectives that the participants felt were missing from the workshop. It was noted that researchers working at the interfaces, including ecologists and evolutionary biologists, were not well represented. Perspectives of clinicians and those in the medical community were missing as well. How to best garner interest and participation in the workshop, when researchers and clinicians at the forefront of fighting the pandemic, was observed as a major challenge.

The question was then posed whether it is possible to develop well-formed questions and recognize answers without having deep knowledge in a particular field. The development of these questions can foster a more effective collaborative research environment; however, the challenge is finding a research question that is interesting and motivating to all parties involved. It is critical to build these interdisciplinary relationships before pandemics occur such that there is trust within the group to ensure the team operates smoothly during times of crisis.

Finally, the discussion turned towards the value and availability of data. It was noted that the most useful data for pandemic modeling is held in corporate hands. Due to privacy, security, and business concerns, accessing this data is extremely difficult. Privacy preserving data transformations have been done previously, but the inability to use discovery-driven interrogation makes utilization of this type of data limited.

Final Discussion Day 2

The final discussion on Day 2 centered around actionable responses and next steps as a community. Discussion topics included:

- Creating a special edition for research focused on pandemic prediction and preparedness in specific journals;
- Immediately working on the non-scientific but labor-intensive tasks;
- Organizing a recurring conference on pandemic prediction and preparedness;
- Developing Prize competitions to stimulate high-risk, high-reward ideas;
- Organizing future workshops on specific groups within pandemic prediction science;
- Developing a follow-up survey with a listing of topics where participants can vote to distinguish research topics that are interesting to everyone;
- Organizing researcher happy hour and "speed-dating" to increase visibility of other research disciplines and collaboration opportunities; and
- Partnering with other funding agencies or research organizations for a more holistic approach to pandemic science.

Breakout Session Overview

Over the course of two days, the invited speakers and discussants participated in three breakout sessions. The breakout sessions focused on the following topics:

- Breakout Session 1: Basic Research Challenges of Integration with Foundational Understanding
- Breakout Session 2: Applied Research Challenges of Integration in Real-World Scenarios
- Breakout Session 3: Interdisciplinary Research and Cross-Community Initiatives

Within each breakout session, breakout groups discussed the most relevant contribution from their domain of expertise that would be most valuable to pandemic prediction, the barriers to interdisciplinary research, and interdisciplinary research challenges.

In this summary report, the ideas discussed during the breakout sessions, plenary presentations, and panel discussions have been combined and organized topically into major themes, summarized in Chapter 2.

2. Summary of Results

Barriers to Interdisciplinary Research

Throughout the workshop, plenary speakers and active discussants described barriers to interdisciplinary research. These are not technical research questions, but the barriers researchers face when trying to collaborate with others. Barriers with particular focus in discussions are summarized below.

People: To foster effective interdisciplinary collaboration, there must be a balance between disciplinarians and interdisciplinarians. Often, interdisciplinarians can act as bridges between disciplinarians to foster a more open, collaborative environment. However, having an avenue to find the right partners and developing a research question that is both interdisciplinary and interesting to everyone presents significant challenges. Further, interdisciplinary results are not often published in the journals of highest esteem making it difficult for these results to garner wide attention.

Communication: Differences in terminology present significant challenges between researchers in different fields. The same words often don't mean the same thing across disciplines. For effective interdisciplinary collaboration, a common language must first be established to mitigate any miscommunication and confusion.

Two approaches may be used to develop a common understanding. The first is to collaborate on analyzing the same data set and then integrating each other's perspectives and understandings around the common anchor of the shared data set. The second is to start with an overarching conceptual model and each discipline contribute their own "piece" to develop a holistic model. This top-down approach may be better suited for integration of ideas by providing the big-picture for everyone to work from.

Finally, clearer communication between research, policymakers, the medical field, and the general public is needed. The data and information gathered by researchers often aren't easily digested and interpreted outside of the research domain. It is critical for researchers to provide actionable information for policymakers and clinicians and provide clear, consistent, and concise information to the general public.

Institutional Structures for Research: Institutional structures of academia and research organizations limit motivation to work on interdisciplinary research topics. Hiring and promotion traditionally values advancing a specific discipline, de-incentivizing research faculty, especially young faculty, to explore interdisciplinary research questions. The "boom-bust" cycle of funding for research on trendy pathogens or diseases is particularly harmful in establishing sustained research efforts, building meaningful collaborative relationships, and leads to numerous unfinished projects. To mitigate the siloed structuring of the research community, academia must recognize interdisciplinarity as a valid career track, train students more broadly, and incentivize research careers that inform policy.

Participants noted that funding of longer-term (20 year) centers and inter-agency partnerships would be more beneficial to support sustained interdisciplinary work. It was also strongly stressed to make sufficient funds available for individual principal investigator efforts to avoid concentrating funding into the hands of the few.

Coordination of Data and Scientific Results: With an entrenched intradisciplinary research structure, finding the desired scientific results and data may present significant challenges to interdisciplinary collaboration. As noted above, each field uses its own databases, data format, and terminology such that accessing data and interpreting results across fields becomes cumbersome. Coordinating disparate scientific studies to meet interdisciplinary challenges presents additional barriers. Building a collaborative, real-time repository of data and results that may be queried without disciplinary jargon can help mitigate these challenges.

Interdisciplinary Research Challenges

Numerous technical interdisciplinary research challenges emerged throughout the workshop. Challenges that were given additional focus in conversations are detailed below.

Modeling: Developing a multi-scale model that succinctly integrates interactions at all scales and couples both mechanistic and statistical approaches may perhaps be the grand challenge in pandemic prediction. Each discipline has their own models for a specific domain and scale, but integrating these models can be challenging. Naming conventions, data access and retrieval, and code syntax may all be different for respective fields. Developing a unified language among researchers is only the first step towards developing a holistic predictive model for pandemics. As noted above, a top-down approach may be more beneficial in large, interdisciplinary efforts.

There was agreement that incorporating human behavioral data is the top priority for robust, pandemic prediction models. For this purpose, it is critical to fully integrate social-behavioral sciences in pandemic research. As was noted in the plenary session, integration of human behavior in infectious disease theories will greatly help in building predictive models.

Finally, data standardization will enable models to dynamically incorporate data and adapt as it becomes available. With cleaner, consistent data, machine learning techniques can be used more effectively to evaluate potential virus escape routes and viral therapeutics.

Foundational Science: Pandemic prediction is a very complex, multi-dimensional problem. In general, three layers of understanding are needed for proper prediction: 1) pandemic emergence and behavior in the observable system, 2) emergence of substrate systems in which pandemics emerge, and 3) thresholds of system behaviors to determine that a pandemic has emerged. Each of these layers has their own foundational research challenges.

Discussion centered around needing a more fundamental understanding of emerging pathogens on all levels (molecular, physiological, and environmental) to determine pre-indicators of pandemics. One of the primary gaps in knowledge is the occurrence, prevalence, and mechanisms of viral spillover from animals to humans. Furthermore, much knowledge is needed on the pathogen evolution in the animal kingdom and whether certain external factors (population density, climate change) can impact zoonotic transmission likelihood.

Data Access and Quality: Open access to databases, data collection techniques, and data standardizations will only encourage robust scientific discovery. The most oft-cited complaint of many researchers across disciplines is the difficulties in accessing data and lack of consistent data formatting, hindering constructive peer-review. Additionally, several plenary speakers noted the messy, inconsistent datasets that must often be used, limiting insights and modeling capabilities. It was noted that NSF could institute and enforce data management plans to try to align datasets from disparate research fields.

A broader discussion focused on the value of data. Hospitals and private entities are increasingly wary about sharing patient data, that may be critical in developing predictive models, due to privacy, security, economic reasons. As more institutions and organizations become hesitant to openly share data, the need to purchase data will take away precious funds from actual research endeavors.

Epidemiology and Viral Surveillance: Development of a robust, viral surveillance system can help epidemiologists track emerging pathogens and may help predict the next pandemic. However, the methods and frequency of sample collection and data storage are riddled with privacy and security concerns. Wastewater sampling and testing may be one solution that alleviates many of these worries. As more data is collected, formal risk assessment protocols, including viral surveillance threshold values, may provide epidemiologists, public health officials, and policymakers with a clearer decision-making process to allow for a consistent, centralized response to any potential pandemic.

Integration Across Scales: As noted many times throughout the workshop, pandemics are multi-scale, multi-dimensional problems requiring expertise across all scales. Integration of this knowledge must come from disparate research teams, agencies, and organizations necessitating a collaborative environment. Developing a holistic framework that can incorporate multi-scale phenomena would greatly help in developing models for pandemic prediction. However, the mechanisms of pandemic emergence are still unclear. Are pandemics rare because the things that lead to them are independently rare or is the confluence of pandemic causing mechanisms rare? Integrating knowledge across scales may help answer this question. As Dr. Bashir noted in his mini-talk, a systems-engineering approach may be needed to tackle these multi-scale, multi-pronged endeavors to integrate components and knowledge at all levels.

Research to Action: A challenge for the scientific community at large is generating timely, actionable information for policymakers. During the current pandemic, it has become abundantly clear that the timescales between scientists and policymakers are drastically different. Scientists desire longer timescales to fully develop theories and models to make the most accurate predictions, while policymakers must make decisions quickly, often with incomplete information, to try to mitigate the pandemic's effects and save lives. As a research community, we must communicate clearly, concisely, and consistently to inform policy and gain public trust during times of crises.

Participant input from the breakout sessions have been topically organized and summarized in Table 1. A complete collection of breakout session input is included in *Appendix C: Breakout Session Participant Input*.

Table 1: Summary of Interdisciplinary Research Challenges
Modeling
● Developing new models to replace traditional modeling practices ● Developing local heterogeneous dynamics models ● Developing a mathematical, systems model for pathogens ● Developing ecological niche models that define abiotic or environmental limits of species ● Developing modeling and planning tools that consider various factors ● Integrating agent-based and network models ● Developing a common testbed for testing and validation of models ● Integrating human behavior into models ● Developing models that incorporate intervention efficacy
Foundational Science
● Identifying fundamental drivers of pathogen spillover from animal kingdom to human populations ● Better understanding of evolution of pandemics in the animal kingdom ● Identifying pre-indicators for pandemic emergence ● Better understanding of rare pathogens, including understanding of "uninteresting" or experimental viruses that may provide useful insights ● Identifying distinct markers of viruses ● Understanding network dynamics in the context of viruses ● Elucidating connection between genotype and transmissibility, disease severity, and mutagenesis ● Understanding pathogen behavior to external, environmental stimuli
Data and AI/ML
● Leveraging deep learning to evaluate virus escape routes ● Developing robust anomaly detection algorithms ● Leveraging machine learning to iteratively design therapeutic molecules ● Accessing patient and hospital data ● Open data sources for accelerated analysis in times of great need (i.e., pandemics) ● Leveraging statistical approaches to allow for a variety of perspectives in data analysis ● Creating adaptive, dynamic models using AI to incorporate new data/information as it is available ● Dealing with messy, incomplete, or missing data. Often the case in social sciences
Epidemiology and Viral Surveillance
● Developing a surveillance system that is robust, non-invasive, and secure ● Balancing sampling frequency and method with privacy and security ● Developing formal risk assessment protocols for pandemics ● Identifying threshold values of certain parameters to indicate pandemic emergence
Integration Across Scales
● Integrating knowledge and expertise from disparate research disciplines and scales ● Developing a single framework to describe processes from smaller scales to larger scales ● Integrating models at different scales and understanding what happens at the "seams"
Research to Action
● Contextualizing data sources and results for clear, concise communication to policymakers, clinicians, and the general public. ● Balancing the need for more time to fully flesh out predictions/analysis and providing policymakers answers that are "good enough"

Post-Workshop Survey

A post-workshop survey was sent to all participants to allow them the opportunity to provide additional thoughts and feedback they did not get to express or think of during the workshop. Nearly all survey respondents stated that they are interested in participating in an ongoing community following the workshop. Over half of the respondents stated that the meeting helped them to consider new problems and inspire new research directions in pandemic prediction. Comments from the respondents covered a wide range of topics, including:

- publishing a white paper for the wider community that summarizes the discussions and conclusions from the workshop,
- coordinating a joint NSF-NIH institute or section that focuses on long-term, interdisciplinary research,
- creating an initiative for pandemic prediction similar to OneHealth,
- integrating the four PIPP workshop take-aways into a cohesive document,
- studying plant diseases and their effects on global society,
- highlighting the importance of interdisciplinary collaborations and how to best foster these relationships,
- highlighting what they thought went well with the workshop and what could be improved, and
- finding new intersections of their work with work of others.

A complete list of survey responses can be found in *Appendix D: Post-Workshop Survey Responses*.

Finally, respondents were asked to distribute $100 million on various research topics to identify topics or research areas that may require the most resources. As *Table 2* shows, there is no single topic area that has significantly more funding allocation than the others. This may suggest no single topic area requires significantly more resources – and therefore development – in pandemic prevention. However, it must be noted that this only illustrates the views of survey respondents and not of the other workshop participants or greater research community.

Table 2: Breakdown of total funds by percentage and average funding for each topic area identified in the post-workshop survey

Topic Area	Average Funding ($ Million)	Percentage of Total Funds
Basic Cell Biology Research	12.5	8%
Vaccine Pipeline	19.1	14%
Disease Modeling	17.0	14%
Social Responsiveness	14.1	12%
Zoonotic Transmission	12.2	9%
Mathematical Control Theory	6.9	4%
Testing Methodology	10.5	7%
Machine Learning for Early Detection	12.2	9%
Disaster Preparedness	14.1	11%
Ecological Disease Pathways	12.9	9%
Other	16.9	3%

Appendix A: Agenda

Day 1 – Thursday, February 25		
Time (ET)	**Segment**	**Speaker**
11:00 – 11:10 AM	Opening Remarks	Sethuraman Panchanathan, NSF
11:10 – 11:20 AM	Welcome Statement	Katharina Dittmar, NSF
11:20 – 11:30 AM	Workshop Introduction	Symposium Chairs
11:30 – 11:35 AM	Workshop Agenda, Structure, and Processes	Emmanuel Taylor, Energetics
11:35 AM – 12:30 PM	Plenary Mini-Talks	Plenary Speakers
12:30 – 1:00 PM	Break	
1:00 – 1:30 PM	Plenary Mini-Talks, continued	● Plenary Speakers ● Symposium Chairs
1:30 – 2:20 PM	Panel Discussion	● Plenary Speakers ● Invited Discussants ● Symposium Chairs
2:20 – 2:30 PM	Webinar Wrap-Up	Nina Fefferman, UTK
2:30 – 3:30 PM	Break	
3:30 – 4:30 PM	Breakout Session 1	Active Participants
4:30 – 4:45 PM	Break	
4:45 – 5:45 PM	Breakout Session 2	Active Participants
5:45 – 6:00 PM	Closing Discussion	Symposium Chairs

Day 2 – Friday, February 26		
Time (ET)	**Segment**	**Speaker**
11:00 – 11:10 AM	Welcome to Day 2	Symposium Chairs
11:10 AM – 12:15 PM	Day 1 Breakout Session Report Outs	Symposium Chairs
12:15 – 12:30 PM	Break	
12:30 – 1:20 PM	Panel Discussion	● Plenary Speakers ● Invited Discussants ● Symposium Chairs
1:20 – 1:30 PM	Workshop Webinar Closing Remarks	Katharina Dittmar, NSF
1:30 – 2:30 PM	Break	
2:30 – 3:45 PM	Breakout Session 3	Active Participants
3:45 – 4:00 PM	Break	
4:00 – 5:15 PM	Final Discussion	● Plenary Speakers ● Invited Discussants ● Symposium Chairs
5:15 – 5:30 PM	Concluding Thoughts	Symposium Chairs

Appendix B: Workshop Participants

Name	Institution
Scott Acton	NSF
Jimi Adams	University of Colorado - Denver
Prakash Aditya	Georgia Institute of Technology
Kristen Ajmo	Energetics
Ery Arias-Castro	University of California - San Diego
David Banks	Duke University
Rashid Bashir	University of Illinois - Urbana-Champaign
Mitra Basu	NSF
Mario Bernardo	University of Naples Federico II
Michel Boufadel	New Jersey Institute of Technology
Lydia Bourouiba	Massachusetts Institute of Technology
Yana Bromberg	Rutgers University
Carter Butts	University of California - Irvine
Kartik Chandran	Columbia University
Philip Chan	Florida Institute of Technology
Cynthia Chen	University of Washington
Misha Chertkov	University of Arizona
Gerardo Chowell	Georgia State University
Sara Citrenbaum	SoSA Corp
Alin Coman	Princeton University
Angelique Corthals	CUNY -John Jay College
Fred Crowson	Energetics
Siddhartha Dalal	Columbia University
Pamela de lost Reyes	Energetics
Utkan Demirci	Stanford University
Mamadou Diallo	NSF
Katharina Dittmar	NSF
Andrea Egizi	Monmouth Country Tick-Borne Disease Laboratory
Stephen Eubank	University of Virginia
Nina Fefferman	University of Tennessee - Knoxville
Rebecca Ferrell	NSF
David Finnoff	University of Wyoming
Marti Head	Oak Ridge National Laboratory
Juliet Iwelunmor	Saint Louis University
Christine Johnson	UC-Davis
James Jones	Stanford University
Admela Jukan	NSF
Yannis Kevrekidis	Johns Hopkins University
Henry Lam	Columbia University

Name	Institution
Mary J Lancaster	Pacific Northwest National Laboratory
Heather Liddell	Energetics
Eric Lofgren	Washington State University
Elebeoba May	NSF
Matthew Mietchen	Washington State University
Marissa Milstein	University of Minnesota College of Veterinary Medicine
Urbashi Mitra	University of Southern California
James Moody	Duke University
Cris Moore	Santa Fe Institute
Martina Morris	University of Washington
José Moura	Carnegie Mellon University
Viet Anh Nguyen	Stanford University
Wendy Nilsen	NSF
Alex Olshevsky	Boston University
Mona Papeş	University of Tennessee - Knoxville
Yannis Paschalidis	Boston University
Shai Pilosof	Ben-Gurion University of the Negev
Radha Poovedran	University of Washington
Kavita Ramanan	Brown University
Audrey Reinert	The University of Oklahoma
Sadie Ryan	University of Florida
Ridah Sabouni	Energetics
Themis Sapsis	Massachusetts Institute of Technology
Saswati Sarkar	University of Pennsylvania
Daniel Segre	Boston University
Diane Sellers	Energetics
Saray Shai	Wesleyan University
Kenta Shimizu	Energetics
Joanna Shisler	NSF
Vivek Singh	Rutgers University
Chris Stone	Illinois Natural History Survey
Nian Sun	Northeastern University
Basar Tamer	University of Illinois - Urbana-Champaign
Emmanuel Taylor	Energetics
Paul Torrens	New York University
Maya Trotz	University of South Florida
Venu Veeravalli	University of Illinois - Urbana-Champaign
Maya Wang	Georgia Institute of Technology
Joseph Whitmeyer	NSF
Krysta Wigginton	Michigan
Shelby Wilson	JHU Applied Physics Laboratory
Brian Wood	UCLA

Name	Institution
Goli Yamini	NSF
John Yin	University of Wisconsin - Madison
Preeti Zanwar	Texas A&M University
John Zhang	NSF
June Zhang	University of Hawaii at Manoa

Appendix C: Breakout Session Participant Input

The tables below show a more comprehensive summary of the breakout session input and are included for completeness. The input summarized in this section has been minimally edited and clarified. The insights that have been drawn from this data is highlighted in the main body of this report.

Breakout Session 1: Basic Research Challenges of Integration in Foundational Understanding

Breakout Session 1 identified basic research challenges through four breakout groups organized along the following themes:

1) Integration Across Disciplines
2) Integration Across Scales
3) Integration of Real-World with Foundational Progress
4) Integration of Knowledge with Action

The participant discussions in each breakout group focused on identifying A) the greatest contribution to pandemic science, B) barriers to interdisciplinary collaboration, and C) interdisciplinary research challenges.

A. Greatest Contribution to Pandemic Science
Integration Across Disciplines
● Knowledge base in network science, epidemiology, etc.; can we marry the two? ● Contact tracing; why only directly exposed contacts? delay in testing ● Multi-hop contact tracing; roots in communication networks ● On pandemic response, disjoint between beliefs and norms ● Impact of norms vs beliefs on behavior; when they're aligned; how they shape behavior; ● Challenge between; bridging the gap between network conception, which often assumes we know the network/graph; takes human work and intelligence to understand the graph; varies by disease and transmission mechanism; Cultural gap within the sciences, between those whose work explicitly assumes we can find out the network; others desire to go beyond compartmentalized models; middle ground, inventing synthetic networks, qualitatively similar to the real network ● Different fields have different notions for validating hybrid / mixed models ● Missing data to figure out the missing spaces in the models we're building ● Need data to support theoretical models and estimates ● Many efforts done in parallel, but not synced up ● The data itself would be a worthwhile contribution ● Society has to invest in the capacity to reduce the change disease outbreaks become pandemic ● Investments need to be made, when you don't think you need it; before things come into play ● If it does make the jump, investments should allow us to lower the consequences ● Boom-bust cycle of investment in this science, modeling; can be dangerous ● Many epidemiologists do not understand the modeling; disconnect between academia and surveillance

● Understanding infrastructure challenges when attempting to move funding in the right direction ● Building the surveillance infrastructure, how we collect data; collaboration between universities and agencies
Integration Across Scales
● Use of deep learning to evaluate viruses escape route. ● Development of local heterogenous dynamics models. Detecting anomalies outside the baseline normal. Establishing a normal and then detecting. ● Enhanced understanding of processes across scales - develop a single framework to describe the processes from the smaller scales to the larger scales ● Connecting ecological mechanisms to something that can be put on a landscape ● Ecological niche modeling: use models to define the abiotic or environmental limits of specifies ● Building computational platform to understand at atomistic level using physics models and ML to iteratively design molecules that have the potential for therapeutics ● Calibration of models across scales (agent-based models) - to generate synthetic data to train graphical models ● Stationary distribution. Add continuous time dynamic. Gives probability of which individual in the population is susceptible to infection or region at risk ● Ongoing dynamics in self-organization for dynamic fuzzy feedback control
Integration of Real-World with Foundational Progress
● Integrate toward all hazards ● Need for academic and "on the ground" inputs ● Test capabilities with better sensitivities ● Collaboration across all disciplines at all levels (student to experienced researcher) ● NSF to bring together collaborators from different disciplines ● Need means of predicting pre-indicators of a pandemic for new diseases ● Underlying substrate of risk before breakout on a massive scale
Integration of Knowledge with Action
● Need for constant surveillance and to detect anything that's off and determining if anomalies are meaningful ● Statistical approach allows you to approach data from a variety of perspectives ● From public health perspective: contextualizing data sources (where it's coming from) and bringing results to public health sphere ● From AI-enabled support system perspective: the ability to adapt the models to new information that becomes available ● From social science perspective, a barrier is that availability of data is not always available when it's needed. There's an opportunity to learn from large data sets and their lessons learned ● Variants are emerging, data is available on behavior of historic viruses

B. Barriers to Interdisciplinary Collaboration
Integration Across Disciplines
● Funding for collaborative / interdisciplinary work can be limited ● Venues for dissemination; journals and conferences with editorial boards that include different disciplines / communities; also, readers from different communities ● Disciplines focus on general results; devil is in the details, but not all disciplines appreciate this ● Economists like to use the tools of others, not necessarily interdisciplinary. How were the tools formulated? constraints? fundamental assumptions? may be overlooked ● Reward structures within disciplines; power differentials, assumed hierarchies of expertise within and across disciplines ● Theorists don't take time to gain domain knowledge ● OTS tools for network analysis are often used without understanding if they're appropriate; are theoretical or data analysis tools appropriate? ● When resources are scarce, supported work (winners) are supported by EVERY discipline ● Disagreement can serve as a veto, can require endorsement from all disciplines ● Perception: anthropologists are difficult to work with ● Funding and university structure promotes siloed work, along with reward structures, publication requirements
Integration Across Scales
● Communications between disciplines, don't know the language of other areas ● Industry - had clear mission and encouraged to work across disciplines. National labs - lack of reward structure for interdisciplinary work ● Mechanism of communication is data. Lack of a data architecture that can be understood across disciplines ● Rewards system: it's a question system. How to find a question that is interesting for all these people? Finding shared questions.
Integration of Real-World with Foundational Progress
● Disciplinary collaborations ● Training in the various disciplines ● Domain knowledge; knowledge gaps ● Fostering initiatives; put PIs in groups

C. Interdisciplinary Research Challenges
Integration Across Disciplines
● Trying to pull in collaborators as early as possible; even if they are unsure about their contribution; early involvement has shown positive results ● Barriers can be more structural

- Lack of a specific discipline can be a barrier for those whose work crosses traditional academic barriers
- Need to dig deeper within one's one discipline can discourage collaboration across disciplines
- people don't always consider behavior as a solution to optimization problems; people stray from quantifying costs to people

Integration of Real-World with Foundational Progress

- Money and resources
- Need experimental models and means of testing/validating
- Experimental viruses needed to study and model conditions without a real pandemic
- Classes of viruses to experimental purposes to model and predict new biological materials
- Identify classes of risk sets
- NIH and NSF involvement through cooperative funding
- Ground-truthing

Integration of Knowledge with Action

- From economic perspective, we know the cost of the pandemic, but it's unclear what the cost of preventing pandemic. You can't quantify benefits of prevention; hard to sell to funding sources
- Unclear if academia is the best place for establishing pandemic prevention. Also need to understand surveillance
- From academic side, there's no natural home for doing modeling with available frameworks, data needed, conditions under which you might use one tool over another. This area does not have a home to produce the knowledge base and skillset to respond to pandemics
- Computer scientists have broad exposure to many disciplines but seek better understanding of the nuances of specific disciplines.
- Models don't always reflect response to intervention. Models can tell you what can happen in current setting but can't address what transpired over the past year (e.g., social behavior, community behavior). Need to model societal responses to actions
- Need better understanding of evolution of a pandemic in animal world. Understanding the potential actions that may block the jump into humans
- There's a lot of data available on pathogen studies but disconnect with medical community to share that information. Budget is also limited
- Pandemic preparedness doesn't have a natural home in a particular discipline or funding agency. It's unclear whether NSF, NIH, CDC should be called upon in understanding pandemic prediction. It's also hard for researchers from other disciplines to find each other
- Similar barrier in academia - no home for pandemic preparedness
- From economic perspective, we know the cost of the pandemic, but it's unclear what the cost of preventing pandemic. You can't quantify benefits of prevention; hard to sell to funding sources
- Interdisciplinary teams don't necessarily go deep enough into specialties

Breakout Session 2: Applied Research Challenges of Integration with Real World Scenarios

Breakout Session 2 identified applied research challenges through four breakout groups organized along the following themes:

1) Prediction, Detection, Control, and Prevention
2) Endogenous vs Exogenous Threat
3) Research Infrastructure and Data Sharing
4) Balancing Prediction for Severity vs Likelihood of Risk

The participant discussions in each breakout group focused on identifying A) the greatest contribution to pandemic science, B) barriers to interdisciplinary collaboration, and C) interdisciplinary research challenges.

A. Greatest Contribution to Pandemic Science
Prediction, Detection, Control, and Prevention
● Succinct description of the contribution ● Model virus transport, surfaces ● Statistical modeling of disease; capturing spatial variability ● Model system for prediction; point of care sensor for covid ● Attempting to predict occurrences in high dimensional space ● How do we develop model systems to validate theories? ● Parallel development of models, data collection, validation, etc. ● Is there a way to develop models in advance of when the next pandemic emerges? ● Regarding computational epidemiology models; models can give you different information, depending on the phase of the epidemic ● Beginning, assess the risk of pandemic; later, assess the risk of new strains ● Network based models; we want data that's represented over a graph, most of the time, we have total aggregate data, the type of data we have isn't enough to fit the models, estimate from eh aggregated data, the much finer, high dimensional state ● Modeling, agencies, county level; to make it applied, we rely on data ● Graph data is already statistical, cannot be used directly in agent-based models ● Opportunity to develop theoretical models can generate a chain of relations (data), actual and synthetic data ● Low cost, high sensitivity virus models, quickly developed; develop them using molecular amplification-based approaches vs antigen approaches ● If using compartmental models; it's simple to think of human behavior as fixed, people change behavior based on circumstances; implications for pandemic prevention; people will be most risky when risk low; this can drive upswings ● Managing appropriate tradeoffs; like testing; one hop testing can miss large clusters; exploit vs explode; exploration vs exploitation ● Tracking SARS-COVID-2 and its diversity in surrogate streams, like wastewater; shedding can start before systems manifest themselves, and persist after symptoms cease; translating the responses from pool test scenarios, which indicate what's happening in a community; tracking back to the community

● Local epidemiology looking at smaller epidemics as a system; contributions to larger areas; systems thinking, what output is driving epidemics in other areas
Endogenous vs Exogenous Threat
● Ability of doctors without borders to build in country capacity so there is not a great shock to the system ● Providing greater access to large volume of verifiable data and data collection techniques (e.g., looking at cellphone movement for contact tracing). More creative data and access to it. ● Better understanding of the transmission of rare pathogens (and harmless). Are there other viruses expanding? Can we isolate conditions? Need to have funding for study of uninteresting viruses. ● Better understanding of markers of viruses ● Need modeling and planning tools that take into account the various factors (e.g., similar to DARPA/DoD) ● Greater understanding of the network dynamics in the context of viruses. Identify subnetworks most at risk (e.g., prisons). And parameters themselves. Thresholds that you cross. ● Viruses: Three types of dynamical systems. Primary host. Intermediate animal population. ● Work needs to be done on what it means when we ask these questions -- Formal risk assessment protocols. ● THIS conversation
Research Infrastructure and Data Sharing
● Models for mechanisms onto landscape ● Models of behavior matter for pandemic control ● Scale for making decisions for contact structure (privacy/proprietary) ● Socio-behavioral elements in the models (people are not the same) ● Socio-behavioral (hesitancy to get vaccine in model) ● Keeping networks going between pandemics ● Socio-politico aspects ● Data sharing templates - practice open science progress
Balancing Prediction for Severity vs Likelihood of Risk
● Molecular therapeutics for COVID-19 using computation platform: looking for molecules that reduce severity of the disease and balance that with the risk of creating safety hazard or triggering mutations ● Epidemiology perspective - basic estimation of who's at risk, likelihood of outcomes. ● Data science / AI perspective - 1) model drives to specific outcome associated with severity. As the model is developed, it provides the likelihood of outcome. Outcomes could be expressed in costs that take into account severity or likelihood. ● In ML, when the model predicts a likelihood that correlates with severity, it's easy to identify something that's severe, but not as easy to identify something mild or moderate. There's more data on what's severe than what's on moderate.

- Evaluating severity vs. likelihood between diseases - Trying to predict what disease settles into which category is challenging
- Challenge - not always sure what we're looking for in ML.
- Supervised vs unsupervised ML methods. ML handles supervised problems better. Unsupervised is harder with statistical estimates, detecting anomalies, etc.
- From distributional ecology domain, which focuses on predicting distributions of the elements of disease ecology (vectors, reservoirs), the contribution is providing maps of likelihood of outbreak risks whose reservoir we know, or list of reservoirs. Mapping of risk of the element of disease, probability of suitability in species of interest

C. Interdisciplinary Research Challenges

Prediction, Detection, Control, and Prevention

- How our evolutionary pressures, in the world today, climate, population density, etc.; how do they fundamentally impact switchovers from animals to humans, etc.; what are the fundamental drivers? Happening more often, basic science to be done here
- Pre-indicators, panel of markers for pandemic emergence; truly predictive of an event about to take off
- Lack of funding to support collaborative research (seed money); can you pull people from other projects, to focus on pandemic research; or related teaching; major programs exist, barriers to entry / success; do not reflect the breadth of this challenge
- Time is required to learn to work with other disciplines; seed money must support sustained effort
- Funding schemes, in agencies and countries; what schemes lead to better innovation? large vs small pots? smaller, more distributed investments can be used to build a baseline of innovation, taskforce that can respond
- Dogmas; compartmental models; space for new models, new thinking; how to encourage / fund this? how to inject it into these big changes
- Pandemics are global by definition; international collaborations are helpful; funding for global work should be systematically incentivized; from any agency
- Whether research and innovation in climate modeling; required bringing many fields together; data access, multi-scale modeling; many similarities to pandemic emergence; massive investment into centers, trainings, agreements for data sharing, etc.; could not have happened through disjoint efforts at different agencies; intentional collaboration; much to learn from that effort, in building the needed infrastructure
- Tendency to look where the light is shining the brightest, not considering other possibilities; what else is in the water? environmental surveillance is useful, and many knew, but it took time for the approach to be accepted; US has moved; CDC national scale surveillance campaign. NSF, others have followed; looking where else the repositories of information lie, not just the conventional

Endogenous vs Exogenous Threat

- Lack of tools and techniques are not one-size fits all.

Research Infrastructure and Data Sharing
• Lack of well-organized data templates and data sharing agreements • Need to include socio-behavioral parameters in models and data • Basic skills gaps - need better skill base to deal with interdisciplinary needs • Disciplines that are reluctant to engage - solution: population and interdisciplinary centers ($$?) • Interdisciplinary grant opportunities - some disciplines get little funding and rely on other well-funded disciplines to support their research • Interdisciplinary research requires more time but not the same for funding • Incentives for applying for funding to address the applied research challenges • Inter-institutional challenges • Need research infrastructure • Open modeling as well as open data especially for an accelerated time frame
Balancing Prediction for Severity vs Likelihood of Risk
• Evaluating severity vs. likelihood between diseases - Trying to predict what disease settles into which category is challenging • Challenge - not always sure what we're looking for in ML. • Supervised vs unsupervised ML methods. ML handles supervised problems better. Unsupervised is harder with statistical estimates, detecting anomalies, etc. • Epidemiology we have good retrospective look, but not insight into hand off between the fields of species • Behavior of pathogen in species and in the environment - not always clear. What is it about the specific individual that makes the disease behave the way it does? • Understanding of physiological differences of bat response to other types of coronaviruses - and using this to predict human response • Network effects - even though proteins are the same, the protein interactions might be different between diseases • Interaction of human host proteins are different across diseases. Individual responses may be similar, but lead to different outcomes in aggregation in communities • It's hard to estimate probability of events but may be easier to estimate the path. Are we at that limit where we know the deterministic pathways, or are there multiple pathways that lead to the event? • Formation of a single home to address this challenge is needed • There is a lot of disease specificity in current research efforts, but it's rare to find researchers studying broader parameters • Estimates of abiotic space or environmental space for species depends on what we know about that species. In emerging diseases, the vectors and reservoirs aren't broadly known. • What if we don't know what we're looking for yet? Researchers are working on their pet species and diseases. Use unsupervised learning to identify sequences that are coming from something that will possibly impact someone. (e.g., if a camel pathogen has the risk of jumping to humans, the camel research community might not be large enough to yield data) • Interaction with epidemic spreading community is needed to understand impact of virus that is spreading from species to species

- Ecologists and biologists could develop "dangerous" animals from the type of pathogens they have, and have epidemiologist or social scientist assess likelihood of communities interacting with that animal
- Feedback for NSF: Researchers are lacking a funding mechanism for disciplines to goes beyond their own disciplines

Breakout Session 3: Reflections on the Workshop

The third, and final, breakout session focused on reflecting on how the workshop had changed the participants' perspectives and thinking through five questions:

1. How has this workshop changed your thinking so far?
2. What commonalities do you see in the challenges discussed by the different breakout rooms yesterday?
3. How do we balance figuring out what we need and advocating for what we need?
4. How should NSF structure its initiatives to fund interdisciplinary collaboration in pandemic preparedness (prevention, intervention)?
5. What community-building activities (e.g., conferences, recurring workshops) can help?

Reflections on the Workshop
How has this workshop changed your thinking so far?

- Not changed so much as re-focused. Provided an opportunity to step back from day-to-day pandemic response and think about the process more.
- There's clearly a willingness. The thing I'm questioning is to how to sustain enthusiasm/interest/viability post-pandemic.
- Made me think more about the role of research (theoretical and applied) in ongoing crises - how can preparedness be organized across domains / time scales and integrated into operations?
- Important to think outside of the box and to bring in new perspectives and to welcome and find ways to integrate more smoothly critical views and new approaches into innovation networks and solutions. More work is needed to make sure that structural changes enable such integration to be regular not just random or occasional. Key to not fall back on classical tools/models/clicks/monolithic funding schemes that clearly did not work so far as best as one would hope to prepare for a pandemic.
- It feels like the sole problems of interaction are communication (what's important to you?) and rewards (funding/publication) mechanisms. I had not thought much about talking to sociologists to enrich my work. In fact, I would need an intermediate from public health or biosensing communities to see the link. However, the collected data and insight into that data could definitely make a difference. Bottom line -- I underestimated the expanse of questions (and hence the difficulty)
- I think interdisciplinary research is a must in fighting an emergent pandemic—COVID-19. Availability of instantaneous records is still an issue, but a generalization of the pandemic transmission is a proper and most fitting solution right now.

- We need to collect and share "war stories" of how scientists responded to requests from policymakers for actionable recommendations on short time scales: e.g., "tell me right now whether we should reopen our elementary school!" How do we rise to society's demands while still being principled academics?
- This workshop has made me aware of the full range of issues that go into modeling the pandemic and connected me with several people whose work I would want to glance through (I have already done some of this), and could potentially write to clarify doubts, and ask questions to determine where I could be most effective.
- I think bringing people to the table without defensiveness of "my discipline already solved our version of this problem" is harder than I thought (and I already knew it was hard). I think perhaps it means good new collaboration communities should start with repositories of curated contributions.
- This workshop as solidified my views of the many silos that remain in research in general. It is a lot harder than I thought to break them. The bridge between the social and so-called natural sciences and mathematics needs to be build better. It would be great to have NSF, NIH and DoD form a new center for interdisciplinarity and intersectional, and inter-administration center that is resilient to politics, no matter what executive administration is in place
- We need more social and behavioral-science integration. Human behavior can have profound impacts on dynamics, typically nonlinear, and often swamping other effects. This is a two-sided problem but flattening the hierarchies across interdisciplinary teams would go a long way toward getting social scientists more engaged. Can't get enough $$ from NSF to fund the personnel we need and (at least I) can't get NIH interested.
- It feels like there is a genuine lack of awareness regarding the ways in which "non-traditional" industries/communities can contribute to these major research initiatives.
- Can we identify and discuss some of the domains or areas of expertise to pursue successful research on pandemics?
- We need robust control approaches (more like resilience than stability in ecology/complex systems). How do we distribute vaccines when we have pockets of anti-vaccine sentiment that are themselves contagious, for example?
- While I feel this interdisciplinary workshop was crucial as a catalyst and was wonderful to get an idea of the full scope of the problem, it would be nice to subsequently also have smaller interdisciplinary meetings, possibly between just two or three sub-disciplines where we could talk about specific issues, models, and collaborations, and then perhaps meet again in a large group after several of these smaller interactions.
- We have seen the need for data and on COVID-19 there are NYTimes, Johns Hopkins and others but can we discuss what are relevant repositories of data?
- I don't think that I was aware to then kind of mismatch between the data that we have and the models/techniques that we have to deal with missing/noisy/uncertain data. Seems like we need better theory that takes into account the kind of data and the kind of uncertainty that we have in the data (especially compared to other disasters like weather and so on where we have far more accurate data)
- "How to create incentives (tenure mechanisms, grants, research recognition) for prioritizing cross-discipline work? How to reach out to those not in the ""choir""?

- It feels like it is important to distinguish between rapid-response issues, and investments in longer term research infrastructure/methods/research. The NSF response to each would be quite different.
- Emphasizes the importance of data interdependencies/sharing. How to best open access?
- This area must be addressed jointly by NSF and NIH, otherwise there is the risk of wheel reinvention and unaddressed gaps
- Clear role for interdisciplinary centers; how to fund long-term?
- Workshop reinforced that there's a disconnect between answering questions that address operational gaps and addressing research gaps.
- I was surprised to see that we mostly agree on the major issues: communication, time, resources
- It hadn't occurred to me previously that there was such a mismatch between the expertise in modeling and time it takes to put together data streams, modelers, models, get to peer review, and all those goals, AND the timeline for actually doing pandemic response. That was repeatedly mentioned and buying something called TIME is a weird ask for a funder, so I'm not sure what we'll do with that
- We need model sharing (in the form of robust, scientifically reviewed software) as well as data sharing
- We've had discussion on the importance of early warning signs of emerging pathogens and predicting "the next big thing", and that understanding transmission ecology of currently rare pathogens is important to that, but very little on concretely how to do that and what kind of interdisciplinary work would help us move toward that.
- Easier than I thought? I think we have loads of tools/training in informatics, data management, de-identification, human subjects, privacy, etc. so we can connect those to people - just needs to be done!
- I still don't know whether NSF can increase the size of funding chunks or fund clinical work to make these connections, or if they will have to join forces with NIH/CDC/DOD. It is now impossible to fund a graduate student to fully train them within one NSF grant. "
- Agreeing on goals and reward of interdisciplinary resources, shared resources (cross disciplinary data sharing architectures) seem harder than I suspected. This portion seems like it will require a larger agency to prioritize and incentivize these goals.
- Interoperability of data structures continues to be a hard nut to crack. Unclear if that's due to lack of resources to address it or not considered a big enough problem.
- Funding streams will have to be crossed in the future--the funding agencies (e.g., NIH, NSF, DoD, HHS) to jointly fund efforts of interest across their domains. This will require them to coordinate priorities among their mission spaces

What commonalities do you see in the challenges discussed by the different breakout rooms yesterday?

- We need a funding program and (at least) a training program to bring in more human behavior. The money available from the SBE programs simply isn't enough to fund the personnel necessary.
- DATA. Other common challenges were too big for me to deal with (structure of academia, funding, etc.) -- I can't deal with those things!

- The biggest barriers do seem aligned around incentives/rewards. Perhaps we could start a professional letter-writing/awards in interdisciplinary science/ways to demonstrate the value within the community to hiring committees, tenure review boards, etc.?
- Put our money where our talk is: actually, implement interdisciplinarity, and from all the breakout room, it seems funding is a major part of implementing it.
- The opportunity is for us to go out of our silos in engineering and computer science and partner with biologists and social scientists and behavioral scientists
- Everyone wants to reach out to different disciplines but has no idea how to go about it I'm thinking there needs to be a tinder for cross-disciplinary research collaborations.
- one opportunity is a frank discussion of how each field treats data/theory/models. What data is available? What kind of models do they use? How robust are these models' predictions if data is unavailable or wrong? Is the goal of the models to produce qualitative insights (e.g., transmission in hospitals or households is important, identity groups can polarize around behaviors) or quantitative ones (exactly how much, or when, will this happen?)
- Commonality: Resource dependence, funding uncertainty.
- Language/communication and opportunities - but it's hard to define what kind or what shape that would have to take (e.g., is it more conferences or more centers, and how would you know you wanted to go to one)
- Common base challenge: Systems models -- feedback, cycles, dynamics.
- Insufficient funding over long time-frames.
- Incentives to truly participate in interdisciplinary work.
- Strong belief that a multidisciplinary approach is required to solve complex problems. This is not found across all domains.
- Are the incentives there for me to pursue interdisciplinary research (is obtaining funding easier, papers accepted in higher impact journals, etc.)? If not, can we change that?

How do we balance figuring out what we need and advocating for what we need?

- By showing the impact of what we propose using a language that is accessible t policy makers and public in general --simple but compelling words
- Perhaps we have professional society positions focused on advocacy back to funders/administrators/policy makers? That way, as groups decide what they need, they have a designated voice who has a clear way to show that as service to their discipline?
- I guess we need more slack -- can't be careening from crisis to crisis. This means more personnel and less need for constantly hustling to get the next too-small grant. HHMI style maybe or something like SFI.
- I feel like I'm not understanding the question. You have to figure out what you need before you can advocate for it. What is there to balance?
- Squashing your research question into the shape of the latest RFP?
- These are too closely linked to be disentangles, I think.
- don't forget also balancing doing the work. Each of these "tasks"--figuring out, advocating, and research/writing--can be full time jobs by themselves. The balance is hard.
- How much effort goes into influencing the direction/priorities of funding calls?

How should NSF structure its initiatives to fund interdisciplinary collaboration in pandemic preparedness (prevention, intervention)?

- I would want to see a funding stream dedicated to building interdisciplinary teams. The NIH has a similar mechanism which provides researchers enough money to hold a few workshops and clearly articulate the problem prior to submitting a full application
- Partner with CDC to solicit proposals on this topic. May require longer term sustained funding because traditional public health funding tends to be very reactionary ("boom and bust" as was mentioned earlier)
- Create venue for interdisciplinary funding. Solicit proposals that require different fields, but require that they really mesh together
- Should funding for intervention be based at NSF?
- Start with small RFP, 1-2 years. If team shows valuable progress, then NSF can provide larger funding amounts later
- Adopt model like supercomputing centers, perhaps in collaboration with CDC
- Suggestion for NSF to serve as collaboration center point, collection of data supporting research needs, and also playing outreach role that ensures distribution of data to public officials and other decision-makers
- Map the boundaries between disciplines and where the opportunities lie

What community-building activities (e.g., conferences, recurring workshops) can help?

- Un-workshops or lightning talks where researchers from different disciplines offer a short explanation of the big problems they are facing and what sort of help they need.
- Whatever type of activity (summit vs conference vs workshop etc.) it should be annual/ongoing and not a one-time thing so over the years more and more different disciplines/experts can be drawn in and have a change to participate (and also as advancements are made in individual fields there are new opportunities to remix)
- Speaking to the need for incentives is there a way to make these activities prestigious/career forwarding in some way so that attendance is viewed favorably within siloed academic departments
- Summit focusing on pandemics would be helpful
- NSF could publish collective wisdom in pandemic research across specialties
- Support summer school or winter school education program across different communities
- Encourage connections with local communities and regions; see if DHS outreach to local officials can help coordinate pandemic preparedness response

Appendix D: Post-Workshop Survey Responses

Below is a summary of the responses gathered from the post-workshop survey. In all, 35 people responded to the survey.

Table 2: Summary of Post-Workshop Survey Responses
Are there any thoughts you didn't get to share at the meeting or that have occurred to you since that we should include in our recommendations for how the NSF should go forward from here?
● These were very well organized and orchestrated sessions ● Suggest publishing a white paper to share the info from this workshop to wider community; and suggest inviting experts to give webinar hosted by NSF to continue the dialogue, and then to have another workshop in one year. ● One Health-type initiative like this workshop should devote more attention to plant disease. ● We need infrastructure and systematic integration of existing pandemic related knowledge to be able to better predict and prepare for the next one. ● NSF is sponsoring 4 workshops in this area with many overlaps that are apparent to those taking part in more than one. Disseminating/discussing those overlaps should be a point of emphasis going forward. ● The NSF and NIH must create a pandemic institute/section that is independent from the whims of the administration (and its politics) in place. We will never be able to prevent the next pandemic with an administration such as the one in the last four years. There must be a mechanism for continued funding that is also independent. ● We talked about animal disease mostly in terms of surveillance for possible pandemic zoonoses. A One Health perspective suggests the importance of predicting "panzootics" (if that's a word) and, especially with mono-culture practices, widespread outbreaks of plant disease (I won't even try to guess at what that's called). There's an obvious direct impact these can have on global food supply and less obvious impacts on animal- or plant-derived medicines and other critical infrastructure. ● I was hoping that the meeting is more technical to determine the research gaps. ● I am really interested in the genomics of pathogens and in the movement of humans and non-humans that carry various pathogens as a means of surveillance and prediction. ● I attended all or parts of the three NSF workshops and wondering how the ideas generated at each one will be integrated? ● I'm not totally sure what the recommendations are that are going forward, but am happy to see them and add, if needed ● I think that there are fundamental properties about adaptive, co-evolving systems of nodes and links that are important to understand to make better pandemic predictions. ● I learned new things from the short discussion at the workshop, this might be due to the interdisciplinary discussion form participants with different backgrounds and pinning out the issue from their point of views. It is clear that current models of prediction have failed us with current pandemic, and I wish for this workshop to continue to at least prepare active researchers from falling with the same in future ones. ● While relying on those already funded by NSF may be a useful pruning strategy, it likely limits the range of ideas included for consideration. These should be seen as opportunities to expand, rather than re-reward the existing funding pool.

- How do we form cross-disciplinary collaborations that lead to meaningful scholarship, funding and outcomes (impact) of such collaborations?
- No, I felt the thoughts I shared in a few of the break-out groups regarding the need for interdisciplinary research was sufficient.

New Research Directions

- The connection between the social side of disease emergence relative to the science and engineering needs to be further addressed. In the case of COVID the science has clearly indicated many paths (mask wearing, social distancing) that make sense scientifically, but are challenging due to the politics/people-side.
- More work on adding socioeconomics in biological models of infectious diseases
- I got very interested in vaccine hesitancy and disinformation campaigns.
- Pursuing more problems at the intersection of biology, mathematics, engineering, behavioral science.
- The simultaneous occurrence of more than one extreme event. In particular, the possibility that earthquakes strike during a pandemic and how to predict the risk of this happening and managing the after-fall
- The zoonotic aspect of pathogen detection is a really wonderful direction I would be interested in pursuing with the right collaborators.
- I think there are fantastic opportunities in statistical modeling, machine learning and reinforcement learning in this field.
- I am director of the Colorado State University One Health Institute so I have tried to brainstorm large projects that might be feasible related to the different topics discussed.
- It gave me a few ideas about using Explainable AI for exploring how pandemics evolve
- I was becoming aware of the importance of feedbacks from the point-of-care clinical provider, and that was reinforced at the workshop. I am now simply trying to engage better at that level, in order to improve how to frame my work from the outset.
- Understanding adaptive, co-evolving systems of nodes and links.
- Better integrating social and ecological factors within a spatial epidemiology framework.
- In vague terms, it brought forth ideas I would have never thought of alone
- Real-time public health policy making and technologies to curb pandemic spread.
- Antibody drugs and quantification of virus particles
- I gain new knowledge in the regard that were unforeseen at that moment.
- A common theme in the workshop has been uncertainty in our estimates of the various epidemic parameters or network structure. Accounting for this uncertainty is an interesting direction moving forward.
- I came to recognize the importance of integrating engineering into public health issues.
- Integrating social behavior and cultural norms for managing healthcare systems during pandemics with and without natural disasters.
- Human behavior modeling from local news data covering the pandemic --> prediction of human's response to pandemic-related policies from news data
- Estimating and communicating the cost and impact of pandemic prevention (upstream) instead of pandemic prediction (downstream)

Other thoughts to share

- Unfortunately, I didn't receive the breakout sessions and barely had time to background listen the talks, so I wouldn't too heavily weight my responses. My current professional work is in disease surveillance, so I am listening in on these things in order to stay current in the field.
- The social science is still weak. Supply- and demand-side problems. Physical scientists need to take the social science more seriously because it's important for dynamics, control, response, preparedness, etc. Social scientists need to step up their game and be able and willing to contribute.
- It was frustrating that the tight limits on the space in the breakout sessions were not communicated in advance
- Similarly, I would have enjoyed the meeting more if the pre-recorded content had been shared in advance with all attendees (not just the plenary speakers and official participants). "
- We need more money to fund a network of biobanks and their invaluable associated data, such as the Scandinavian model or the Canadian model. Currently, there is 1 call at NSF and a couple at NIH, but with so few resources that most team would not consider them as 'funding' resources.
- This is one of my focus areas moving forward. I currently concentrate on computational biology and bioinformatics. I am definitely interested in identifying potential collaborators with interests in new innovations in computational epidemiology and genomic surveillance.
- Great job organizing this meeting and developing a sense of community over zoom.
- Also, from a broader One Health perspective I wanted to make sure the organizers were aware of the Ecological Forecasting Initiative, which is an international, interdisciplinary consortium working to build a community of practice around predicting ecological systems, which includes a number of folks from the disease ecology community, but also may thinking more broadly about ecosystem services.
- It was a very interesting workshop. At times I questioned whether I should have been there due to being a graduate student. It seemed I might have been the only one, at least that I encountered. Maybe more students should be recruited if that is the case. Otherwise, looking forward to more coming out these efforts.

Appendix E: Speaker Biographies

Rashid Bashir, Distinguished Professor, Department of Electrical and Computer Engineering, University of Illinois – Urbana-Champaign

Dr. Rashid Bashir completed his Ph.D. from Purdue University in Oct. 1992. In Oct. 2007, he joined the University of Illinois at Urbana-Champaign as the Abel Bliss Professor of Engineering, and Professor of Electrical and Computer Engineering & Bioengineering. In Nov 2018, he was appointed as the 15th Dean of the College Engineering at the University of Illinois at Urbana-Champaign.

Lydia Bourouiba, Associate Professor, Department of Civil and Environmental Engineering, Mechanical Engineering, and Institute of Medical Engineering and Science, Massachusetts Institute of Technology

Dr. Lydia Bourouiba is an Associate Professor in the Department of Civil and Environmental Engineering at the Massachusetts Institute of Technology, where she founded and directs the Fluid Dynamics of Disease Transmission Laboratory. Her research specializes in developing and joining advanced fluid dynamics experiments, biophysics, and applied mathematics to elucidate the fundamental multi-scale dynamics of fluid fragmentation, with particular interest in the resulting mixing, transport, and persistence of particles and organisms relevant for contamination and health, where drops, multi-phase, and complex flows are at the core.

Yana Bromberg, Associate Professor, Department of Biochemistry and Microbiology, Rutgers University

Dr. Bromberg received her degrees from SUNY Stony Brook and Columbia University. Her work has been recognized by private and federal agencies, including NASA and NIH. She received an NSF CAREER award and is also a Fellow of the Munich Institute for Advanced Study. Her findings consistently indicate that our world functions via dependencies and interactions at all scales.

Gerardo Chowell, Professor, Department of Population Health Sciences, Georgia State University

Dr. Gerardo Chowell is professor of mathematical epidemiology in the Department of Population Health Sciences in the School of Public Health. He also holds an external affiliation as a Senior Research Fellow at the Division of International Epidemiology and Population Studies at the Fogarty International Center, National Institutes of Health. Before joining Georgia State, Dr. Chowell was an associate professor in the School of Human Evolution and Social Change at Arizona State University.

Utkan Demirci, Professor, Department of Radiology and Canary Center at Stanford for Cancer Early Detection, Stanford University

Dr. Utkan Demirci is currently a Professor with tenure at Stanford University School of Medicine and Principal Investigator of the Demirci Bio-Acoustic MEMS in Medicine (BAMM) Lab at the Canary Center at Stanford for Cancer Early Detection. He received his B.S. degree in Electrical Engineering in 1999 as a James B. Angell Scholar (summa cum laude) from University of Michigan, Ann Arbor. He received his M.S. degree in 2001 in Electrical Engineering, M.S. degree in Management Science and Engineering in 2005, and Ph.D. in Electrical Engineering in 2005, all from Stanford University.

Nina Fefferman, Professor, Department of Ecology and Evolutionary Biology and Department of Mathematics, University of Tennessee – Knoxville

Dr. Nina Fefferman is the incoming Director of the National Institute for Mathematical and Biological Synthesis (NIMBioS) and the Associate Director of the One Health Initiative at the University of Tennessee, Knoxville, where she is also a Professor in both the Departments of Ecology & Evolutionary Biology and Mathematics. Her research uses mathematical modeling to explore the behavior, evolution, and control of complex systems with application in areas from basic science (evolutionary sociobiology and epidemiology) to deployable technology (biosecurity, cybersecurity, and wildlife conservation). Dr. Fefferman has been an active member of the Command, Control, and Interoperability Center for Advanced Data Analysis (CCICADA), a Department of Homeland Security Center of Excellence. She has served on scientific advisory panels/boards for the EPA, Mathematical Biosciences Institute (MBI), and Los Alamos National Laboratories and regularly consults to governmental agencies and private companies. Her work has been funded by NSF, NIH, DHS, DoD, USFWS, and USDA, among others. Dr. Fefferman is passionate about disease prevention and public health, and about communicating the utility and beauty of mathematics as a tool to make people's lives better.

James Holland Jones, Associate Professor, School of Earth, Energy, and Environmental Sciences, Stanford University

Dr. James Holland Jones is a biological anthropologist with research interests in human ecology, demography and life history theory, and the ecology and evolutionary biology of infectious disease. A sampling of current projects includes: (1) human dimensions of primate retroviral transmission, (2) the impact of mobility and social contacts on the spillover and transmission of avian influenza, (3) the demography of residential mobility among Hadza hunter-gatherers, (4) fertility change, economic shocks, and reproductive decisions.

Eric Lofgren, Assistant Professor, Paul G. Allen School of Global Animal Health and Department of Math and Statistics, Washington State University

Dr. Eric Lofgren is an infectious disease epidemiologist whose research focuses on the use of mathematical and computational models of disease transmission, particularly the transmission of antimicrobial resistant infections within and outside healthcare settings, as well as emerging infectious diseases. His work often focuses on producing policy-relevant results, working hand-in-hand with clinicians and policy makers to produce reproducible, quantitative guidance for designing and evaluating public health interventions.

James Moody, Distinguished Professor, Department of Sociology, Duke University

Dr. James Moody is the Robert O. Keohane professor of sociology at Duke University. He has published extensively in the field of social networks, methods, and social theory. His work has focused theoretically on the network foundations of social cohesion and diffusion, with a particular emphasis on building tools and methods for understanding dynamic social networks. He has used network models to help understand school racial segregation, adolescent health, disease spread, economic development, and the development of scientific disciplines.

Martina Morris, Professor Emerita, Department of Sociology, University of Washington

Dr. Martina Morris a sociologist with interests in the analysis of social structure and population dynamics. Her research is interdisciplinary, intersecting with demography, economics, epidemiology and public health, and statistics. Examples from her current projects include the study of partnership networks in the spread of HIV/AIDS, the impact of economic restructuring on inequality and mobility, and the development of Relative Distribution methods for statistical analysis. Dr. Morris joined the faculty at the University of Washington in September 2000.

Alex Olshevsky, Assistant Professor, Department of Electrical and Computer Engineering, Boston University

Dr. Alex Olshevsky is an assistant professor in the Department of Electrical and Computer Engineering at Boston University. He received a B.S. in applied mathematics and electrical engineering from Georgia Tech in 2004, and an M.S. and Ph.D. from MIT in 2006 and 2010, both in electrical engineering and computer science. Previously, he was a postdoctoral scholar at Princeton University and an assistant professor at the University of Illinois, Urbana-Champaign. Dr. Olshevsky is a recipient of the NSF CAREER Award, the Young Investigator award from the Air Force, two best paper awards from SIAM and INFORMS, and three awards for teaching/advising during his time at the University of Illinois.

Yannis Paschalidis, Professor, Department of Electrical and Computer Engineering, Division of Systems Engineering, and Department of Biomedical Engineering, Boston University

Dr. Yannis Paschalidis is a Professor in the College of Engineering at Boston University with joint appointments in the Department of Electrical and Computer Engineering, the Division of Systems Engineering, and the Department of Biomedical Engineering. He is also a Founding Professor of Computing & Data Sciences. He is the Director of the Center for Information and Systems Engineering (CISE) – a Boston University research center with more than 40 affiliated faculty and $8 million of annual research expenditures. He completed his graduate education at the Massachusetts Institute of Technology (MIT) receiving an M.S. (1993) and a Ph.D. (1996) degree, both in Electrical Engineering and Computer Science. In September 1996 he joined Boston University where he has been ever since. He has held visiting appointments with MIT and Columbia University.

Sadie Ryan, Associate Professor, Department of Geography, University of Florida

Dr. Sadie Ryan joined the Emerging Pathogens Institute (EPI) in the fall of 2014. Along with her work with EPI, Ryan works in the College of Liberal Arts and Sciences Department of Geography. Ryan received her Ph.D. from the University of California at Berkeley in 2006. Her research interests include disease ecology, tropical conservation, human-wildlife interface, and spatial modeling. Her interdisciplinary work incorporates tools from quantitative and applied ecology, geography and social science.

Themis Sapsis, Associate Professor, Department of Mechanical Engineering, Massachusetts Institute of Technology

Dr. Themis Sapsis is the Doherty Associate professor in Ocean utilization in the Department of Mechanical Engineering at the Massachusetts Institute of Technology. He received a diploma in naval architecture and marine engineering from the National Technical University of Athens in Greece and his Ph.D. in Mechanical engineering from MIT. His lab focuses on understanding, predicting, and/or optimizing complex engineering and environmental systems where uncertainty or stochasticity is equally important with the dynamics.

Venu Veeravalli, Distinguished Professor, Department of Electrical and Computer Engineering, University of Illinois – Urbana-Champaign

Dr. Venu Veeravalli received the Ph.D. degree in 1992 from Illinois, the M.S. degree in 1987 from Carnegie-Mellon University, and the B. Tech. degree in 1985 from the Indian Institute of Technology, Bombay, (Silver Medal Honors), all in electrical engineering. He joined Illinois in 2000 and is currently a professor in the ECE Department. He also holds appointments in Department of Statistics, the Coordinated Science Laboratory and the Information Trust Institute. Prior to joining Illinois, he was on the faculty of the School of ECE at Cornell University. He served as a program director for communications research at the U.S. National Science Foundation in Arlington, VA during 2003-2005.