OUTLOOK

WE HOPE THAT WITH THIS BOOK WE HAVE BEEN ABLE TO PROVIDE A GLIMPSE INTO THE EMERGING SCIENCE OF COMPUTATIONAL EPIDEMIC MODELING, WHICH PROMISES TO QUANTITATIVELY PROJECT THE "WHEN," "WHERE," AND "HOW" OF EPIDEMICS.

ADVANCES IN MEDICAL TREATMENT, improved healthcare systems, and knowledge of infectious disease agents have provided humankind with an armory of weapons in the fight against infectious diseases. The introduction of antibiotics. The culling of common diseases such as measles, mumps, rubella, and polio. The eradication of smallpox. Each new milestone led practitioners and the public at large to believe that in a few decades we could defeat infectious diseases once and for all. Unfortunately, infectious diseases have had quite a comeback in recent years, with several outbreaks of coronaviruses (more commonly known as SARS and MERS), a major flu pandemic, and an Ebola epidemic of unprecedented proportions. Vector-borne diseases are also on the rise, as exemplified by the elusive Zika epidemic which marched through the Americas in 2015 and 2016. We also realized that our societies are now far more interconnected than in the past. Diseases are able to take advantage of our transportation infrastructures, hopping flights from city to city and country to country, spreading with unprecedented ease. More troubling, the vastly interdependent social, technological, and economic systems characterizing our modern world would be extremely fragile with respect to the disruptive mortality rates of past epidemics like the infamous influenza pandemic of 1918.

The war against infectious diseases is, and will always be, fought in the hospital trenches by medical doctors, healthcare workers, and public health responders. We hope, however, that with this book we have been able to provide a glimpse into the emerging science of computational epidemic modeling, which promises to quantitatively project the "when," "where," and "how" of epidemics.

Computing and data sciences are the keys to predictive modeling, accessing and harnessing also a wealth of novel "intel" such as electronic health records, social media, Internet, mobile phones, and remote sensors. From mining Twitter posts in order to analyze the flu season to using cell-phone data and satellite imagery in order to understand the population movements driving the dissemination of epidemics, a computational approach would strengthen the usual disease surveillance system and provide public health institutions with new intelligence to fight infectious diseases.[1]

In view of the huge potential of predictive modeling, we must also be aware of the many foundational and technical challenges, as well as limitations that have yet to be overcome. While hurricanes do not care about our forecasts, people change their behavior according to the awareness and knowledge of the risks poised by an epidemic. The real-time modeling of the feedback loop between the disease progression and the behavioral adaptation of social systems is still a major issue affecting the predictive power of mathematical and computational models. Another issue is the lack of systematic understanding of the predictive performance of different types of models. How does the accuracy of prediction scale with the complexity of the model? How does data quality affect the reliability of epidemic predictive models? Can we quantify the impact of the intrinsic noisy data-gathering process on the predictions? Which ensemble modeling approach provides the best predictive power? These and many other research questions are still objects of research, often through post hoc assessment[2] or ad hoc "forecasting challenges,"[3] that compare predictive modeling results from different teams and modeling approaches against real-world outbreak data. This is a slow learning process

DATA-DRIVEN MODELS DO MORE THAN JUST FORECAST. MORE, IN GENERAL, DESCRIPTIVE AND PREDICTIVE MODELS PROVIDE RATIONALES AND ANALYSIS TO QUANTITATIVELY SUPPORT PUBLIC HEALTH DECISIONS AND INTERVENTION PLANS.

1 Shweta Bansal et al., "Big data for infectious disease surveillance and modeling," The Journal of Infectious Diseases **214**, S375–S379 (2016)

2 Jean-Paul Chretien et al., "Mathematical modeling of the West Africa Ebola epidemic," Elife **4**, e09186 (2015)

3 Matthew Biggerstaff et al., "Results from the Centers for Disease Control and Prevention's Predict the 2013–2014 Influenza Season Challenge," BMC Infectious Diseases **16**, 357 (2016); "CHIKV Challenge Announces Winners, Progress toward Forecasting the Spread of Infectious Diseases", www.darpa.mil/news-events/2015-05-27

because, luckily enough, epidemic outbreaks are not presenting us with a continuous and abundant flow of events to predict as in meteorology science. For this reason, challenges featuring synthetic datasets of simulated outbreaks have now been introduced to assess predictive modeling performance in a controlled environment.[4]

Data-driven models, however, do more than just forecast. More in general, descriptive and predictive models provide rationales and analysis to quantitatively support public health decisions and intervention plans. They are used to increase situational awareness, for intervention planning, and to find epidemiological explanations. Models also provide ways to create counterfactual scenarios otherwise impossible to explore and to look into causal arguments that can be checked against real-world data. More importantly, they also provide means to fill the gaps when data are scarce or not available. For example, the 2015 Zika epidemic in the Americas remained under the radar of the medical and research communities until early 2016, but it likely emerged in Brazil during the last months of 2013. Computational models are, in this case, used to recreate the evolution of the disease and potentially shed light on the many puzzles concerning the past impact of the epidemic in various parts of Latin America.[5]

The field of predictive epidemic modeling is rapidly evolving, and several more policies and interdisciplinary scientific challenges need to be addressed, from rigorously validating new methodologies to defining appropriate data sharing policies to be adopted during health crises. There is an urgent need to develop the collaborations and scientific initiatives needed to advance the field: it is not a matter of "if" but "when" we will fight the next battle against a pandemic pathogen, and this is a call to arms that should bring the entire research community together, as well as the rest of society.

4 The RAPIDD Ebola challenge, Comparison of disease forecasting models, www.ebola-challenge.org

5 T Alex Perkins et al., "Model-based projections of zika virus infections in childbearing women in the Americas," Nature Microbiology **1**, 16126 (2016)

Suggested Reading

This book is not intended as an academic review of the field of computational and data-driven epidemic modeling. As such, we did not provide references within the text to the huge body of work in the area, as well as to the many seminal works upon which the field is built. Here we propose a number of further readings related to some of the topics discussed throughout the book. This list is far from being exhaustive, and it has obvious biases based on what could be the natural follow-up to dive deeper into what we presented in the book. We apologize in advance to all the outstanding colleagues and fantastic scientists who feel that their contributions are missing from the following list.

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