

# Sen Pei

Assistant Professor  
Department of Environmental Health Sciences  
Mailman School of Public Health  
Columbia University  
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## Research Interest

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My research interests center on the environmental, social, and ecological determinants of infectious disease, with the goal to better understand, predict and prepare for recurrent and emerging outbreaks. I develop mathematical models and computational tools to advance surveillance, forecasting, and control of seasonal and emerging infectious agents. My recent studies focus on respiratory viruses such as influenza and COVID-19 and antimicrobial-resistant pathogens in healthcare systems.

## Academic Appointments

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### Assistant Professor

DEPARTMENT OF ENVIRONMENTAL HEALTH SCIENCES, MAILMAN SCHOOL OF PUBLIC HEALTH, COLUMBIA UNIVERSITY

New York City, USA

Aug 2021 – present

### Associate Research Scientist

DEPARTMENT OF ENVIRONMENTAL HEALTH SCIENCES, MAILMAN SCHOOL OF PUBLIC HEALTH, COLUMBIA UNIVERSITY

New York City, USA

Dec 2018 – Jul 2021

- Research: Data-driven statistical inference and forecast of infectious disease outbreaks

### Post-doctoral Research Scientist

DEPARTMENT OF ENVIRONMENTAL HEALTH SCIENCES, MAILMAN SCHOOL OF PUBLIC HEALTH, COLUMBIA UNIVERSITY

New York City, USA

Dec 2015 – Nov 2018

- Research: Mathematical modeling and real-time forecast of infectious disease spread
- Advisor: Prof. Jeffrey Shaman

## Education

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### Ph.D. in Mathematics

SCHOOL OF MATHEMATICS AND SYSTEMS SCIENCE, BEIHANG UNIVERSITY

Beijing, China

Sep 2010 - July 2015

- Research: Dynamical modeling and empirical study of spreading processes in networks
- Advisor: Prof. Zhiming Zheng

### Visiting Ph.D. Student

LEVICH INSTITUTE AND PHYSICS DEPARTMENT, CITY COLLEGE OF NEW YORK

New York City, USA

Sep 2012 - Dec 2013

- Research: Searching for superspreaders in spreading dynamics
- Advisor: Prof. Hernán A Makse

### B.S. in Mathematics

SCHOOL OF MATHEMATICS AND SYSTEMS SCIENCE, BEIHANG UNIVERSITY

Beijing, China

Sep 2006 - Jun 2010

- Research: One-dimensional chaotic dynamical systems

## Publication

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### PEER REVIEWED JOURNAL

1. Dai, K., Foerster, S., Vora, N.M., Blaney, K., Keeley, C., Hendricks, L., Varma, J.K., Long, T., Shaman J., **Pei, S.** Community transmission of SARS-CoV-2 during the Delta wave in New York City. *BMC Infectious Diseases* 23, 753 (2023).
2. Zhang, R., Tai, J., **Pei, S.** Ensemble inference of unobserved infections in networks using partial observations. *PLoS Computational Biology* 19, e1011355 (2023).

3. Prasad, P.V., Steele, M.K., ..., **Pei, S.**, ..., Biggerstaff, M. Multimodeling approach to evaluating the efficacy of layering pharmaceutical and nonpharmaceutical interventions for influenza pandemics. *Proceedings of the National Academy of Sciences of the United States of America* 120, e2300590120 (2023).
4. Sun, H.C., **Pei, S.**, Wang, L., Sun, Y.Y., Xu, X.K. The Impact of Spring Festival Travel on Epidemic Spreading in China. *Viruses* 15, 1527 (2023).
5. **Pei, S.** Challenges in Forecasting Antimicrobial Resistance (Response). *Emerging Infectious Diseases* 29, 1496-1497 (2023).
6. Zeng, Q., Yu, X., Ni, H., Xiao, L., Xu, T., Wu, H., Chen, Y., Deng, H., Zhang, Y., **Pei, S.**, Xiao, J., Pi, G. Dengue transmission dynamics prediction by combining metapopulation networks and Kalman filter algorithm. *PLoS Neglected Tropical Diseases* 17, e0011418 (2023).
7. Yamana, T.K., Galanti, M., **Pei, S.**, Di Fusco, M., Angulo, F.J., Moran, M.M., Khan, F., Swerdlow, D.L., Shaman, J. The impact of COVID-19 vaccination in the US: Averted burden of SARS-CoV-2-related cases, hospitalizations and deaths. *PLoS ONE* 18, e0275699 (2023).
8. Ryu, S., Han, C., Sheikh, T.A., Achangwa, C., Yang, B., **Pei, S.** Association of public health and social measures on the hand-foot-mouth epidemic in South Korea. *Journal of Infection and Public Health* 16, 859-864 (2023).
9. **Pei, S.**, Blumberg, S., Cascante Vega, J., Robin, T., Zhang, Y., Medford, R.J., Adhikari, B., Shaman, J. Challenges in Forecasting Antimicrobial Resistance. *Emerging Infectious Diseases* 29, 679-685 (2023).
10. Xu, X.K., Liu, X.F., Wang, L., Wu, Y., Lu, X., Wang, X., **Pei, S.** Assessing the spread risk of COVID-19 associated with multi-mode transportation networks in China. *Fundamental Research* 3, 305-310 (2023).
11. Zhang, R., Wang, X., **Pei, S.** Targeted influence maximization in complex networks. *Physica D: Nonlinear Phenomena* 446, 133677 (2023).
12. Du, Z., Zhang, X., Wang, L., Yao, S., Bai, Y., Tan, Q., Xu, X., **Pei, S.**, Xiao, J., Tsang, T.K., Liao, Q., Lau, E.H.Y., Wu, P., Gao, C., Cowling, B.J. Characterizing Human Collective Behaviors During COVID-19 — Hong Kong SAR, China, 2020. *China CDC Weekly* 5, 71-75 (2023).
13. Borchering, R.K., Mullany, L.C., ..., **Pei, S.**, ..., Lessler, J. Impact of SARS-CoV-2 vaccination of children ages 5–11 years on COVID-19 disease burden and resilience to new variants in the United States, November 2021–March 2022: A multi-model study. *The Lancet Regional Health-Americas* 17, 100398 (2023).
14. Zhang, B., Huang, W., **Pei, S.**, Zeng, J., Shen, W., Wang, D., Wang, G., Chen, T., Yang, L., Cheng, P., Wang, D., Shu, Y., Du, X. Mechanisms for the circulation of influenza A(H3N2) in China: A spatiotemporal modelling study. *PLoS Pathogens* 18, e1011046 (2022).
15. Zhang, C., Zhang, X., Bai, Y., Lau, E.H.Y., **Pei, S.** The structural identifiability of a humidity-Driven epidemiological model of influenza transmission. *Viruses* 14, 2795 (2022).
16. Huang, B., Huang, Z., Chen, C., Lin, J., Tam, T., Hong, Y., **Pei, S.** Social vulnerability amplifies the disparate impact of mobility on COVID-19 transmissibility across the United States. *Humanities and Social Sciences Communications* 9, 415 (2022).
17. Du, Z., Wang, L., Shan, S., Lam, D., Tsang, T.K., Xiao, J., Gao, H., Yang, B., Taslim, S., **Pei, S.**, Fung, I.C., Liao, Q., Wu, P., Meyers, L.A., Leung, G.M., Cowling, B.J. Pandemic fatigue impedes mitigation of COVID-19 in Hong Kong. *Proceedings of the National Academy of Sciences of the United States of America* 119, e2213313119 (2022).
18. **Pei, S.**, Kandula, S., Cascante Vega, J., Yang, W., Foerster, S., Thompson, C., Baumgartner, J., Ahuja, S.D., Blaney, K., Varma, J.K., Long, T., Shaman, J. Contact tracing reveals community transmission of COVID-19 in New York City. *Nature Communications* 13, 6307 (2022).
19. Zhang, R., Wang, Y., Lv, Z., **Pei, S.** Evaluating the impact of stay-at-home and quarantine measures on COVID-19 spread. *BMC Infectious Diseases* 22, 648 (2022).
20. Du, Z., Wang, C., Liu, C., Bai, Y., **Pei, S.**, Adam, D.C., Wang, L., Wu, P., Lau, E.H., Cowling, B.J. Systematic review and meta-analyses of superspreading of SARS-CoV-2 infections. *Transboundary and Emerging Diseases* 69, e3007-e3014 (2022).

21. Schneider, T., Dunbar, O.R., Wu, J., Böttcher, L., Burov, D., Garbuno-Inigo, A., Wagner, G.L., **Pei, S.**, Daraio, C., Ferrari, R., Shaman, J. Epidemic management and control through risk-dependent individual contact interventions. *PLoS Computational Biology* 18, e1010171 (2022).
22. Chen, Y., Liu, T., Yu, X., Zeng, Q., Cai, Z., Wu, H., Zhang, Q., Xiao, J., Ma, W., **Pei, S.**, Guo, P. An ensemble forecast system for tracking dynamics of dengue outbreaks and its validation in China. *PLoS Computational Biology* 18, e1010218 (2022).
23. Truelove, S., Smith, C.P., ..., **Pei, S.**, ..., Cecile Viboud. Projected resurgence of COVID-19 in the United States in July-December 2021 resulting from the increased transmissibility of the Delta variant and faltering vaccination. *eLife* 11, e73584 (2022).
24. Cramer, E.Y., Ray, E.L., ..., **Pei, S.**, ..., Reich, N.G. Evaluation of individual and ensemble probabilistic forecasts of COVID-19 mortality in the United States. *Proceedings of the National Academy of Sciences of the United States of America* 119, e2113561119 (2022).
25. Gimbrone, C., Rutherford, C., Kandula, S., Martínez-Alés, G., Shaman, J., Olfson, M., Gould, M.S., **Pei, S.**, Galanti, M., Keyes, K.M. Associations between COVID-19 mobility restrictions and economic, mental health, and suicide-related concerns in the US using cellular phone GPS and Google search volume data. *PLoS ONE* 16, e0260931 (2021).
26. Qi, Y., Shaman, J., **Pei, S.** Quantifying the impact of COVID-19 non-pharmaceutical interventions on influenza transmission in the United States. *The Journal of Infectious Diseases* 224, 1500-1508 (2021). (Featured on the cover)
27. **Pei, S.**, Yamana, T., Kandula, S., Galanti, M., Shaman, J. Burden and characteristics of COVID-19 in the United States during 2020. *Nature* 598, 338–341 (2021).
28. **Pei, S.**, Liljeros, F., Shaman, J. Identifying asymptomatic spreaders of antimicrobial resistant pathogens in hospital settings. *Proceedings of the National Academy of Sciences of the United States of America* 118, e2111190118 (2021).
29. Ma, Y., **Pei, S.**, Shaman, J., Dubrow, R., Chen, K. Role of meteorological factors in the transmission of SARS-CoV-2 in the United States. *Nature Communications* 12, 3602 (2021).
30. Zebrowski, A., Rundle, A., **Pei, S.**, Yaman, T., Yang, W., Carr, B.G., Sims, S., Doorley, R., Schluger, N., Shaman, J., Branas, C. A spatiotemporal tool to project hospital critical care capacity and mortality from COVID-19 in US counties. *American Journal of Public Health* 111, 1113-1122 (2021).
31. Teng, X., **Pei, S.**, Lin, Y. StoCast: Stochastic Disease Forecasting with Progression Uncertainty. *IEEE Journal of Biomedical and Health Informatics* 25, 850-861 (2021).
32. Galanti, M., **Pei, S.**, Yamana, T.K., Angulo, F.J., Charos, A., Swerdlow, D.L., Shaman, J. Social distancing remains key during vaccinations. *Science* 371, 473-474 (2021).
33. **Pei, S.**, Teng, X., Lewis, P., Shaman, J. Optimizing respiratory virus surveillance networks using uncertainty propagation. *Nature Communications* 12, 222 (2021).
34. Xu, X.-K.\*, Wang, L.\*, **Pei, S.\*** Multiscale mobility explains differential associations between the gross domestic product and COVID-19 transmission in Chinese cities. *Journal of Travel Medicine* 28, taaa236 (2021). (\* Equal contribution)
35. **Pei, S.\***, Dahl, K.A.\*, Yamana, T., Licker, R., Shaman, J. Compound risks of hurricane evacuation amid the COVID-19 pandemic in the United States. *GeoHealth* 4, e2020GH000319 (2020). (\* Equal contribution)
36. **Pei, S.**, Kandula, S., Shaman, J. Differential effects of intervention timing on COVID-19 spread in the United States. *Science Advances* 6, eabd6370 (2020).
37. Bomfim, R., **Pei, S.**, Shaman, J., Yamana, T., Makse, H.A., Andrade Jr., J.S., Lima Neto, A.S., Furtado, V. Predicting dengue outbreaks at neighborhood level using human mobility in urban areas. *Journal of the Royal Society Interface* 17, 20200691 (2020).
38. **Pei, S.**, Shaman, J. Aggregating forecasts of multiple respiratory pathogens supports more accurate forecasting of influenza-like illness. *PLoS Computational Biology* 16, e1008301 (2020).
39. Kramer, S.C., **Pei, S.**, Shaman, J. Forecasting influenza in Europe using a meta population model incorporating cross-border commuting and air travel. *PLoS Computational Biology* 16, e1008233 (2020).

40. Zhou, B.\* , **Pei, S.\***, Muchnik, L., Meng, X., Xu, X., Sela, A., Havlin, S., Stanley, H.E. Realistic modelling of information spread using peer-to-peer diffusion patterns. *Nature Human Behaviour* 4, 1198–1207 (2020). (\* Equal contribution)
41. **Pei, S.\***, Wang, J.\* , Morone, F., Makse, H. A. Influencer identification in dynamical complex systems. *Journal of Complex Networks* 8, cnz029 (2020). (\* Equal contribution)
42. Li, R.\* , **Pei, S.\***, Chen, B.\* , Song, Y., Zhang, T., Yang, W., Shaman, J. Substantial undocumented infection facilitates the rapid dissemination of novel coronavirus (SARS-CoV-2). *Science* 368, 489–493 (2020). (\* Equal contribution).
43. Zhang, R., Quan, G., Wang, J., **Pei, S.** Backtracking activation impacts the criticality of excitable networks. *New Journal of Physics* 22, 013038 (2020).
44. Sy, K. T., Shaman, J., Kandula, S., **Pei, S.**, Gould, M., Keyes, K. M. Spatiotemporal Clustering of Suicide Deaths from 1999 to 2016: A Spatial Epidemiological Approach. *Social Psychiatry and Psychiatric Epidemiology* 54, 1471–1482 (2019).
45. Kandula, S., **Pei, S.**, Shaman, J. Improved forecasts of influenza hospitalization rates with Google search trends. *Journal of the Royal Society Interface* 16, 20190080 (2019).
46. **Pei, S.**, Cane, M. A., Shaman, J. Predictability in process-based ensemble forecast of influenza. *PLoS Computational Biology* 15, e1006783 (2019).
47. Wang, J., Zhang, R., Wei, W., **Pei, S.**, Zheng, Z. On the stability of multilayer Boolean networks under targeted immunization. *Chaos: An Interdisciplinary Journal of Nonlinear Science* 29, 013133 (2019).
48. **Pei, S.**, Morone, F., Liljeros, F., Makse, H. A., Shaman, J. Inference and control of the nosocomial transmission of Methicillin-resistant *Staphylococcus aureus*. *eLife* 7, e40977 (2018).
49. **Pei, S.**, Kandula, S., Yang, W., Shaman, J. Forecasting the spatial transmission of influenza in the United States. *Proceedings of the National Academy of Sciences of the United States of America* 115, 2752–2757 (2018).
50. Fu, C., Dong, Z., Shen, J., Yang, Z., Liao, Y., Hu, W., **Pei, S.**, Shaman, J. Rotavirus gastroenteritis infection among children vaccinated and unvaccinated with rotavirus vaccine in southern China: A population-based assessment. *JAMA Network Open* 1, e181382 (2018).
51. Kandula, S., Yamana, T., **Pei, S.**, Yang, W., Morita, H., Shaman, J. Evaluation of mechanistic and statistical methods in forecasting influenza-like illness. *Journal of the Royal Society Interface* 15, 20180174 (2018).
52. Wang, J., **Pei, S.**, Wei, W., Feng, X., Zheng, Z. Optimal stabilization of Boolean networks through collective influence. *Physical Review E: Statistical, Nonlinear, Biological, and Soft Matter Physics* 97, 032305 (2018).
53. Zhang, R., **Pei, S.** Dynamic range maximization in excitable networks. *Chaos: An Interdisciplinary Journal of Nonlinear Science* 28, 013103 (2018).
54. **Pei, S.**, Shaman, J. Counteracting structural errors in ensemble forecast of influenza outbreaks. *Nature Communications* 8, 925 (2017).
55. Wang, X., Li, W., Liu, L., **Pei, S.**, Tang, S., Zheng, Z. Promoting information diffusion through interlayer recovery processes in multiplex networks. *Physical Review E: Statistical, Nonlinear, Biological, and Soft Matter Physics* 96, 032304 (2017).
56. Fu, C., Shen, J., Lu, L., Li, Y., Cao, Y., Wang, M., **Pei, S.**, Yang, Z., Guo, Q., Shaman, J. Pre-Vaccination Evolution of Antibodies among Infants 0, 3 and 6 Months of Age: a Longitudinal Analysis of Measles, Enterovirus 71 and Coxsackievirus 16. *Vaccine* 35(31), 3817–3822 (2017).
57. **Pei, S.**, Teng, X., Shaman, J., Morone, F., Makse, H. A. Efficient collective influence maximization in cascading processes with first-order transitions. *Scientific Reports* 7, 45240 (2017).
58. Teng, X., **Pei, S.**, Morone, F., Makse, H. A. Collective influence of multiple spreaders evaluated by tracing real information flow in large-scale social networks. *Scientific Reports* 6, 36043 (2016).
59. Jiang, S., Tang, S., **Pei, S.**, Fang, W., Zheng, Z. Low dimensional behavior of explosive synchronization on star graph. *Journal of Statistical Mechanics: Theory and Experiment* 2015(10), P10007 (2015).

60. Yan, S., Tang, S., Fang, W., **Pei, S.**, Zheng, Z. Global and local targeted immunization in networks with community structure. *Journal of Statistical Mechanics: Theory and Experiment* 015(8), P08010 (2015).
61. **Pei, S.**, Muchnik, L., Tang, S., Zheng, Z., Makse, H. A. Exploring the complex pattern of information spreading in online blog communities. *PLoS ONE* 10, e0126894 (2015).
62. **Pei, S.**, Tang, S., Zheng, Z. Detecting the influence of spreading in social networks with excitable sensor networks. *PLoS ONE* 10, e0124848 (2015).
63. Tang, S., Teng, X., **Pei, S.**, Yan, S., Zheng, Z. Identification of highly susceptible individuals in complex networks. *Physica A: Statistical Mechanics and its Applications* 432, 363-372 (2015).
64. Zhang, Y., Tang, S., **Pei, S.**, Yan, S., Jiang, S., Zheng, Z. Health behavior spreading with similar diminishing returns effect. *Physica A: Statistical Mechanics and its Applications* 425, 18-26 (2015).
65. Zhang, R., **Pei, S.**, Wei, W., Zheng, Z. Evolution of autocatalytic sets in a competitive percolation model. *Journal of Statistical Mechanics: Theory and Experiment* 2014(11), P11018 (2014).
66. Yan, S., Tang, S., **Pei, S.**, Jiang, S., Zheng, Z. Dynamical immunization strategy for seasonal epidemics. *Physical Review E: Statistical, Nonlinear, Biological, and Soft Matter Physics* 90, 022808 (2014).
67. **Pei, S.**, Muchnik, L., Andrade Jr, J. S., Zheng, Z., Makse, H. A. Searching for superspreaders of information in real-world social media. *Scientific Reports* 4, 5547 (2014).
68. Teng, X., Yan, S., Tang, S., **Pei, S.**, Li, W., Zheng, Z. Individual behavior and social wealth in the spatial public goods game. *Physica A: Statistical Mechanics and its Applications* 402, 141-149 (2014).
69. Li, W., Tang, S., **Pei, S.**, Yan, S., Jiang, S., Teng, X., Zheng, Z. The rumor diffusion process with emerging independent spreaders in complex networks. *Physica A: Statistical Mechanics and its Applications* 397, 121-128 (2014).
70. **Pei, S.**, Makse, H. A. Spreading dynamics in complex networks. *Journal of Statistical Mechanics: Theory and Experiment* 2013(12), P12002 (2013).
71. Muchnik, L.\*, **Pei, S.\***, Parra, L. C.\*, Reis, S. D., Andrade Jr, J. S., Havlin, S., Makse, H. A. Origins of power-law degree distribution in the heterogeneity of human activity in social networks. *Scientific Reports* 3, 1783 (2013). (\* Equal contribution)
72. Yan, S., Tang, S., **Pei, S.**, Jiang, S., Zhang, X., Ding, W., Zheng, Z. The spreading of opposite opinions on online social networks with authoritative nodes. *Physica A: Statistical Mechanics and its Applications* 392, 3846-3855 (2013).
73. **Pei, S.**, Tang, S., Yan, S., Jiang, S., Zhang, X., Zheng, Z. How to enhance the dynamic range of excitatory-inhibitory excitable networks. *Physical Review E: Statistical, Nonlinear, Biological, and Soft Matter Physics* 86, 021909 (2012).
74. **Pei, S.**, Tang, S., Zhang, X., Liu, Z., Zheng, Z. Effects of consumption strategy on wealth distribution on scale-free networks. *Physica A: Statistical Mechanics and its Applications* 391, 2023-2031 (2012).
75. **Pei, S.**, Sun, Y., Zhao, Z., Wang, H., She, Z. Topological Conditions on a Class of One-dimensional Chaotic Maps. *Mathematics in Practice and Theory* 19, 033 (2009). (In Chinese)

## REPORT & PRE-PRINT

76. Yamana, T., **Pei, S.**, Kandula, S., Shaman, J. Projection of COVID-19 Cases and Deaths in the US as Individual States Re-open May 4, 2020. *medRxiv* doi:10.1101/2020.05.04.20090670 (2020).
77. **Pei, S.**, Galanti, M., Yamana, T., Shaman, J. Reconciling Diverse Estimates of COVID-19 Infection Rates. (2020).
78. **Pei, S.**, Shaman, J. Simulation of SARS-CoV2 Spread and Intervention Effects in the Continental US with Variable Contact Rates, March 24, 2020. (2020).
79. **Pei, S.**, Shaman, J. Initial Simulation of SARS-CoV2 Spread and Intervention Effects in the Continental US. *medRxiv* doi:10.1101/2020.03.21.20040303 (2020).

## CONFERENCE

80. **Pei, S.**, Zheng, Z. The dynamics of a class of one-dimensional chaotic maps. *Proceedings of 15th WSEAS International Conference on Applied Mathematics, Athens, Greece* 122-127 (2010).

## EDITORIAL

81. Adhikari, B., Yadav, A., **Pei, S.**, Srivastava, A., Kefayati, S., Rodríguez, A., Charpignon, M.-L., Vullikanti, A., Prakash, B.A., epiDAMIK 5.0: The 5th International Workshop on Epidemiology meets Data Mining and Knowledge Discovery *Proceedings of the 28th ACM SIGKDD Conference on Knowledge Discovery & Data Mining* 4850-4851 (2022).

82. Li, H.-J., Wang, L., Wang, Z., Du, Z., Xia, C., Moustakas, A., **Pei, S.** Editorial: Mathematical Modelling of the Pandemic of 2019 Novel Coronavirus (COVID-19): Patterns, Dynamics, Prediction, and Control. *Frontiers in Physics* 9, 427 (2021).

83. Adhikari, B., Srivastava, A., **Pei, S.**, Kefayati, S., Yu, R., Yadav, A., Rodríguez, A., Ramanathan, A., Vullikanti, A., Prakash, B.A., The 4th International Workshop on Epidemiology meets Data Mining and Knowledge Discovery (epiDAMIK 4.0 @ KDD2021). *Proceedings of the 27th ACM SIGKDD Conference on Knowledge Discovery & Data Mining* 4104-4105 (2021).

## BOOK CHAPTER

84. **Pei, S.**, Morone, F., Makse, H. A. Theories for influencer identification in complex networks. In *Complex Spreading Phenomena in Social Systems*, p.p. 125-148, edited by Sune Lehmann and Yong-Yeol Ahn (Springer Nature, 2018).

## BOOK REVIEW

85. **Pei, S.** Review of Vaccines and Immunization by Chuanxi Fu (editor-in-chief). *Human Vaccines, Immunotherapeutics* (2020). DOI: 10.1080/21645515.2020.1835337.

## Grants

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2023	R21, Inference of heterogeneous transmission of antimicrobial resistant pathogens in health care settings. PI, 2023-2025	NIAID
2023	Cooperative Agreement, Modeling and forecast of COVID-19 and RSV to inform public health decision making. PI, 2023-2024	CSTE & CDC
2022	Impact of climate variability on foreign animal disease: forecasting highly pathogenic avian influenza. PI, 2022-2023	USDA
2022	Human behavior-driven mathematical modeling and forecasting of respiratory disease transmission in urban settings. PI, 2022-2026	NSF & CDC CFA
2022	Cooperative Agreement, Modeling and forecast of COVID-19 at state and county scales. PI, 2021-2023	CSTE & CDC
2021	R01, Quantifying Error Growth to Improve Infectious Disease Forecast Accuracy. Co-I, 2021-2026	NIAID
2020	U01 Supplement, Analysis and simulation of bacterial infections and resource strain in hospitals during the COVID-19 pandemic. MPI, 2020-2022	CDC
2020	U01, Inference, forecasting and optimal control of healthcare-associated infections. MPI, 2020-2025	CDC
2020	Calderone Junior Faculty Award, Identifying asymptomatic colonization with antibiotic-resistant pathogens in hospital settings, PI, 2019-2020	Mailman School of Public Health
2020	Columbia Public Health Innovation Fund, Integrating healthcare data and mathematical models to track antimicrobial resistant pathogens in hospitals, MPI, 2019-2020	Mailman School of Public Health

## Awards

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2021	Fellow, Scialog: Mitigating Zoonotic Threats	Research Corporation for Science Advancement (RCSA)
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2021	Finalist of 2020 AAAS Newcomb Cleveland Prize (7 finalists from all disciplines)	AAAS
2020	Calderone Junior Faculty Award	Mailman School of Public Health
2019	First Prize in Scientific Achievement Category, Awards for Outstanding Research Articles in Biosurveillance	International Society for Disease Surveillance
2016	Outstanding Doctoral Thesis Award	Beihang University
2015	Ph.D. Graduate Excellence Awards (10 winners university-wide)	Beihang University
2014	National Ph.D. Scholarship	Ministry of Education
2009	Gold Medal Award for Undergraduate (10 winners university-wide)	Beihang University
2009	First Prize in “Challenge Cup” National Undergraduate Academic Competition	Ministry of Education

## Academic Services

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### EDITORIAL ACTIVITIES

- Guest Editor, PLoS Neglected Tropical Diseases, 2023
- Guest Editor for Special Issue “Mathematical Models and Computational Tools of Infectious Diseases” in Mathematical Biosciences and Engineering (American Institute of Mathematical Sciences). 2022 – 2023
- Associate Editor: Microbiology Spectrum (American Society for Microbiology), May 2022 – present
- Associate Editor: Frontiers in Physics, May 2022 – present
- Associate Editor: BMC Infectious Diseases, September 2019 – present
- Review Editor: Frontiers in Physics, June 2018 – May 2022
- Guest Associate Editor: Frontiers, Research Topic: Mathematical modelling of the pandemic of 2019 novel coronavirus (COVID-19): Patterns, Dynamics, Prediction, and Control, 2020

### COMMITTEE

- Career MODE Application Review Committee, Columbia EHS, 2023
- Dissertation Committee for Emma Gorin, Columbia EHS, 2022
- Dissertation Committee for Stephen Lewandowski, Columbia EHS, 2022
- Career MODE Application Review Committee, Columbia EHS, 2022

### PROFESSIONAL MEMBERSHIP

- Institute for Operations Research and the Management Sciences (INFORMS), 2022 – present
- Modeling Infectious Diseases in Healthcare Network (MInD - Healthcare), 2020 – present
- Models of Infectious Disease Agent Study (MIDAS), 2019 – present
- National Syndromic Surveillance Program Community of Practice (NSSP CoP), 2019 – present
- International Society for Disease Surveillance (ISDS), 2018 – 2019

### PROFESSIONAL ACTIVITIES

- FluSight real-time influenza forecasting challenges, CDC, 2016 – 2017, 2017 – 2018, 2018 – 2019, 2019 – 2020, 2021 – 2023
- FluCode, Informing Pandemic Influenza Intervention Practice: Coordinated Modeling, CDC, 2019 – 2020
- Columbia projection of COVID-19 spread in the United States, 2020

## PEER REVIEW

Science, PNAS, Nature Communications, Nature Human Behaviour, Nature Computational Science, Nature Machine Intelligence, The Lancet Planetary Health, BMC Medicine, American Journal of Epidemiology, American Journal of Public Health, ACM Transactions on Computing for Healthcare, BMC Bioinformatics, BMC Infectious Diseases, BMJ Open, Bulletin of Mathematical Biology, Chaos: An Interdisciplinary Journal of Nonlinear Science, China CDC Weekly, Communications Medicine, Communications Physics, Disaster Medicine and Public Health Preparedness, Ecology Letters, eLife, Emerging Infectious Diseases, Entropy, Environmental Research, Epidemics, Europhysics Letters, Frontiers in Physics, Frontiers in Public Health, Global Environmental Change, Health Affairs, Human Vaccines & Immunotherapeutics, Infectious Diseases of Poverty, Infection, Genetics and Evolution, International Journal for Uncertainty Quantification, International Journal of Environmental Research and Public Health, IEEE Access, IEEE Transactions on Cybernetics, IEEE Transactions on Control Systems Technology, IEEE Transactions on Network Science and Engineering, JAMA Network Open, Journal of Computational Science, Journal of Infectious Diseases, Journal of Mathematical Biology, Journal of Statistical Mechanics: Theory and Experiments, Journal of Travel Medicine, Meteorological Applications, Mathematical Biosciences and Engineering, Physica A: Statistical Mechanics and its Applications, Physica D: Nonlinear Phenomena, Physics Letters A, PLoS Computational Biology, PLoS Neglected Tropical Diseases, PLoS ONE, PNAS Nexus, Scientific Reports, Trends in Microbiology, Wellcome Open Research

## PROGRAM COMMITTEE

- Session Chair, COVID-19, EPIDEMICS 9, Bologna, Italy, November 29, 2023.
- Program Committee Co-Chair, The 6th International workshop on Epidemiology meets Data Mining and Knowledge discovery (epiDAMIK 6.0), in conjunction with the 2023 ACM SIGKDD International Conference on Knowledge Discovery & Data Mining (ACM SIGKDD 2023).
- Program Committee Co-Chair, The 5th International workshop on Epidemiology meets Data Mining and Knowledge discovery (epiDAMIK 5.0), in conjunction with the 2022 ACM SIGKDD International Conference on Knowledge Discovery & Data Mining (ACM SIGKDD 2022).
- Program Committee Co-Chair, The 4th International workshop on Epidemiology meets Data Mining and Knowledge discovery (epiDAMIK 4.0), in conjunction with the 2021 ACM SIGKDD International Conference on Knowledge Discovery & Data Mining (ACM SIGKDD 2021).
- The SI 2021 Workshop on Social Influence, The Hague, Netherlands, 8th November 2021, in conjunction with the 2021 IEEE/ACM International Conference on Advances in Social Networks Analysis and Mining (ASONAM 2021).
- The SI 2019 Workshop on Social Influence, Vancouver, Canada, 27th August 2019, in conjunction with the 2019 IEEE/ACM International Conference on Advances in Social Networks Analysis and Mining (ASONAM 2019).
- The SI 2018 Workshop on Social Influence, Barcelona, Spain, 28th August 2018, in conjunction with the 2018 IEEE/ACM International Conference on Advances in Social Networks Analysis and Mining (ASONAM 2018).
- The 3rd Workshop on Social Influence, Sydney, Australia, July 2017, in conjunction with the 2017 IEEE/ACM International Conference on Advances in Social Networks Analysis and Mining (ASONAM 2017).

## GRANT REVIEW

- Review panel, NIAID Data Science and Emerging Technologies (R21, U01), NIH, 2022
- Review panel, Division of Behavioral & Cognitive Sciences, NSF, 2022
- Secondary Data Analysis Projects, Health Research Board, Republic of Ireland, 2021
- Review panel, MIDAS COVID-19 Modeling Urgent Grant Program – New Initiatives, 2020

## PANELS AND FELLOWS

- Core participant, NSF PRedicting Emergence Of Virulent Entities By Novel Technologies (PREVENT) Seminar, February 22-23, 2021 (online)
- Fellow, USDA & Research Corporation for Science Advancement, Mitigating Zoonotic Threats, September 30-October 1, 2021 (online)

## Public Outreach

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### PRESS INQUIRY AND INTERVIEW

- The New York Times, Wall Street Journal, CNN, NPR, Bloomberg News, BuzzFeed News, Chicago Tribune, WIRED, POLITICO, Slate, MIT Technology Review, ABC News, Scientific American, The Scientist, National Geographic, USA TODAY Network, Communications of the ACM, WebMD, FiveThirtyEight, ProPublica, Live Science, Milwaukee Journal Sentinel, Tufts Daily, The Times-Picayune, Breathe at Berkeley, El Mercurio Chile, MedPage Today, HealthDay, Courthouse News



## FEATURED MEDIA COVERAGE

- Nature's Research Highlights, A simulation exposes the secret spread of hospital infections. September 9, 2021.
- NIH Director's Blog, COVID-19 Infected Many More Americans in 2020 than Official Tallies Show. September 7, 2021.
- The New York Times, Lockdown Delays Cost at Least 36,000 Lives, Data Show. May 22, 2020.
- The New York Times, Coronavirus Could Overwhelm U.S. Without Urgent Action, Estimates Say. March 20, 2020.
- MIT Technology Review, The Emerging Science of Superspreaders (And How to Tell If You're One Of Them). May 13, 2014.

## Invited Talks

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- 2023 *Use modeling to improve surveillance of antimicrobial resistance (AMR) in hospital settings* Transatlantic Taskforce on Antimicrobial Resistance (TATFAR) in-person meeting, Luxembourg, November 15th 2023.
- 2023 *Inference of asymptomatic carriers of antimicrobial-resistant organisms in healthcare settings using multitype observations.* Modeling Infectious Diseases in Healthcare (MIND - Healthcare) Network meeting, June 27th 2023. (Online)
- 2023 *Modeling spatial transmission of infectious diseases.* "Unifying the epidemiological and evolutionary dynamics of pathogens" workshop, Nordic Institute for Theoretical Physics (NORDITA), Stockholm University, Stockholm, Sweden, May 30th, 2023.
- 2023 *Bayesian inference in networked systems and applications in infectious disease modeling.* STAT@UVM Seminar Series, University of Vermont, May 1st 2023.
- 2023 *Impact of the COVID-19 Pandemic on Influenza.* Biomedical Data Science Virtual Lectures, University of Virginia, April 28th 2023. (Online)
- 2023 *Data-driven mathematical modeling of respiratory diseases.* Human Behavior and Disease Dynamics workshop, University of Maryland, April 24th 2023.
- 2023 *Challenges in Forecasting Antimicrobial Resistance.* Transatlantic Taskforce on Antimicrobial Resistance (TATFAR) meeting, March 27th 2023. (Online)
- 2022 *Contact tracing and transmission of SARS-CoV-2 in New York City.* P30 Joint Environmental Science call, The NIEHS Center for Environmental Health and Justice in Northern Manhattan, December 13th 2022. (Online)
- 2022 *Data-driven mathematical modeling of the spatial spread of respiratory diseases.* The 2nd International Symposium on Spatial Lifecourse Health, Wuhan University, Wuhan, China, December 10th 2022. (Online)
- 2022 *Identifying Asymptomatic Spreaders of Antimicrobial Resistant Pathogens in Hospital Settings.* 2022 INFORMS annual meeting, Indianapolis, IN, USA, October 16th 2022.
- 2022 *Identifying asymptomatic spreaders in complex networks with sparse observations.* The Statistical Inference for Network Models workshop, NetSci 2022, July 12th 2022. (Online)
- 2022 *Data-driven mathematical modeling of infectious diseases.* The first symposium of Urban Informatics, The Hong Kong Polytechnic University, June 22nd 2022. (Online)
- 2022 *Real-time Forecasting of Infectious Disease Spread.* Department of Statistics and Data Science, Southern University of Science and Technology, April 13th 2022. (Online)
- 2022 *Modeling, inference and forecasting of the spatial transmission of respiratory pathogens.* GeoHealth Hub Seminar Series, organized by Geography Department, National University of Singapore, April 8th 2022. (Online)
- 2022 *Data-driven modeling and inference of infectious disease dynamics.* Department of Computer Science, Texas Tech University, January 18th 2022. (Online)
- 2021 *Advancing forecast, surveillance and control of infectious disease.* Eco-epidemiology Lab, Department of Ecology, Evolution, and Environmental Biology, Columbia University, November 23rd 2021.

- 2021 *Data-driven modeling and inference of infectious disease dynamics*. MIT School of Computer Science, Brandeis University, November 19th 2021. (Online)
- 2021 *Reconstructing transmission networks of COVID-19 in New York City using contact tracing data*. Survepi Forward Planning, New York City Department of Health & Mental Hygiene, November 4th 2021. (Online)
- 2021 *Role of meteorological factors in the transmission of SARS-CoV-2 in the United States*. HMS Lecture Series, Department of Health Metrics Sciences, University of Washington, October 22nd 2021. (Online)
- 2021 *Open Data Access for Social Good: Responding to COVID-19 with Spatial Data Science* Data Science Connect, October 22nd 2021. (Online, jointly with Niki Kazahaya and Serina Chang)
- 2021 *Understanding the transmission dynamics of SARS-CoV-2 using mathematical models*. Virtual COVID-19 Symposium, Columbia University, October 20th 2021. (Online)
- 2021 *Parameter inference and identification of asymptomatic carriers of antimicrobial-resistant pathogens in hospital settings*. University of California San Francisco MInD group meeting, July 8th 2021. (Online)
- 2021 *Parameter inference and identification of asymptomatic carriers of antimicrobial-resistant pathogens in hospital settings*. Transatlantic Taskforce on Antimicrobial Resistance (TATFAR) meeting, May 26th 2021. (Online)
- 2021 *Forecasting infectious disease spread*. School of Public Health, Zhejiang Chinese Medical University, China, April 22nd 2021. (Online)
- 2021 *Transmission dynamics of COVID-19 in China and the United States*. The Pathogen Dynamics Group Seminar Series, University of Cambridge, UK, March 12th 2021. (Online)
- 2021 *Advancing forecast, surveillance and control of infectious disease*. Department of Biology, University of Notre Dame, Indiana, USA, February 4th 2021. (Online)
- 2021 *Identifying asymptomatic spreaders of MRSA in hospital settings*. Modeling Infectious Diseases in Healthcare (MInD - Healthcare) Network meeting, January 25th 2021. (Online)
- 2020 *Advancing forecast, surveillance and control of infectious disease*. EHS Department Seminar, Columbia University, New York, USA, November 2nd 2020. (Online)
- 2020 *Forecasting COVID-19 spread in the US*. The CDC COVID-19 forecasting meeting, June 9th 2020. (Online)
- 2020 *Modeling and projecting COVID-19 transmission using geolocation data*. Geolocation Economics, Columbia University, New York, USA, May 4th 2020. (Online)
- 2020 *Modeling the transmission dynamics of COVID-19 in China and US*. Dalian University of Technology, Dalian, China, April 21st 2020. (Online)
- 2020 *Modeling the transmission dynamics of COVID-19 in China and US*. Renmin University of China, Beijing, China, March 30th 2020. (Online)
- 2019 *Utilizing big data to track outbreaks of antimicrobial resistant pathogens*. Presidential Advisory Council on Combating Antibiotic-Resistant Bacteria (PACCARB) Public Meeting, McLean, Virginia, USA, July 10th 2019.
- 2019 *Inference and control of the nosocomial transmission of Methicillin-resistant Staphylococcus aureus*. SPHINx19: Spread of Pathogens in Healthcare Institutions and Networks: a modeling conference, Paris, France, June 24th 2019.
- 2019 *Forecasting the spatial transmission of influenza in the United States*. ISDS (International Society for Disease Surveillance) 2019 Annual Conference, presentation as the First Prize in Scientific Achievement Category, Awards for Outstanding Research Articles in Biosurveillance, San Diego, California, USA, January 31st 2019.
- 2017 *Forecast and inference of infectious disease spread using network models*. EHS Department Seminar, Columbia University, New York, USA, November 20th 2017.
- 2017 *Finding influential spreaders in cascading processes in complex networks*. Dalian University of Technology, Dalian, China, June 16th 2017.

- 2015 *Empirical studies on information spreading in online social networks.* Hangzhou Normal University, Hangzhou, China, July 6th 2015.

## Conferences

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- 2023 *Inference of asymptomatic carriers of antimicrobial-resistant organisms in healthcare settings using multitype observations.* EPIDEMICS 9, Bologna, Italy, November 30th 2023.
- 2023 *Inference of asymptomatic carriers of antimicrobial-resistant organisms in healthcare settings using multitype observations.* MIDAS annual meeting, Atlanta, GA, October 30th 2023.
- 2023 *Modeling neighborhood-level COVID-19 spread in New York City using foot-traffic data.* CSTE in-person meeting, Atlanta, GA, September 19th 2023. (Poster Session)
- 2023 *Ensemble inference of unobserved infections in networks using partial observations.* NetSci 2023, Vienna, Austria, July 12th 2023.
- 2022 *Contact tracing reveals community transmission of COVID-19 in New York City.* 2022 MIDAS Network Annual Meeting, Bethesda, MD, USA, September 8th 2022. (Poster Session)
- 2022 *Identifying asymptomatic spreaders of antimicrobial-resistant pathogens in hospital settings.* Ecology and Evolution of Infectious Diseases (EEID) 2022, Atlanta, GA, USA, June 7th 2022. (Poster Session)
- 2021 *Identifying asymptomatic spreaders of antimicrobial-resistant pathogens in hospital settings.* Epidemics8 - 8th International Conference on Infectious Disease Dynamics, November 30th 2021. (Online)
- 2021 *Identifying asymptomatic spreaders of antimicrobial-resistant pathogens in hospital settings.* Networks 2021: A Joint Sunbelt and NetSci Conference, July 8th 2021. (Online)
- 2021 *Optimizing respiratory virus surveillance networks using uncertainty propagation.* SIAM Conference on Applied Linear Algebra (LA21), Latest Advances in Spectral Linear Algebra in Network Science, May 20th 2021. (Online)
- 2021 *Identifying asymptomatic carriers of antimicrobial-resistant pathogens in hospital settings.* 2021 MIDAS Network Annual Meeting, May 10th 2021. (Online)
- 2020 *Real-time projection of COVID-19 in the United States.* COVID-19 Dynamics & Evolution Conference, October 19th 2020. (Online)
- 2020 *Identifying asymptomatic colonization with antimicrobial-resistant pathogens in hospital settings.* New York City Epidemiology Forum, New York, NY, USA, February 28th 2020. (Poster Session)
- 2019 *Optimizing respiratory virus surveillance networks using uncertainty propagation.* Epidemics7 the seventh International Conference on Infectious Disease Dynamics, Charleston, SC, USA, December 5th 2019.
- 2019 *Forecasting influenza-like-illness by aggregating predictions for multiple respiratory pathogens.* Epidemics7 the seventh International Conference on Infectious Disease Dynamics, Charleston, SC, USA, December 5th 2019. (Poster Session)
- 2019 *Stochastic Progression Forecasting for Alzheimer's and Parkinson's Diseases.*, Modeling the World's Systems 2019, Washington DC, USA, May 12th 2019. (Poster Session)
- 2018 *Inference of the nosocomial transmission dynamics of Methicillin-resistant Staphylococcus aureus.* NIH-MIDAS (Models of Infectious Disease Agent Study) 2018 Annual Meeting, Bethesda, MD, USA, April 4th 2018.
- 2017 *Forecasting the spatial spread of influenza in the United States.* Epidemics6 the sixth International Conference on Infectious Disease Dynamics, Sitges, Spain, November 29th 2017.
- 2017 *Forecasting the spatial transmission of influenza.* NIH-MIDAS (Models of Infectious Disease Agent Study) 2017 Annual Meeting, Atlanta, Georgia, USA, May 23rd 2017.
- 2016 *Improving influenza forecast by counteracting structural errors.* Joint Statistical Meeting 2016, Chicago, Illinois, USA, August 4th 2016.

- 2016 *Improving influenza forecast by counteracting structural errors.* NIH-MIDAS (Models of Infectious Disease Agent Study) 2016 Annual Meeting, Reston, Virginia, USA, May 23rd 2016. (Poster Session)
- 2014 *Searching for superspreaders of information in real-world social media.* 2014 International Conference of Mathematics, Information and Computational Science, Beijing, China, October 21st 2014.
- 2013 *Heterogeneity of human activity levels gives rise to power-law distribution in online social networks.* American Physical Society (APS) March Meeting, Baltimore, Maryland, USA, March 19th 2013.
- 2010 *The dynamics of a class of one-dimensional chaotic maps.* The 15th WSEAS International Conference on Applied Mathematics, Athens, Greece, December 31st 2010.

## Teaching

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### COURSES

- 2022 Spring, EHSCP9370 Journal Club, Department of Environmental Health Science, Columbia University

### GUEST LECTURES

- 2023, P8322 Environmental Determinants of Health II, Introduction to infectious disease modeling (March 9th 2023), Department of Environmental Health Sciences, Columbia University
- 2023, E3B GU4127 Disease Ecology, Modeling spatial spread of respiratory pathogens (February 6th 2023), Department of Ecology, Evolution and Environmental Biology, Columbia University
- 2022, P8322 Environmental Determinants of Health II, Introduction to infectious disease modeling (March 3rd 2022), Department of Environmental Health Sciences, Columbia University
- 2022, E3B GU4127 Disease Ecology, Spatial spread of COVID-19 (February 7th 2022), Department of Ecology, Evolution and Environmental Biology, Columbia University
- 2021, Understanding the transmission dynamics of SARS-CoV-2 using mathematical models (October 20th 2021), Icahn School of Medicine at Mount Sinai
- 2020, Modeling COVID-19: Fighting the COVID-19 Pandemic Using Mathematical Models (September 23rd 2020, online), Icahn School of Medicine at Mount Sinai
- 2020, Summer course: COVID-19 from Virus to Vaccine: Biological, Clinical, and Public Health Dimensions; Virtual Lab: tutorials on mathematical models. (August 25th 2020, online), Mailman School of Public Health, Columbia University
- 2017, Inference of the nosocomial transmission of Methicillin-resistant *Staphylococcus aureus* (December 11th 2017), School of International and Public Affairs, Columbia University

## Mentoring

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- 2023 Young Seo Lee, Undergraduate, Computer Science, Columbia University. *Analyzing human mobility pattern in the US.*
- 2023 Wanxin Qi, MS student, Department of Biostatistics, Mailman School of Public Health, Columbia University. *Practicum project: Visualization and analysis of highly pathogenic avian influenza data in the US.*
- 2023 Yan Wang, MS student, Department of Biostatistics, Mailman School of Public Health, Columbia University. *Practicum project: Quantifying information flow between biomarkers.*
- 2022 Eric Wang, MS student, Department of Biostatistics, Mailman School of Public Health, Columbia University. *Practicum project: Built environment and transmission of COVID-19 in New York City.*
- 2022 Wenjun Mo, MS student, Department of Biostatistics, Mailman School of Public Health, Columbia University. *Human mobility pattern in New York City.*
- 2022 Sze Pui Tsang, MS student, Department of Biostatistics, Mailman School of Public Health, Columbia University. *Practicum project: Quantifying information flow between biomarkers.*
- 2022 Katherine Dai, Undergraduate, Molecular, Cellular, & Developmental Biology and Economics, Yale University; incoming Master's in Modeling for Global Health, University of Oxford. *Analyzing contact tracing data in New York City during Delta wave.*
- 2022 Alex Bala, Undergraduate, Computer Science and Mathematics, Columbia University. *Modeling and identifying interactions of respiratory viruses.*

- 2022 Michal Hajlasz, Undergraduate, Computer Science and Mathematics, Columbia University. *Predictability of human mobility in the US.*
- 2022 Kaiyu He, MS student, Department of Biostatistics, Mailman School of Public Health, Columbia University. *Practicum project: Evaluating response rate to COVID-19 contact tracing interviews in New York City.*
- 2021 Saryu Patel, MS student, Department of Biostatistics, Mailman School of Public Health, Columbia University. *Practicum project: Analyzing contact network structure in hospital settings.*
- 2020 Helen Zhang, MPH student, Department of Epidemiology, Mailman School of Public Health, Columbia University. *Thesis project: Exploratory Analysis of the Characteristics of COVID-19 in the United States using Public Line-list Data.*
- 2020 Yuchen Qi, MS student, Department of Biostatistics, Mailman School of Public Health, Columbia University. *Practicum project: Quantifying the impact of COVID-19 non-pharmaceutical interventions on influenza transmission in the United States.* Published in The Journal of Infectious Diseases.
- 2018 Rafael Bomfim, PhD Candidate, Graduate Program in Applied Computing, University of Fortaleza, Brazil. *Predicting dengue outbreaks at neighborhood level using human mobility in urban areas.* Published in Journal of the Royal Society Interface.