



# Optimization of Stochastic Epidemiological Models for Disease Control and Prediction

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Joint work with: Prof. Michael Kokkolaras

*Journées de l'optimisation 2022*

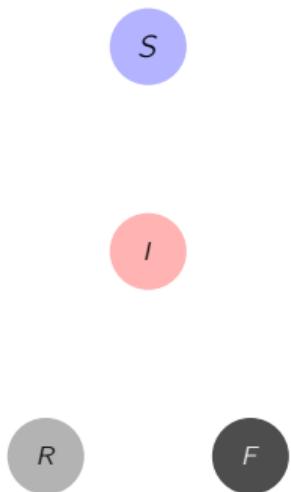
July 24, 2023



# Background: epidemiological models

What are compartmental epidemiological models?

$S$  susceptible     $I$  infected     $R$  recovered     $F$  fatality



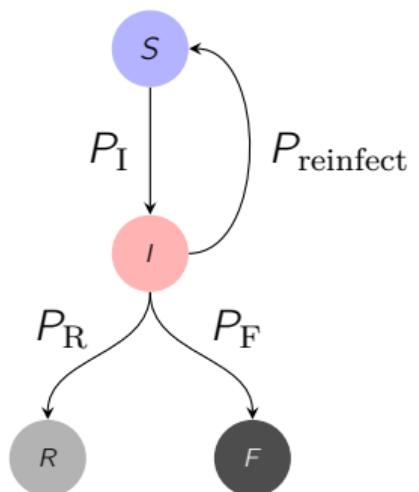


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- Described by a *stochastic* process

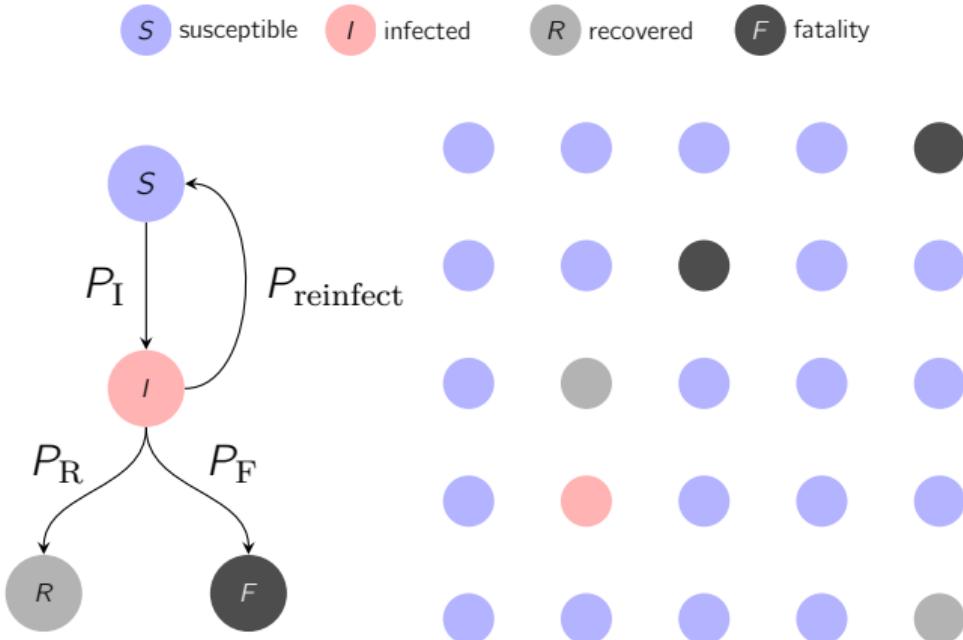




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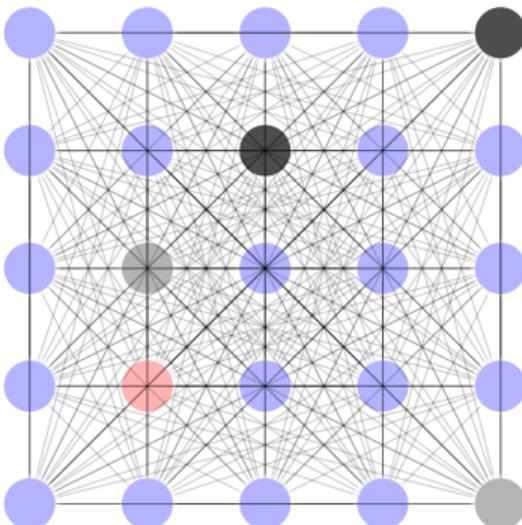
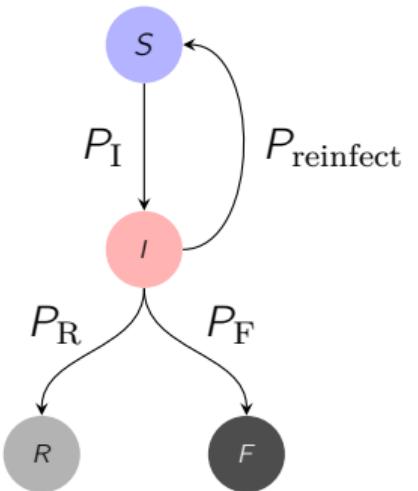


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What are compartmental epidemiological models?

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- Assumes *homogenous* interaction

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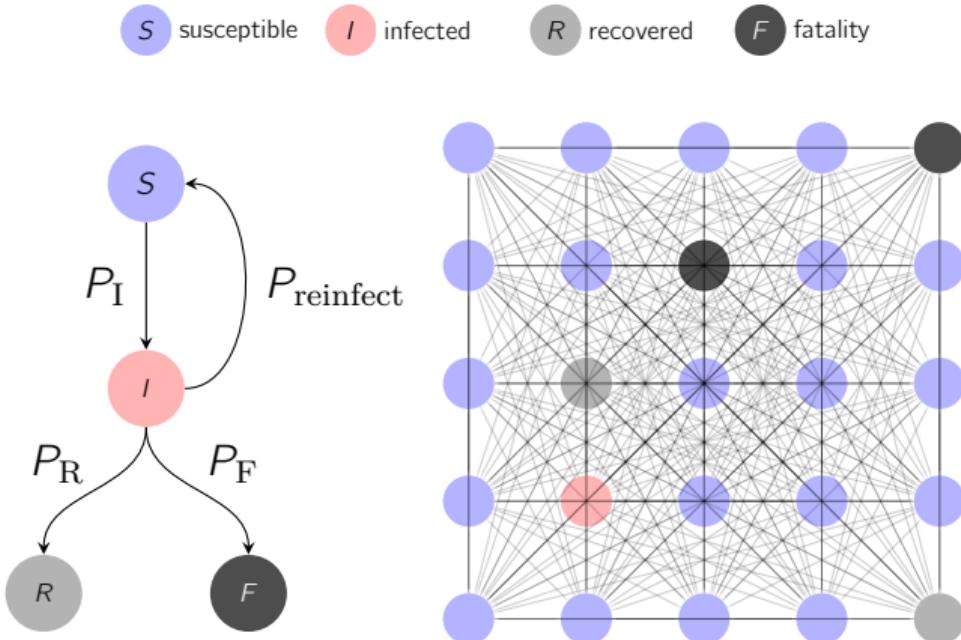




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- Described by a *stochastic* process
- Assumes *homogenous* interaction
- Deterministic response for large  $N$



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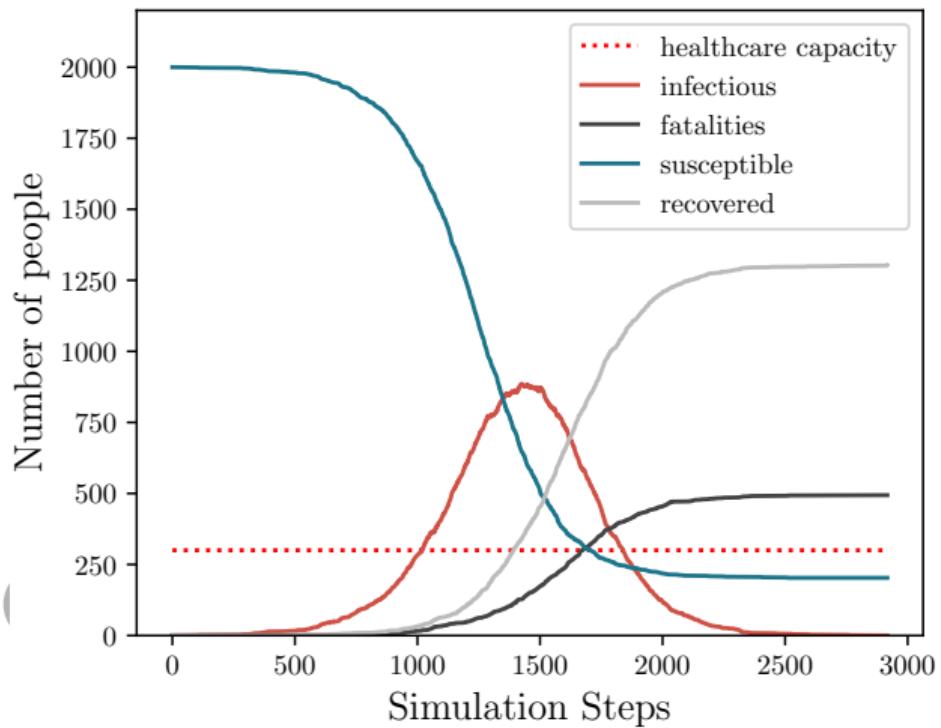
- Described by a *stochastic* process
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- Deterministic response for large  $N$

$$\frac{dS}{dt} = -\frac{\beta IS}{N},$$

$$\frac{dI}{dt} = \frac{\beta IS}{N} - \gamma I,$$

$$\frac{dR}{dt} = \gamma I,$$

where  $N = S + I + R$ ,  $\beta$  controls infection spread, and  $\gamma$  controls recovery rate



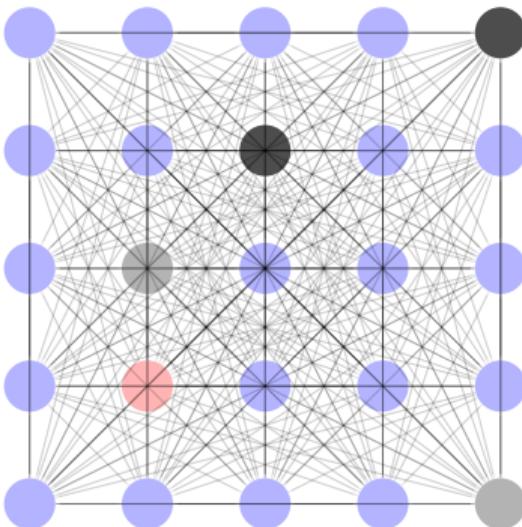
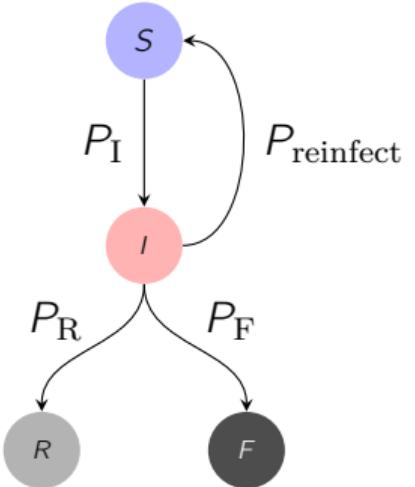


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What are compartmental epidemiological models?

- ✓ Analytical solutions are available

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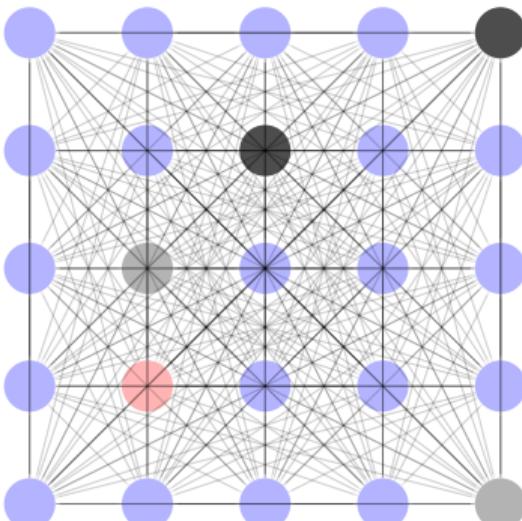
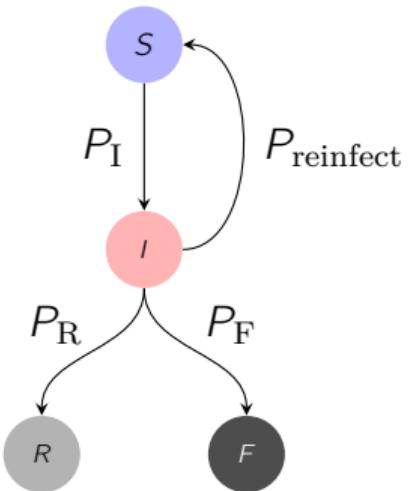


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## What are compartmental epidemiological models?

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- ✓ Captures large-scale population dynamics

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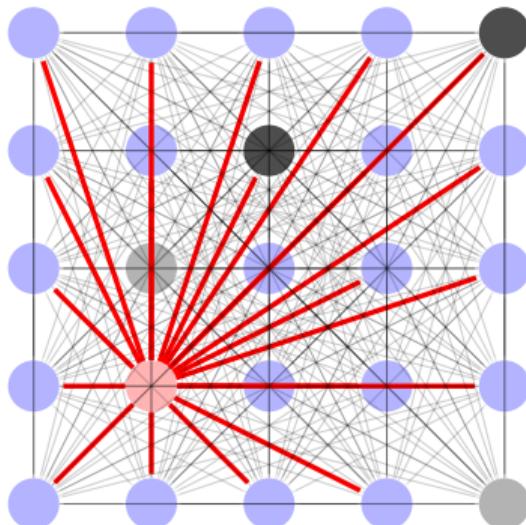
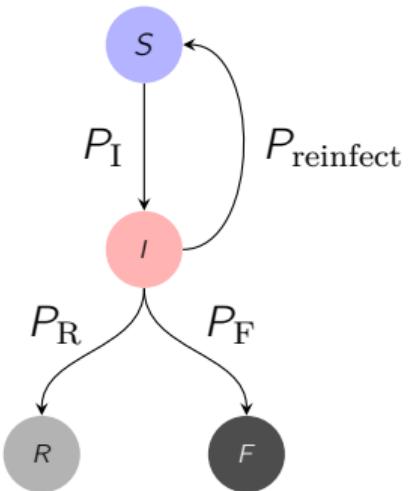


# Background: epidemiological models

## What are compartmental epidemiological models?

- ✓ Analytical solutions are available
- ✓ Captures large-scale population dynamics
- ✗ Does not account for *geography*

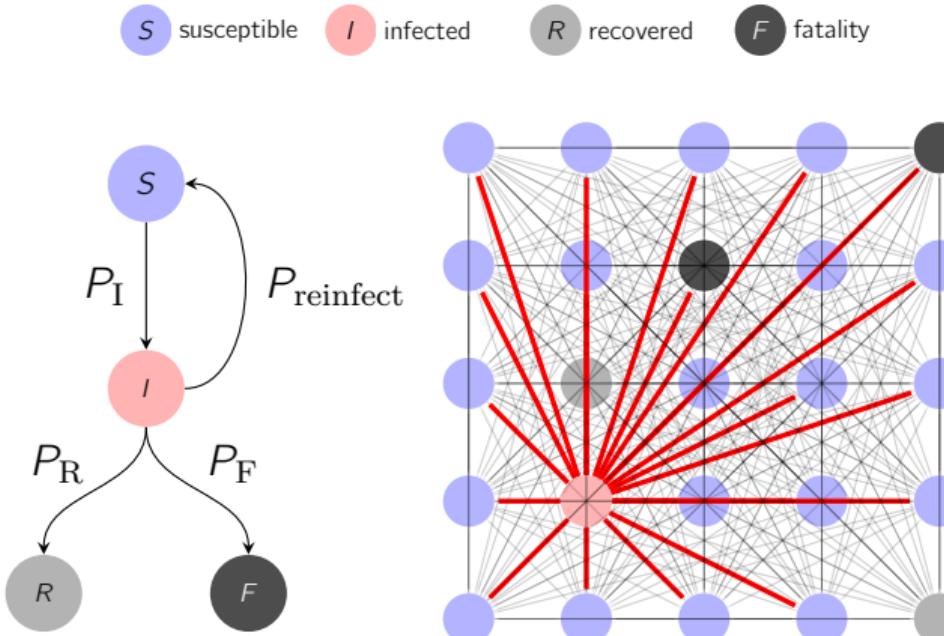
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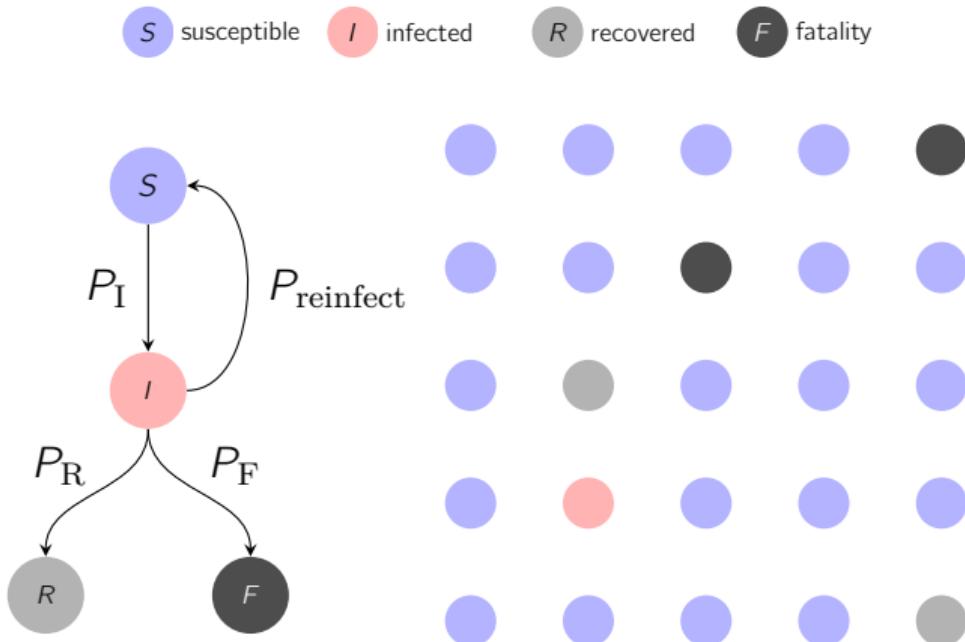
- ✓ Analytical solutions are available
- ✓ Captures large-scale population dynamics
- ✗ Does not account for *geography*
- ✗ Cannot model effect of intervention policies





# Background: epidemiological models

What are agent-based epidemiological models?



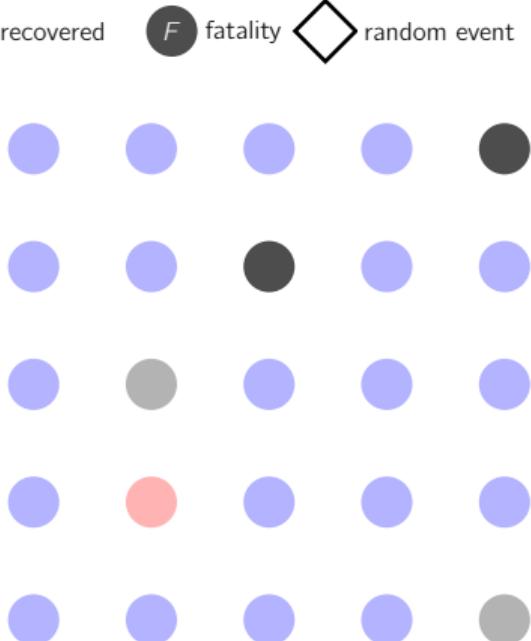
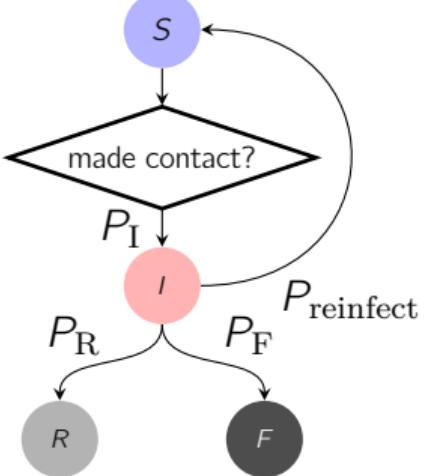


# Background: epidemiological models

What are agent-based epidemiological models?



- Stochastic process



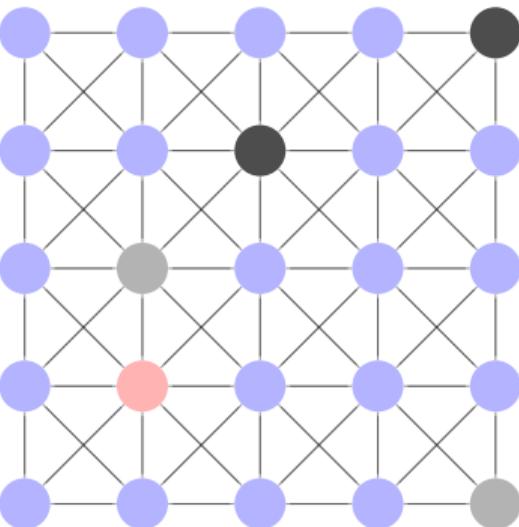
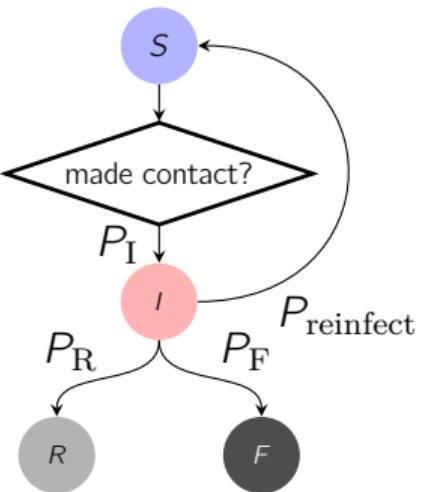


# Background: epidemiological models

What are agent-based epidemiological models?

- *Stochastic process*
- Assume *heterogenous* interaction

susceptible    infected    recovered    fatality    random event

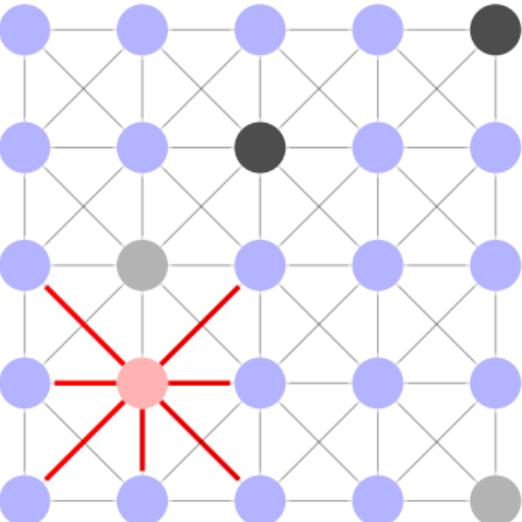
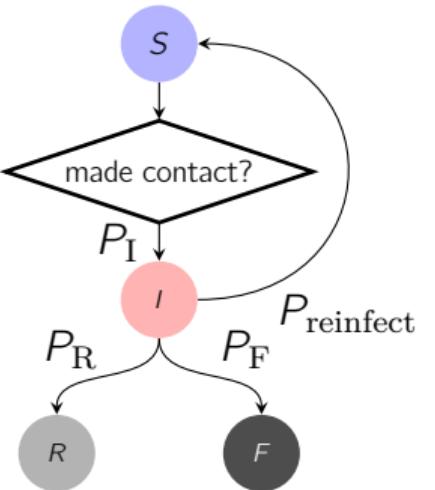




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# Background: epidemiological models

What are agent-based epidemiological models?

Realization 1

- *Stochastic* process
- Assume *heterogenous* interaction
- Stochastic response



# Background: epidemiological models

What are agent-based epidemiological models?

Realization 2

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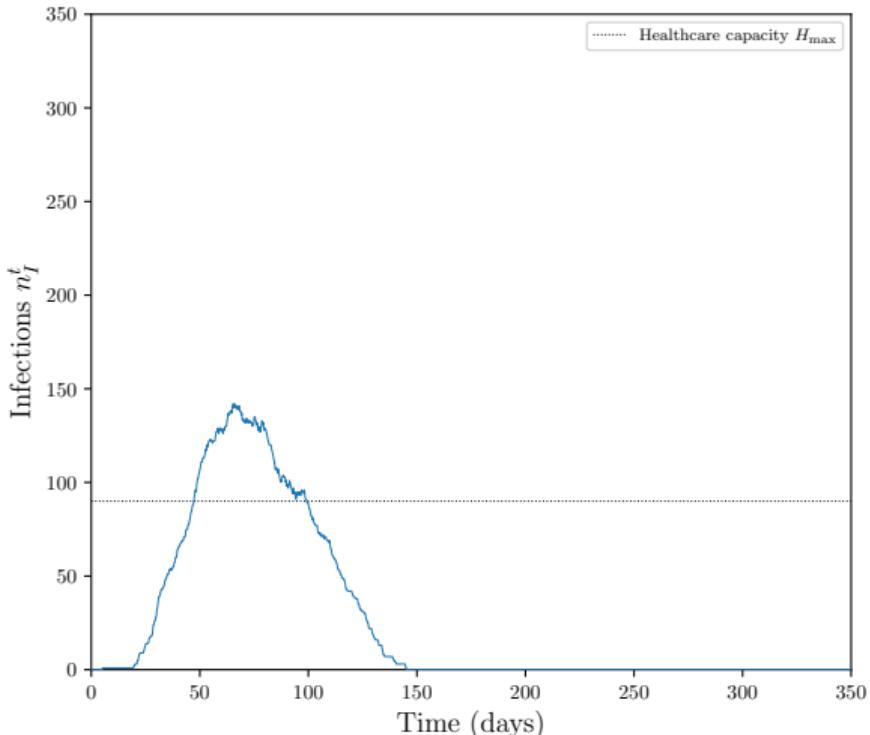


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Realization 1



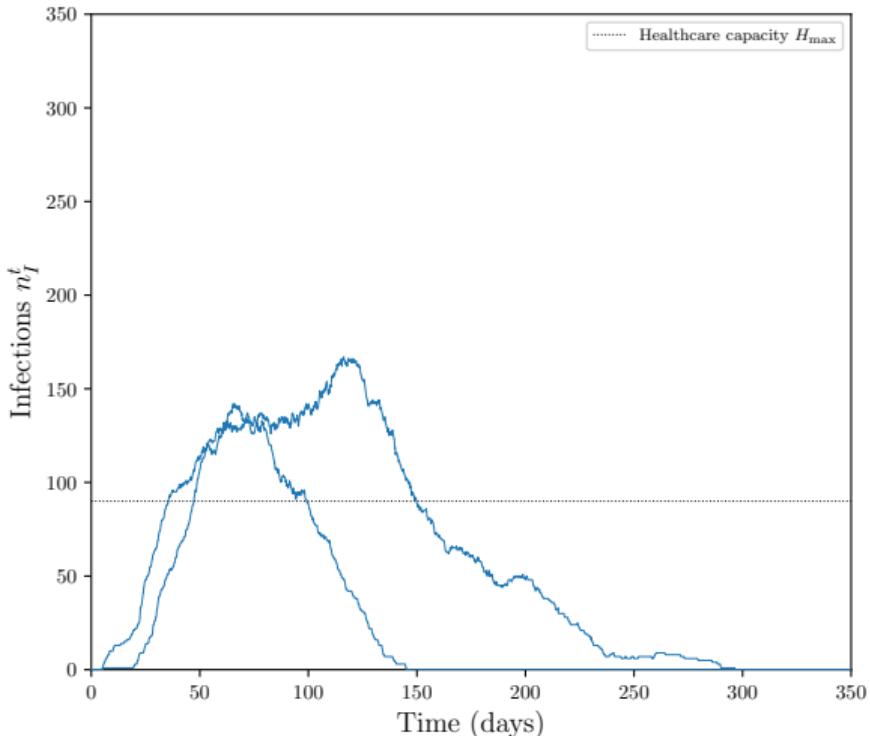


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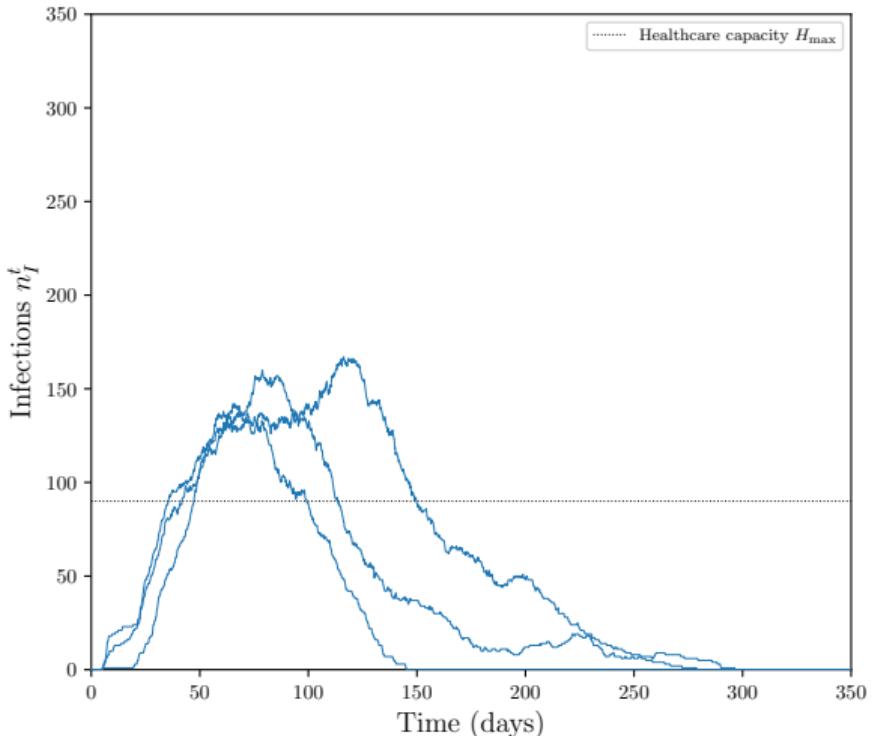




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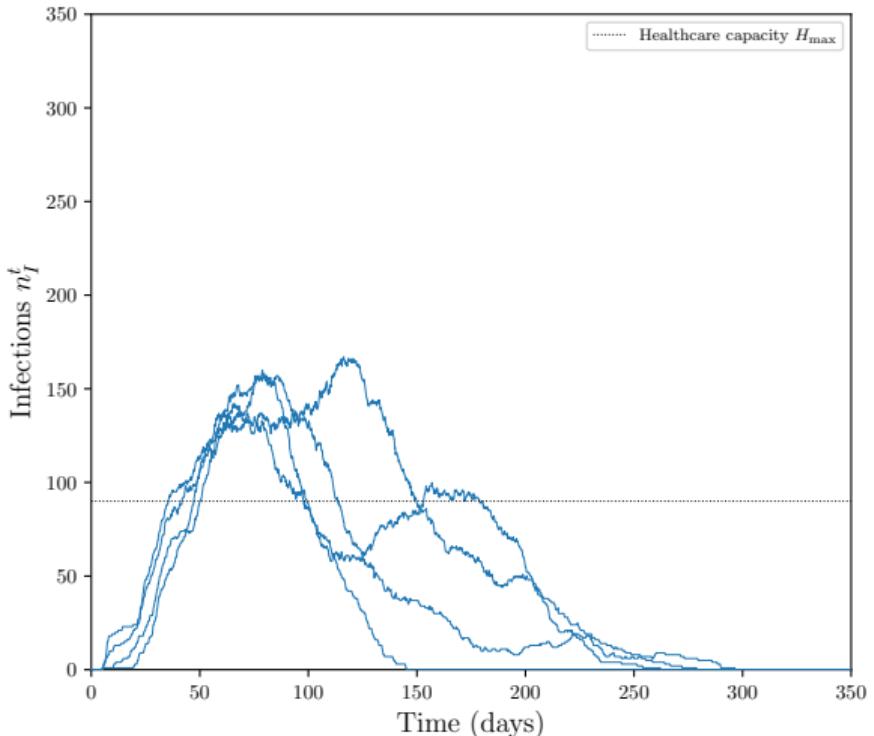




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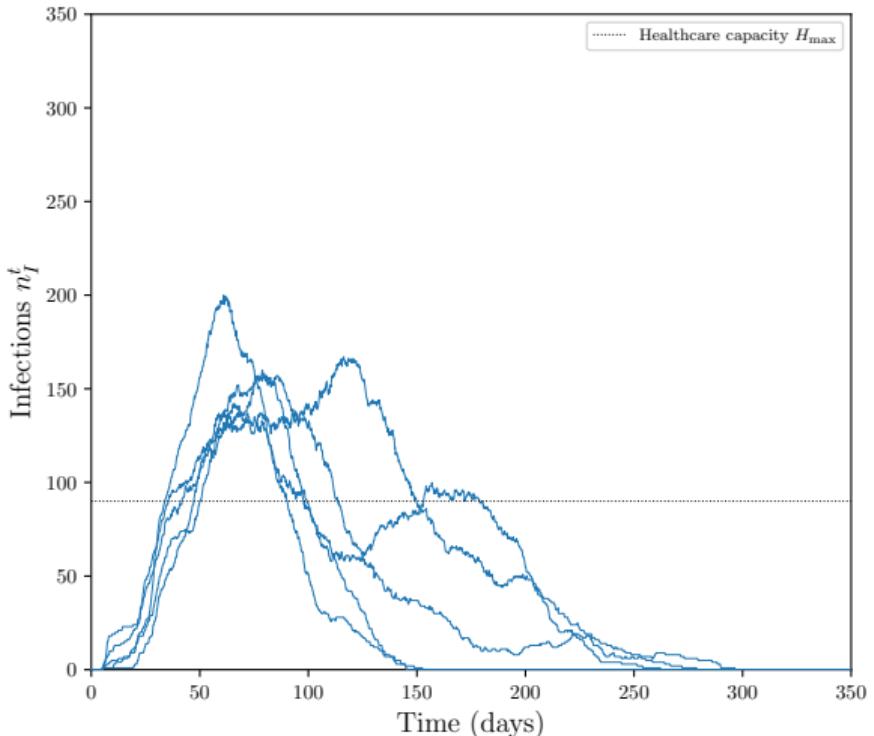




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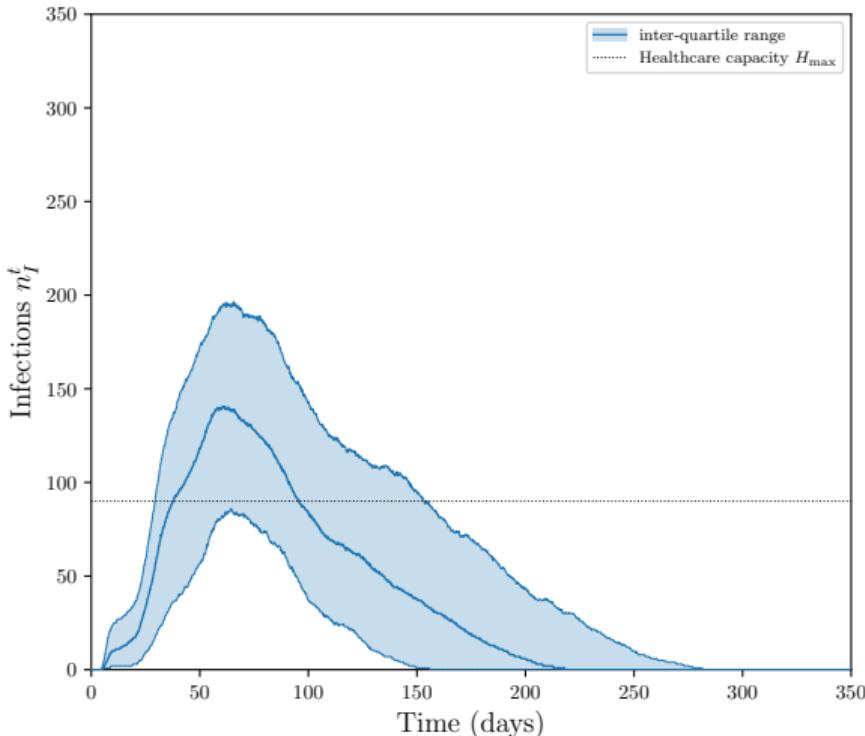




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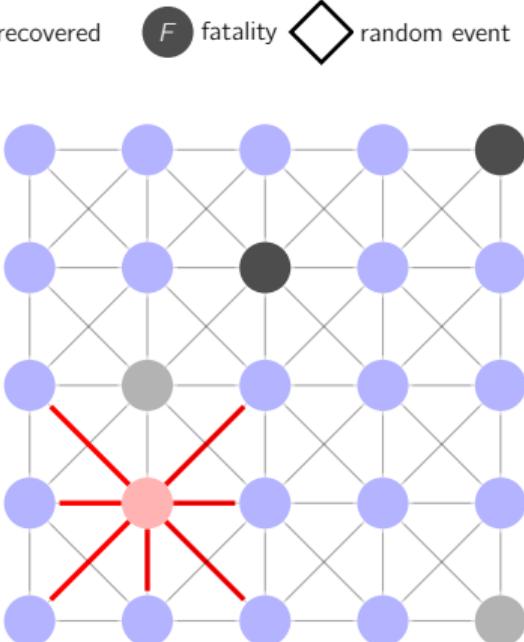
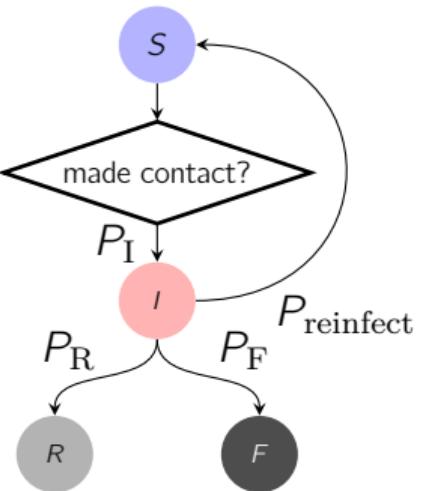


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What are agent-based epidemiological models?

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- ✓ Account for *geography* and *demographics*



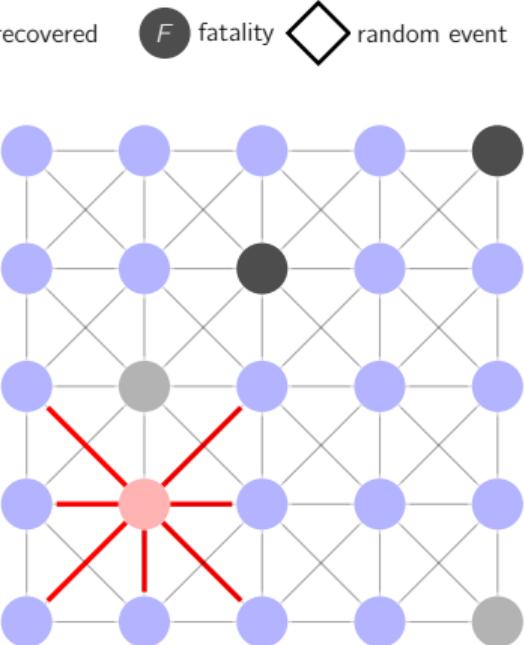
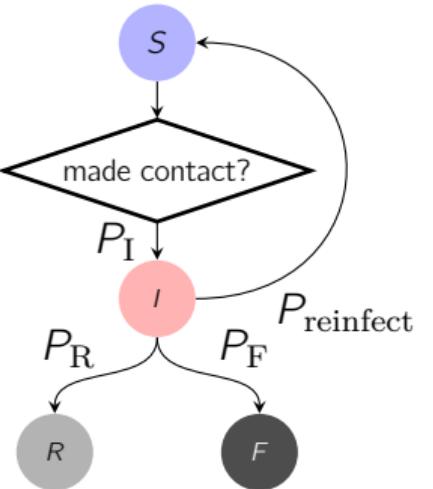


# Background: epidemiological models

What are agent-based epidemiological models?



- ✓ Account for *geography* and *demographics*
- ✓ Describe local phenomena



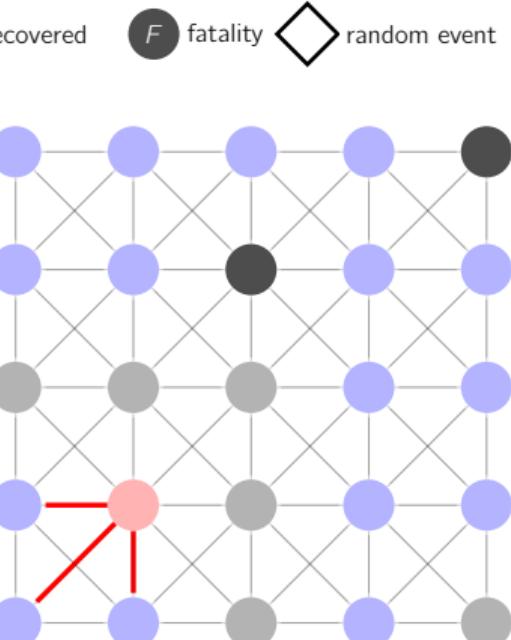
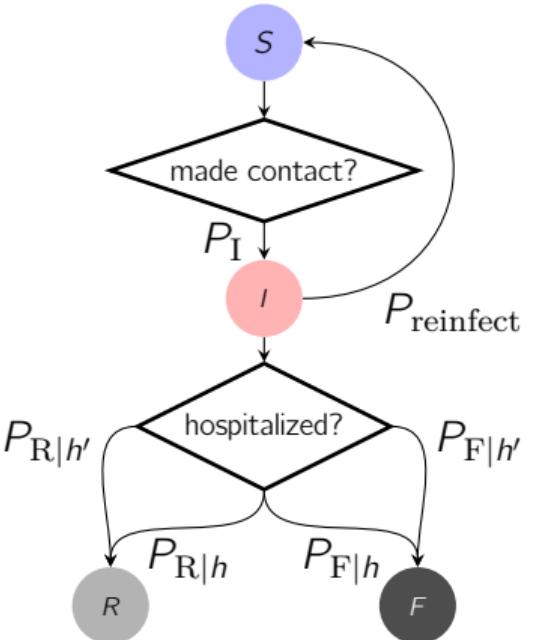


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What are agent-based epidemiological models?

- ✓ Account for *geography* and *demographics*
- ✓ Describe local phenomena
- ✓ Can be used to model intervention policies

susceptible    infected    recovered    fatality    random event



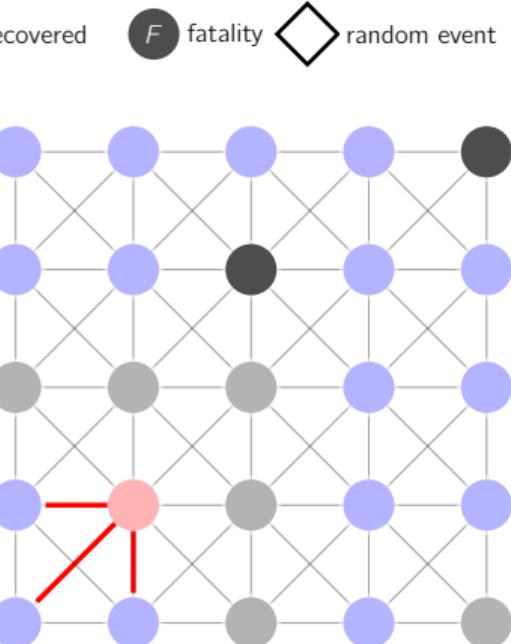
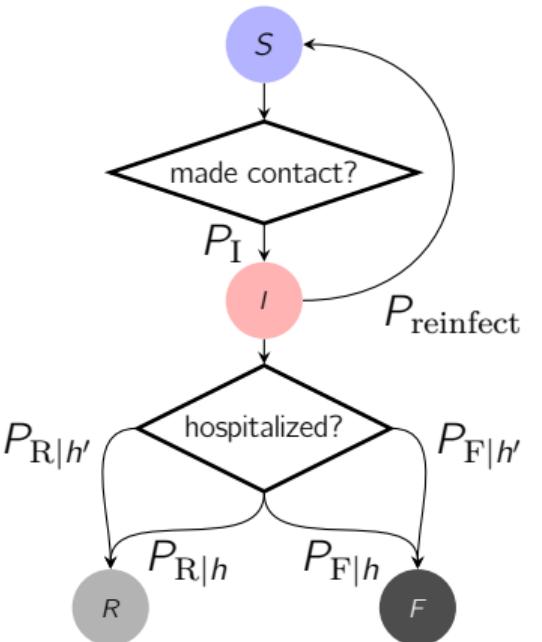


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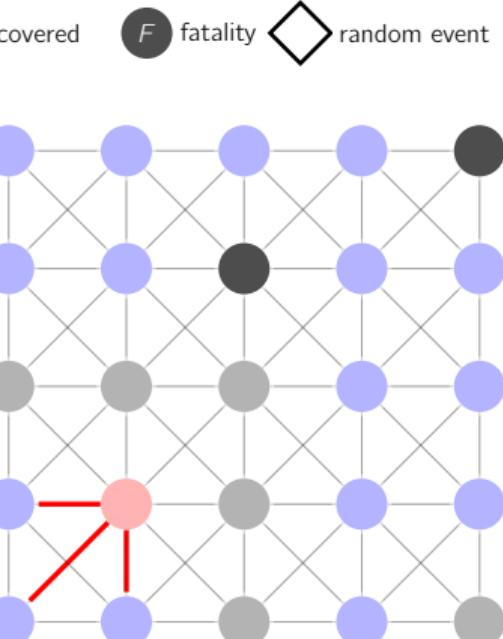
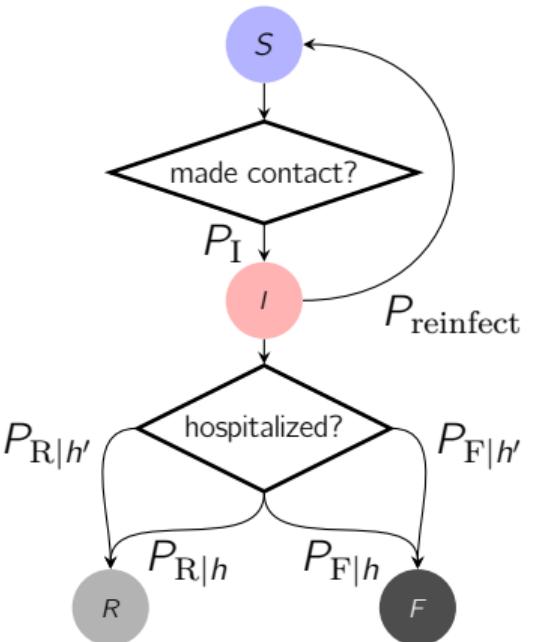


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What are agent-based epidemiological models?

- ✓ Account for *geography* and *demographics*
- ✓ Describe local phenomena
- ✓ Can be used to model intervention policies
- ✗ Stochastic response makes decision making challenging
- ✗ Computationally expensive

S susceptible  
 I infected  
 R recovered  
 F fatality  
 ◇ random event



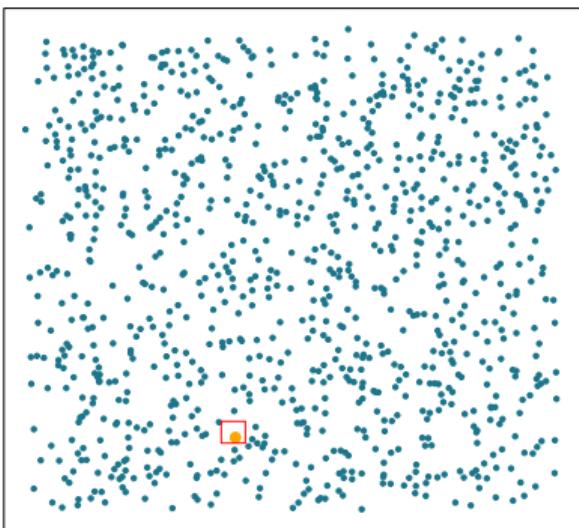


# Public health policy-making problem formulation

What is the **cost** of public health interventions?

No interventions applied

- susceptible
- infected
- recovered
- fatalities
- tracked



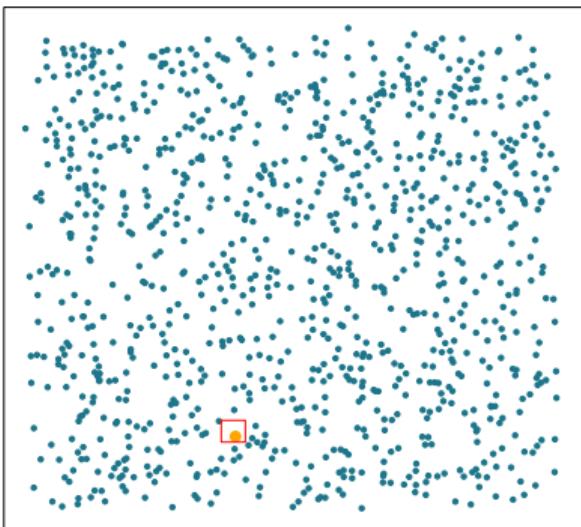
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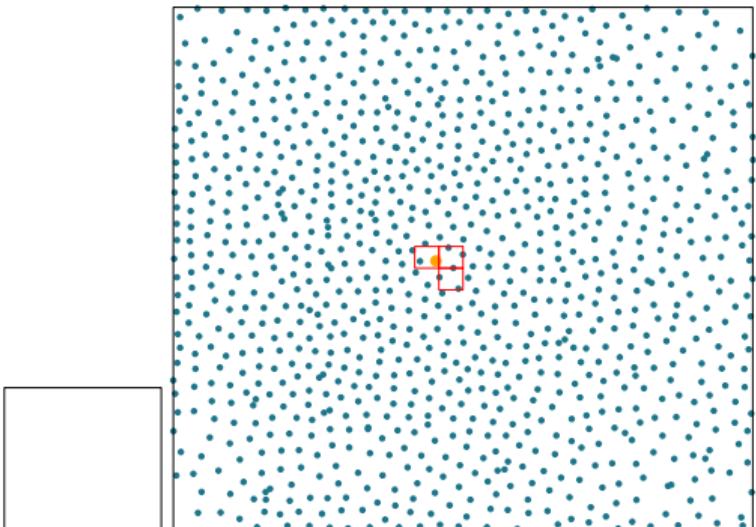
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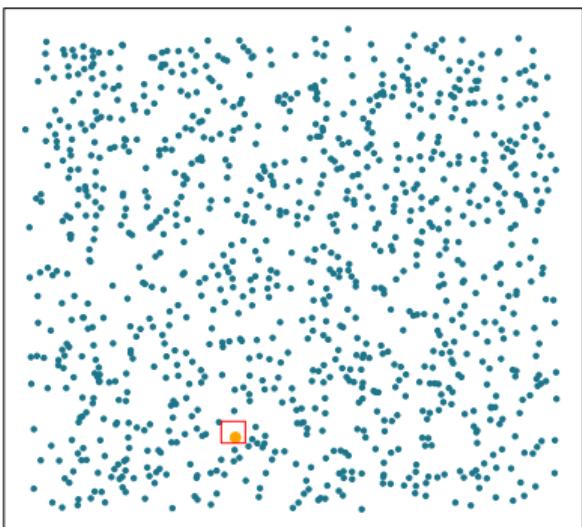
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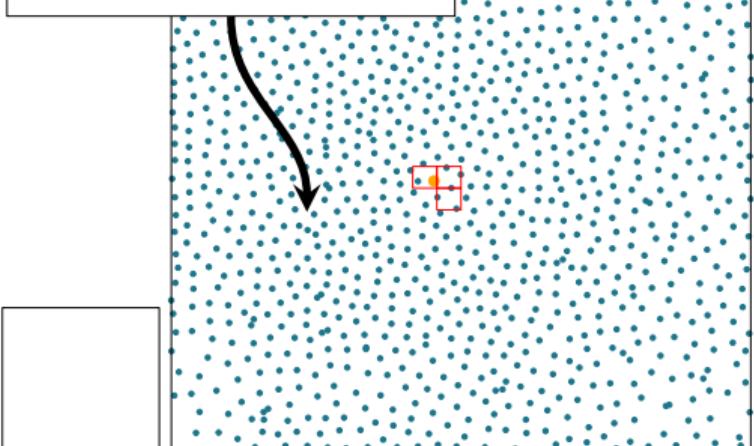
• susceptible   • infected   • recovered   • fatalities   • tracked



with intervention

• susceptible   • infected   • recovered   • fatalities   • tracked

essential workers



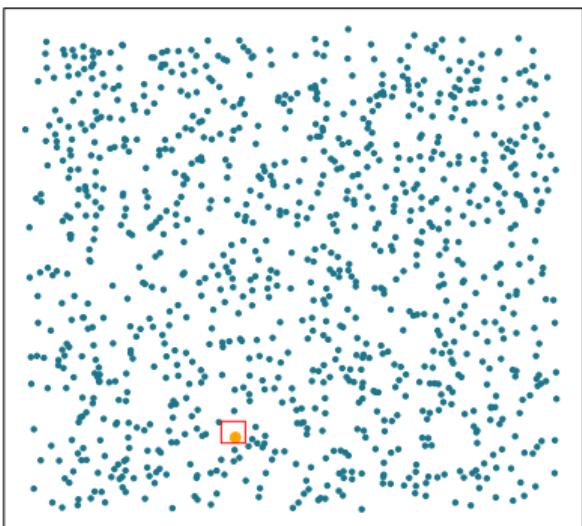
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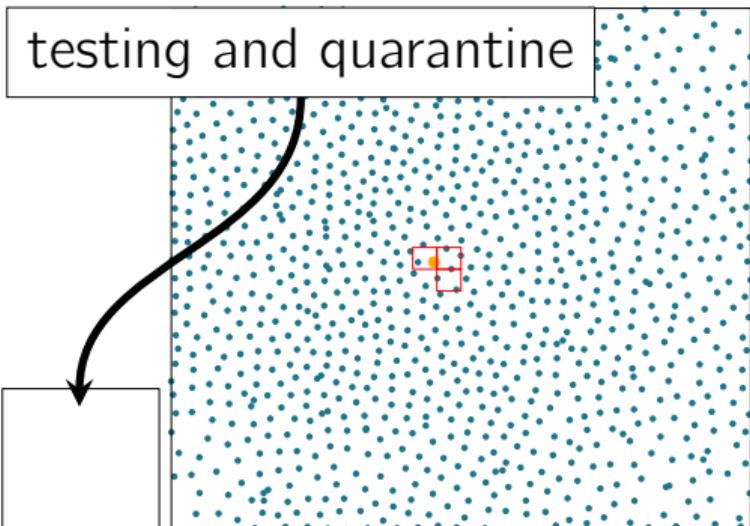
- susceptible
- infected
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with intervention

- susceptible
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testing and quarantine



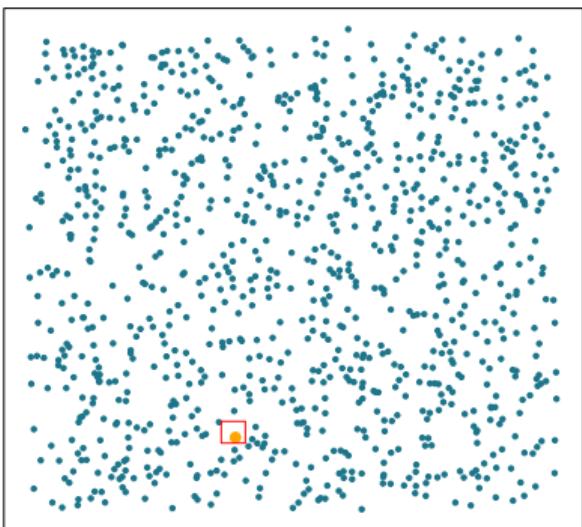
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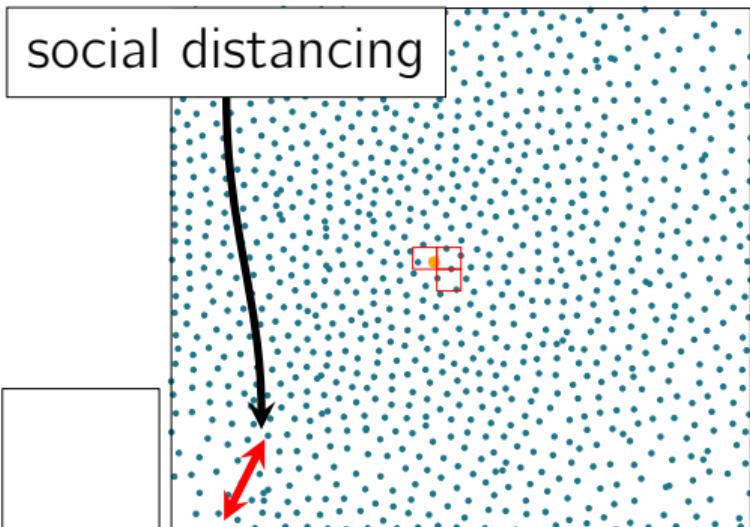
• susceptible • infected • recovered • fatalities • tracked



with intervention

• susceptible • infected • recovered • fatalities • tracked

social distancing





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No interventions applied

with intervention

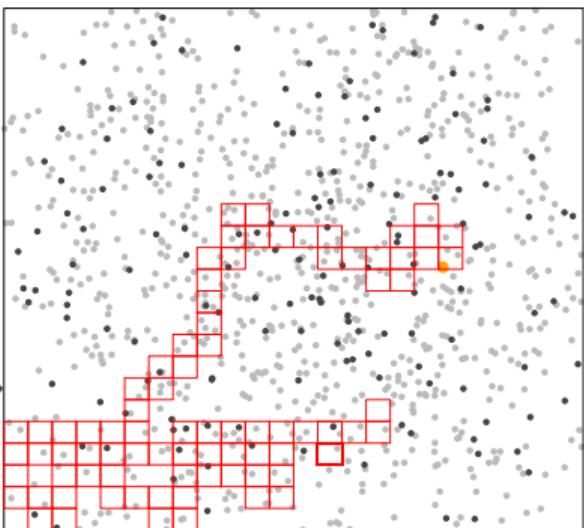
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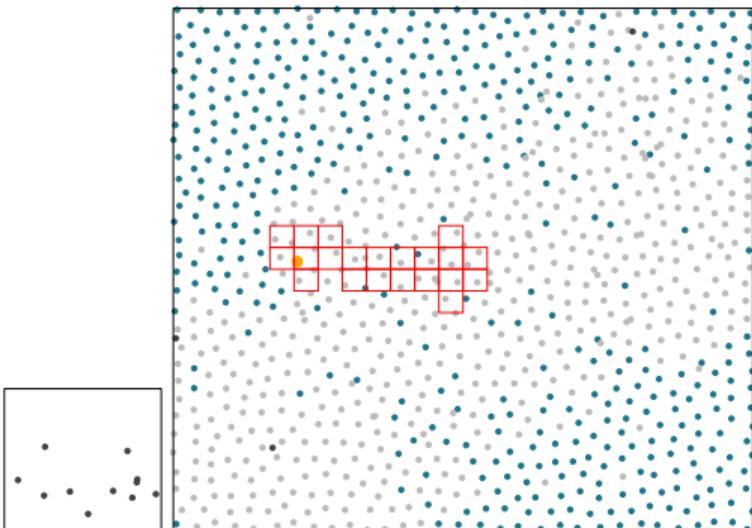
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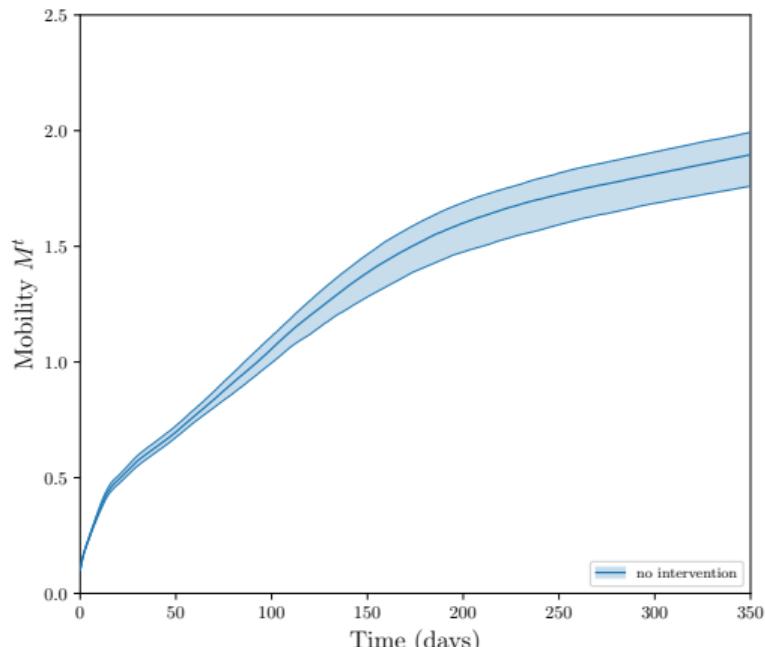
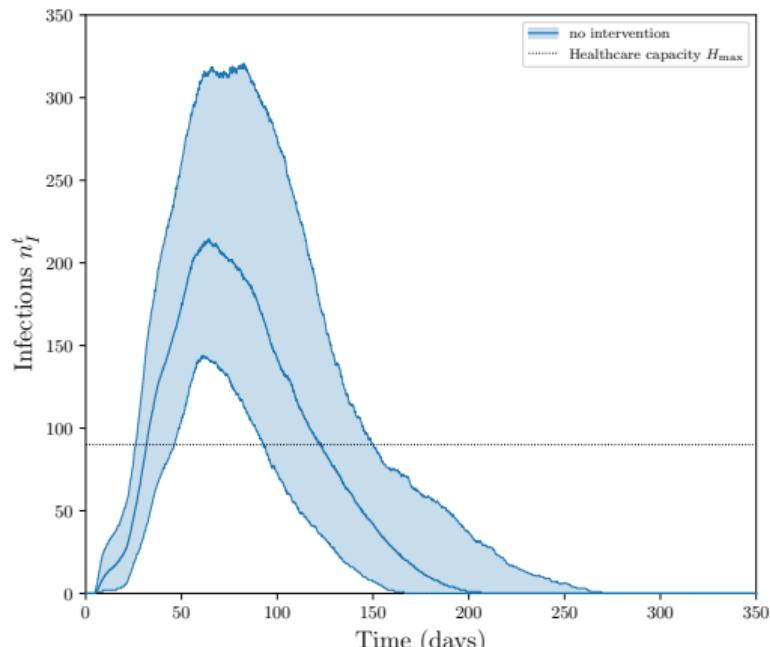
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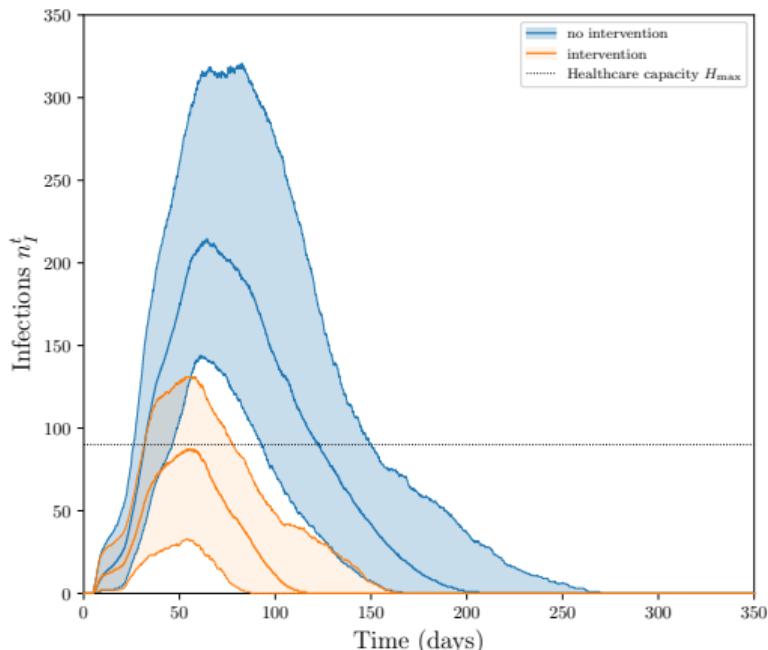
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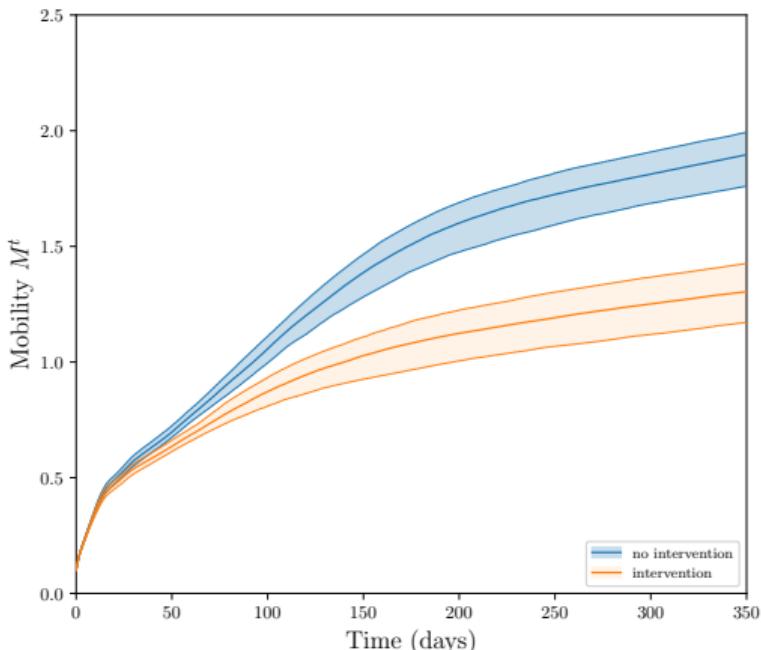
# Public health policy-making problem formulation

What is the **cost** of public health interventions?

infections ↓



mobility ↓



# Optimization problem

## Objective and constraints

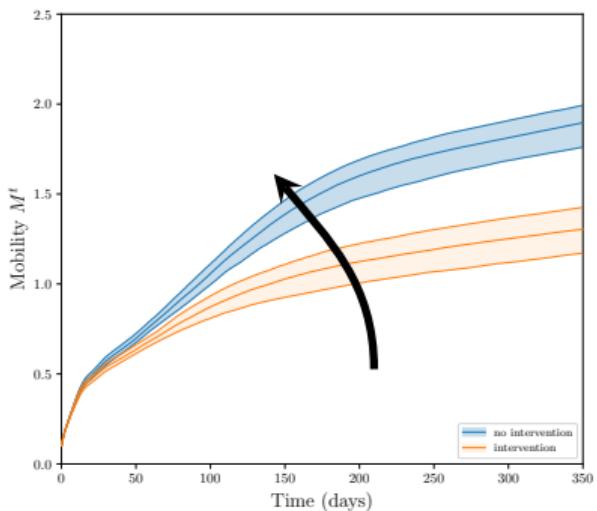
$$\min_x \quad f(x) = -M^T$$

subject to

where  $x = [n_E, S_D, n_T]^T$

## Design variables

- $n_E$  : Number of essential workers
- $S_D$  : Social distancing factor
- $n_T$  : Number of tests daily



# Optimization problem

No gradient information available, blackbox is expensive and noisy

## Objective and constraints

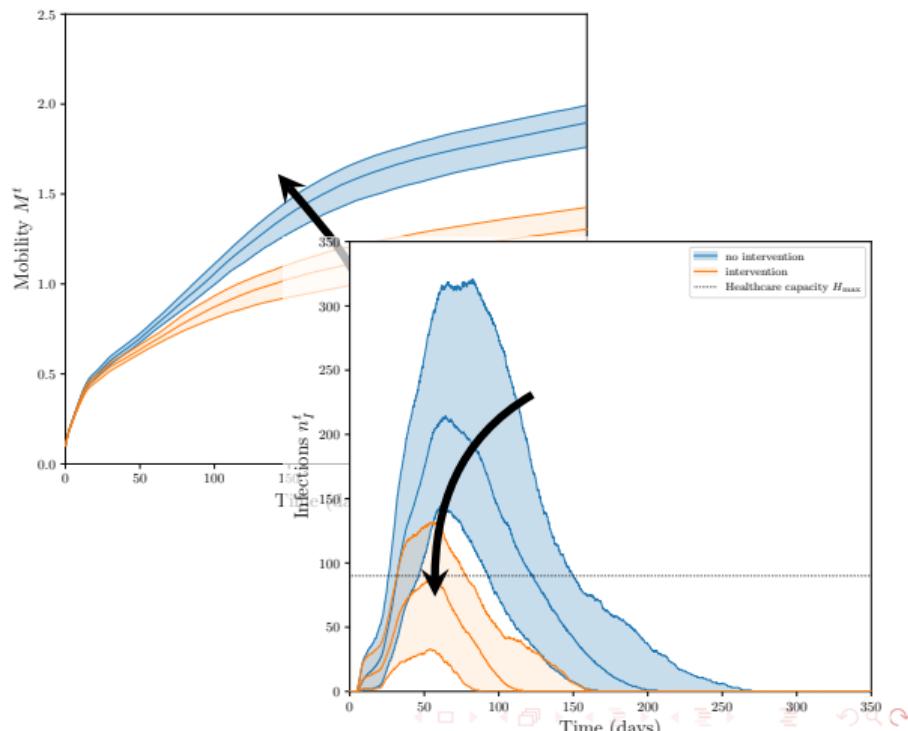
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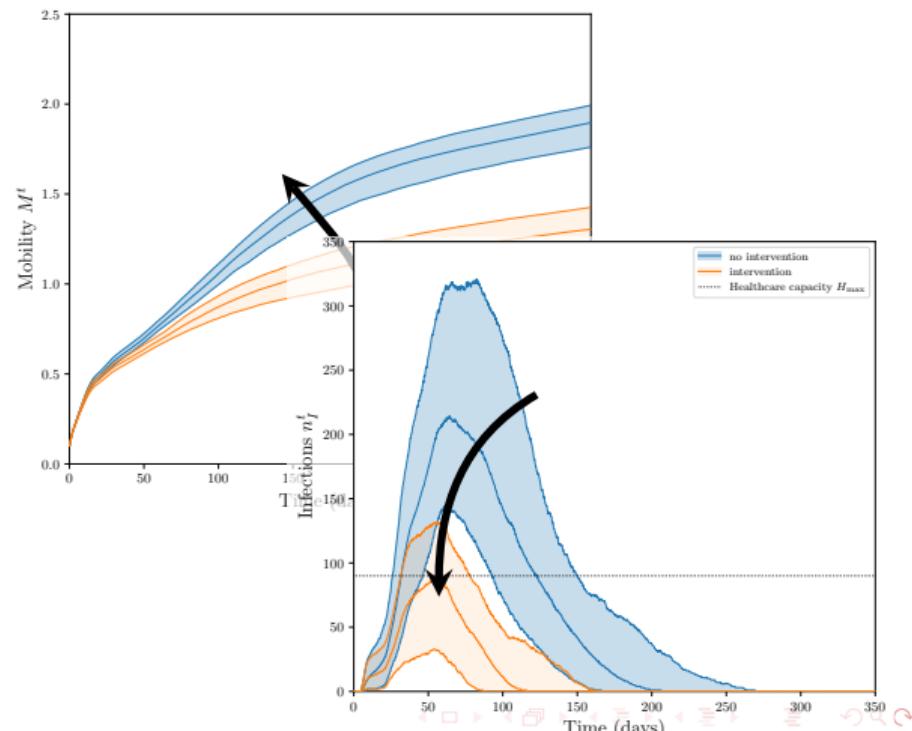
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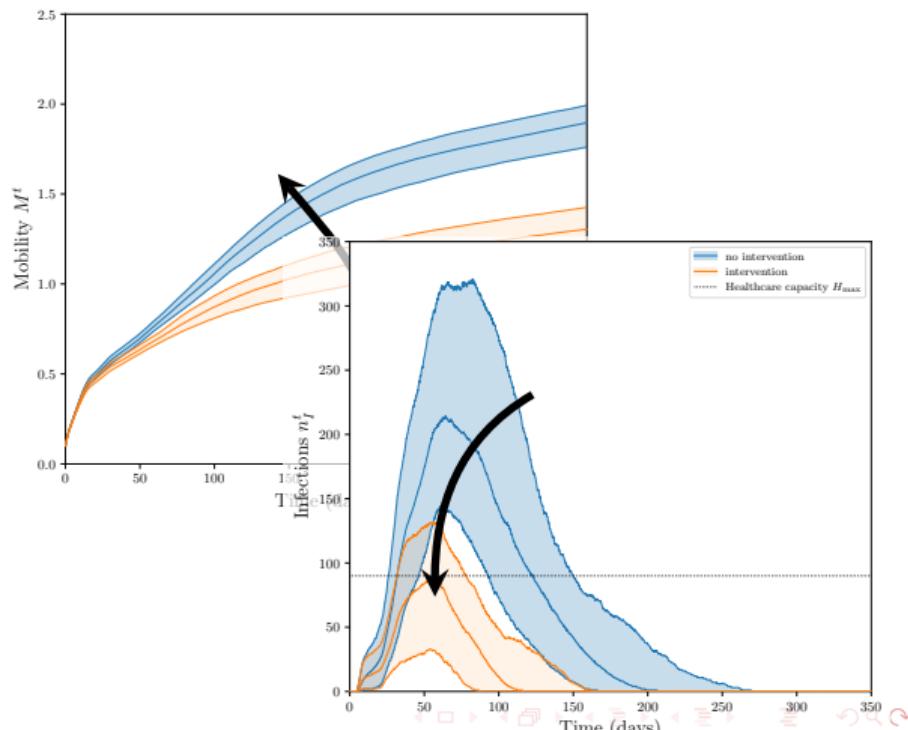
$$\min_x \quad f(x) = \mathbb{E}_{\Theta} [f_{\Theta}(x) = -M^T]$$

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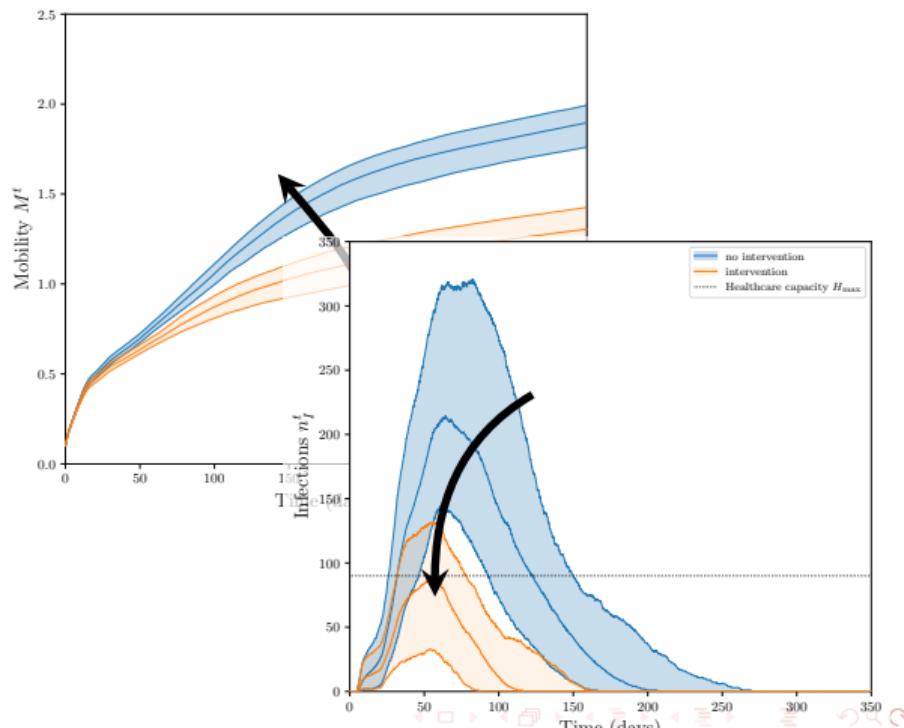
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## Design variables

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## Randomly seeded parameters

- Initial conditions
- Interactions, demographics





# Overview of stochastic mesh adaptive direct search

No gradient information available, blackbox is expensive and **noisy**<sup>1</sup>

## Objective and constraints

$$\min_x \quad f(x) = \mathbb{E}_{\Theta} [f_{\Theta}(x)]$$

$$\text{subject to} \quad c(x) = \mathbb{E}_{\Theta} [c_{\Theta}(x)] \leq 0$$

where  $x$ : variables  $\Theta$ : realizations

- Constructs estimates of objective:

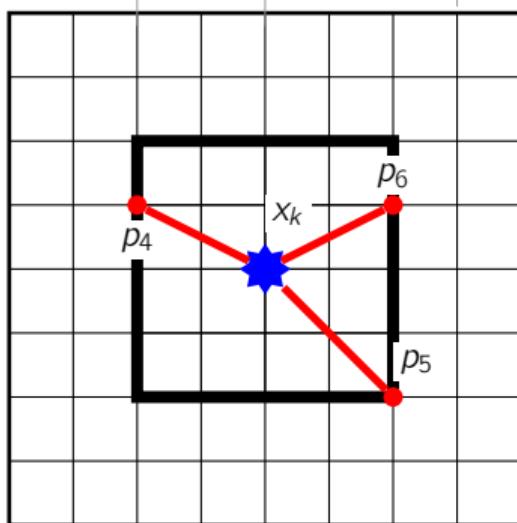
$$f^k = \frac{1}{n^k} \sum_{i=1}^{n^k} f_{\Theta_{0,i}}(x_k)$$

- $n^k$  is the sampling rate

Poll failure

$$\delta_{\text{poll}}^k = \frac{1}{2}$$

$$\delta_{\text{mesh}}^k = \frac{1}{4}$$





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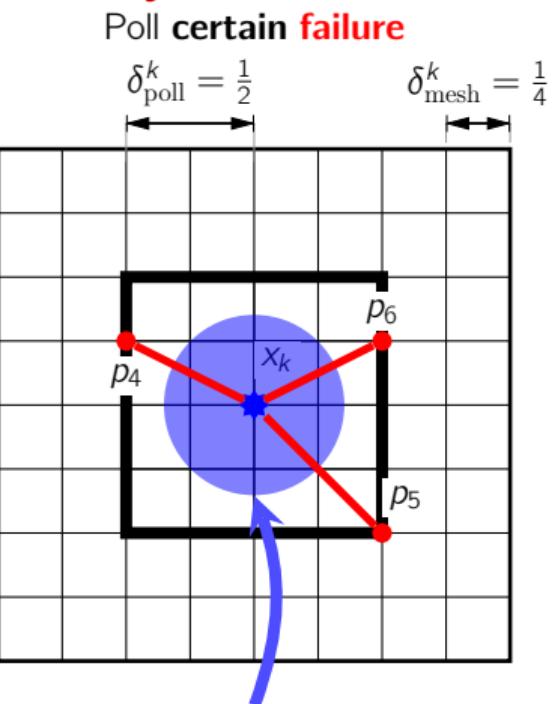
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- Constructs estimates of objective:

$$f^k = \frac{1}{n^k} \sum_{i=1}^{n^k} f_{\Theta_{0,i}}(x_k)$$

- $n^k$  is the sampling rate
- Tracks uncertainty interval  $\mathcal{I}(\delta_{\text{poll}}^k)$  in the estimate





# Overview of stochastic mesh adaptive direct search

No gradient information available, blackbox is expensive and **noisy**<sup>1</sup>

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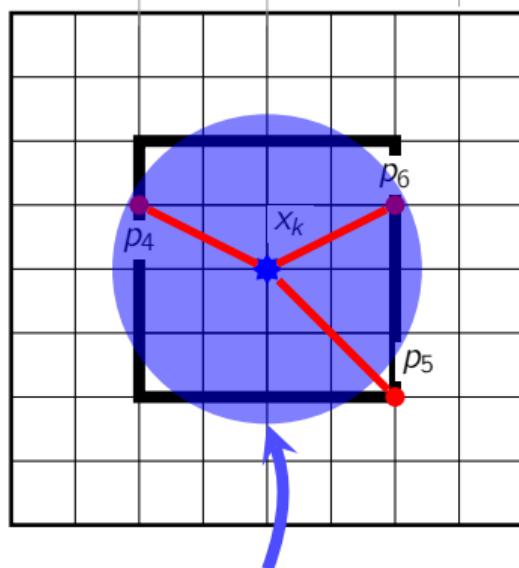
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Poll **uncertain failure**

$$\delta_{\text{poll}}^k = \frac{1}{2}$$

$$\delta_{\text{mesh}}^k = \frac{1}{4}$$



$$\{x : f_s^k - f_0^k \in \mathcal{I}\}$$



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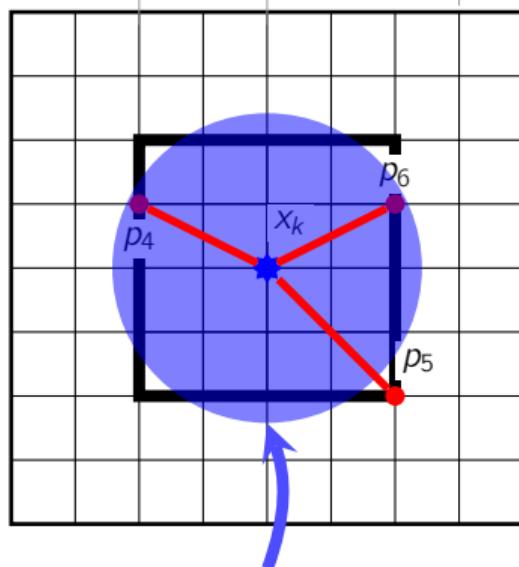
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Constraint handling using the *progressive barrier* approach<sup>2</sup>

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[1] C. Audet, K. J. Dzahini, M. Kokkolaras, and S. Le Digabel, 2021 , *Computational Optimization and Applications*

[2] K. J. Dzahini, M. Kokkolaras, and S. Le Digabel, 2022 , *Mathematical Programming*



# Optimization results

StoMADS, NOMAD<sup>1</sup>, and genetic algorithms were used to solve the problem<sup>2</sup>

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## Design variables

- $n_E$  : Number of essential workers
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## Randomly seeded parameters

- Initial conditions
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[1] S. Le Digabel, C. Tribes, V. Rochon Montplaisir, and C. Audet, 2018 , [https://www.gerad.ca/nomad/Downloads/user\\_guide.pdf](https://www.gerad.ca/nomad/Downloads/user_guide.pdf)

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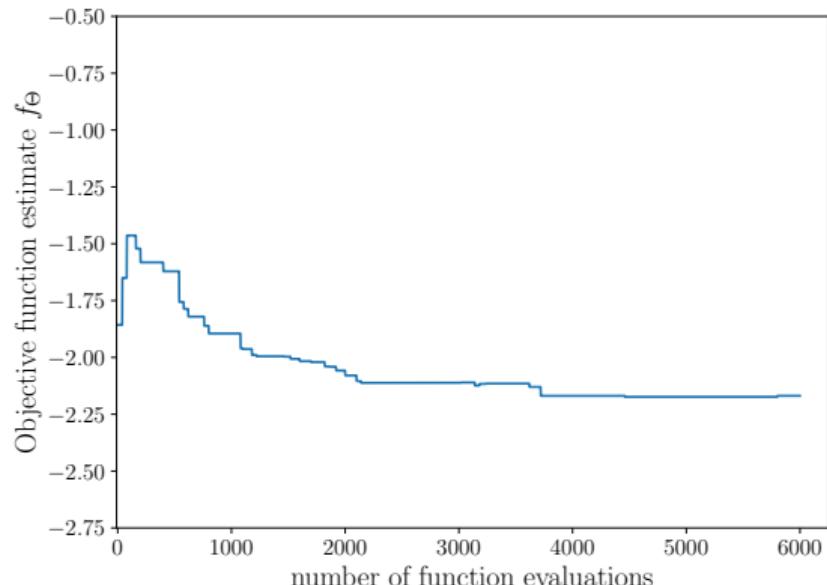
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— StoMADS-PB    - - -  $\bar{c}_{\Theta} = 0$



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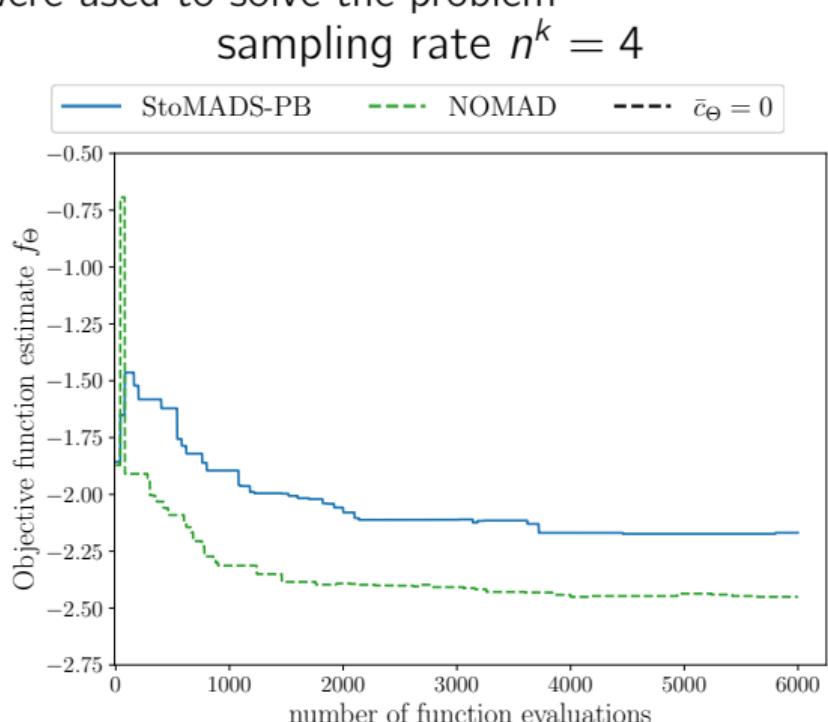
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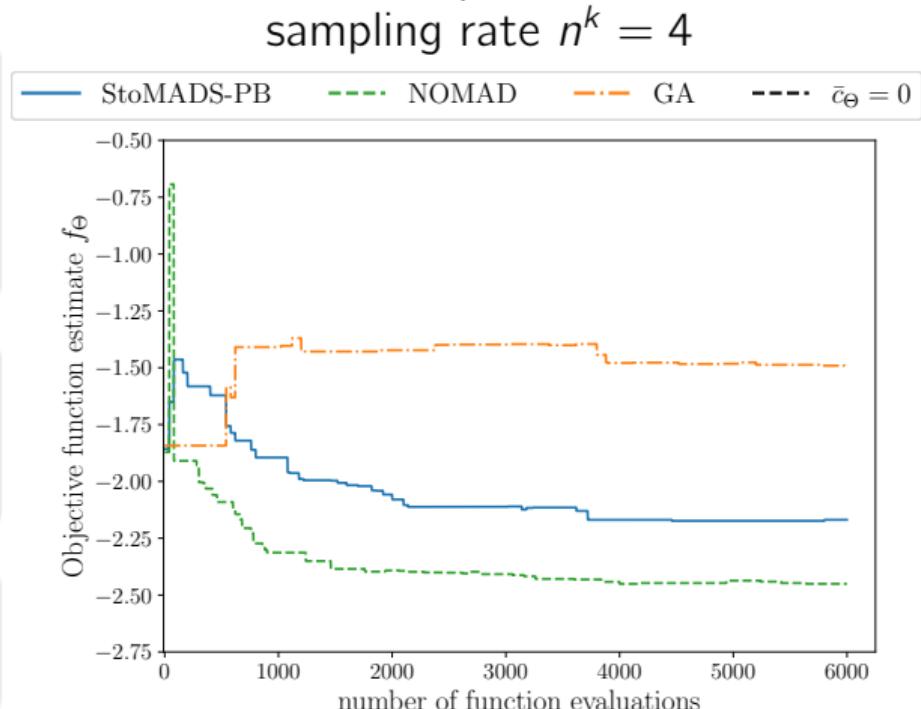
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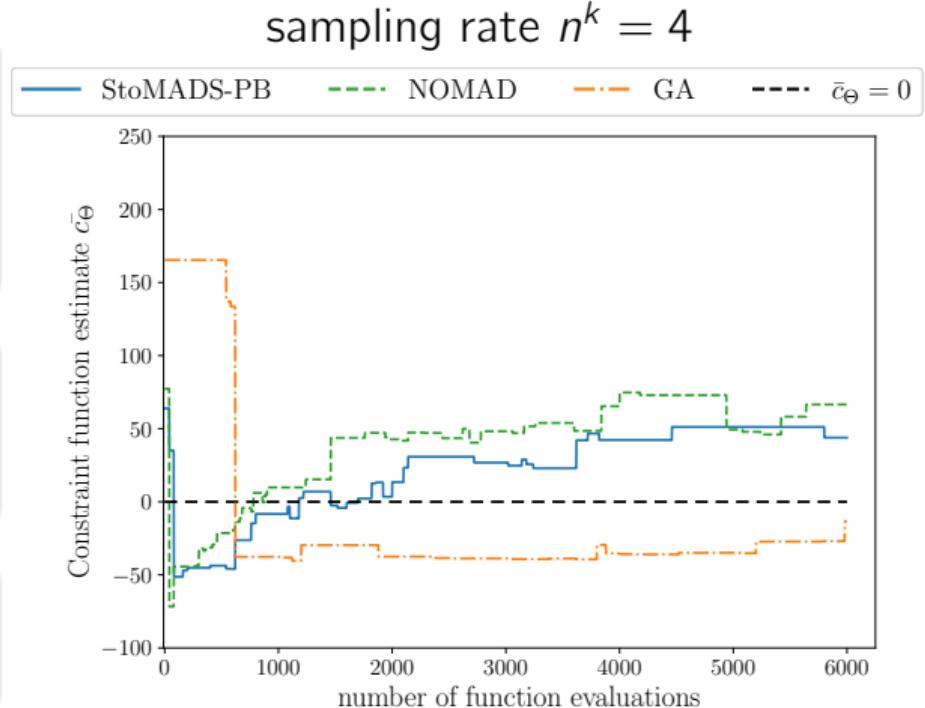
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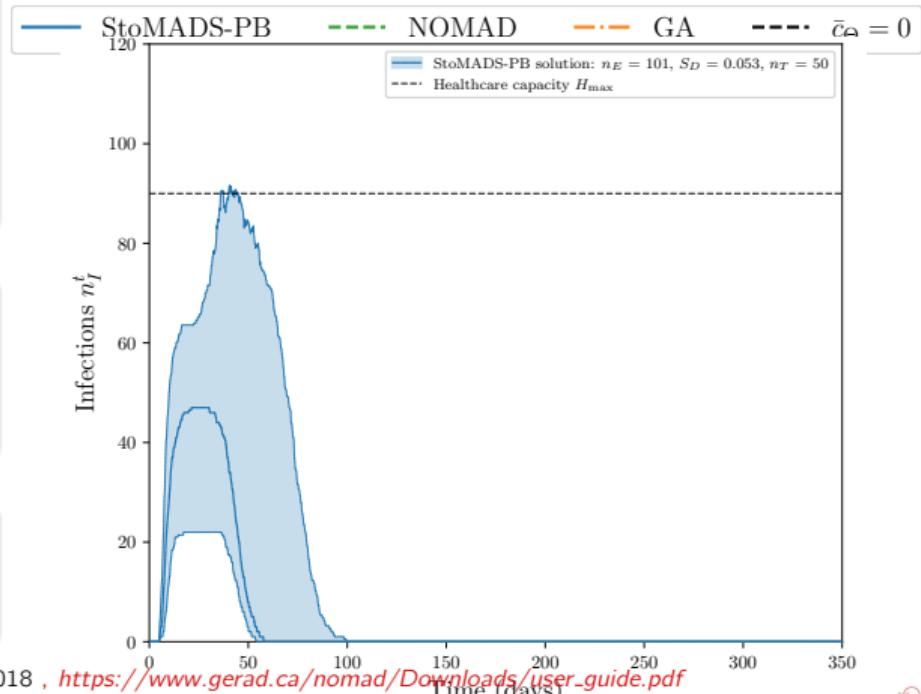
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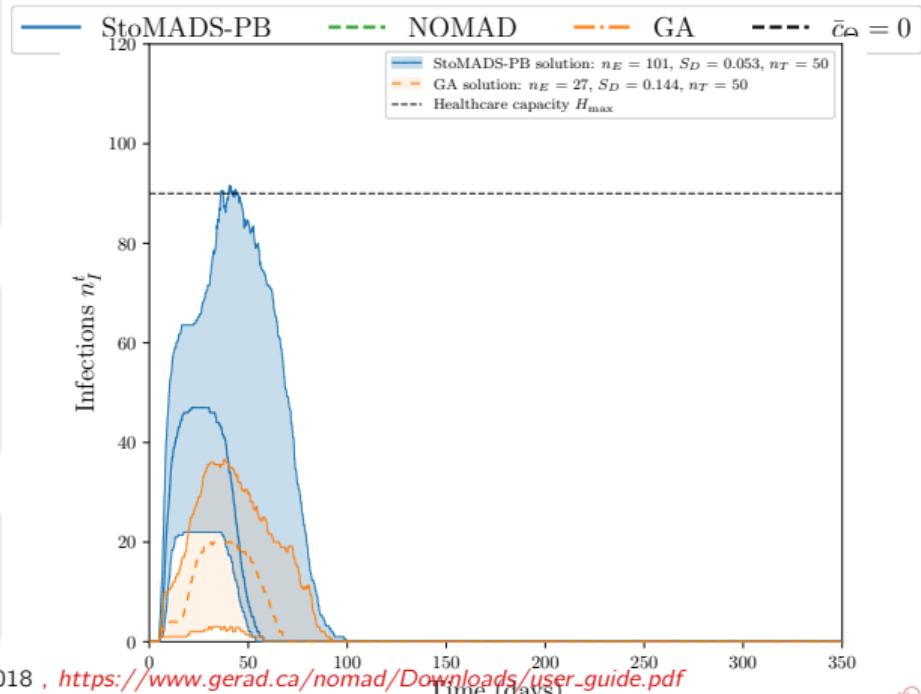
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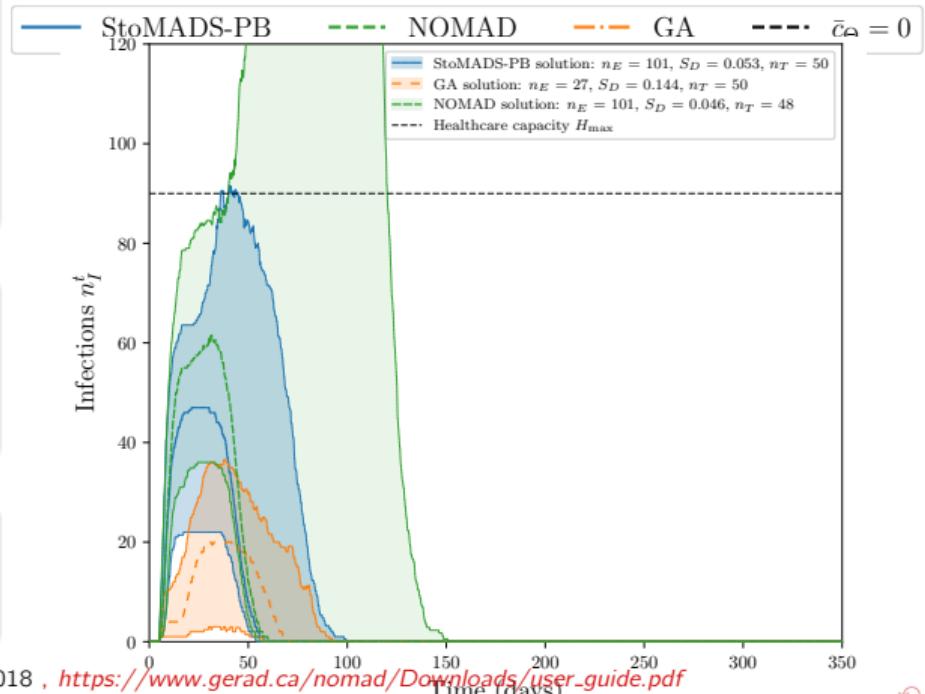
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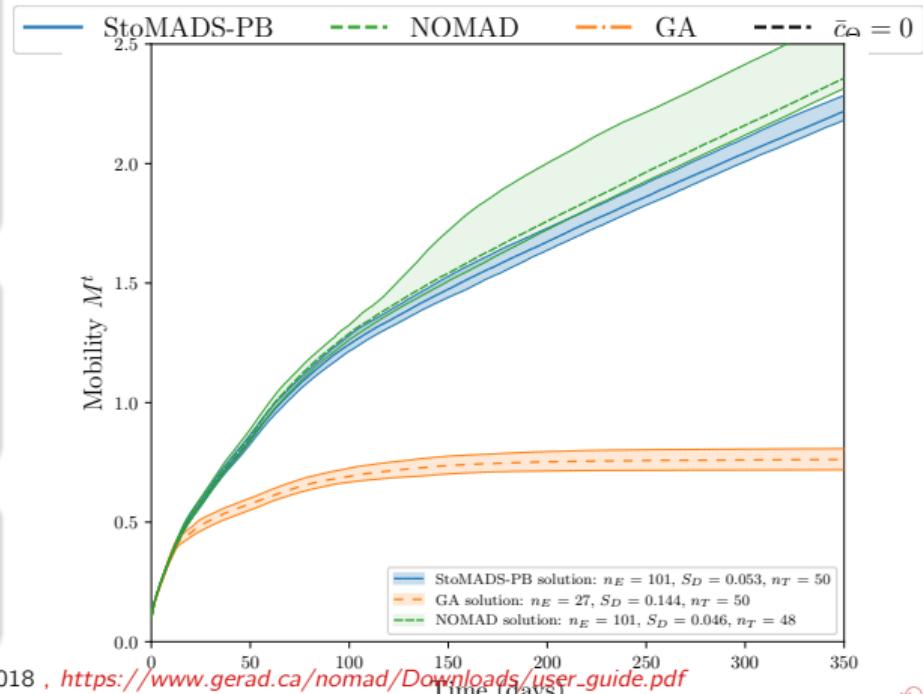
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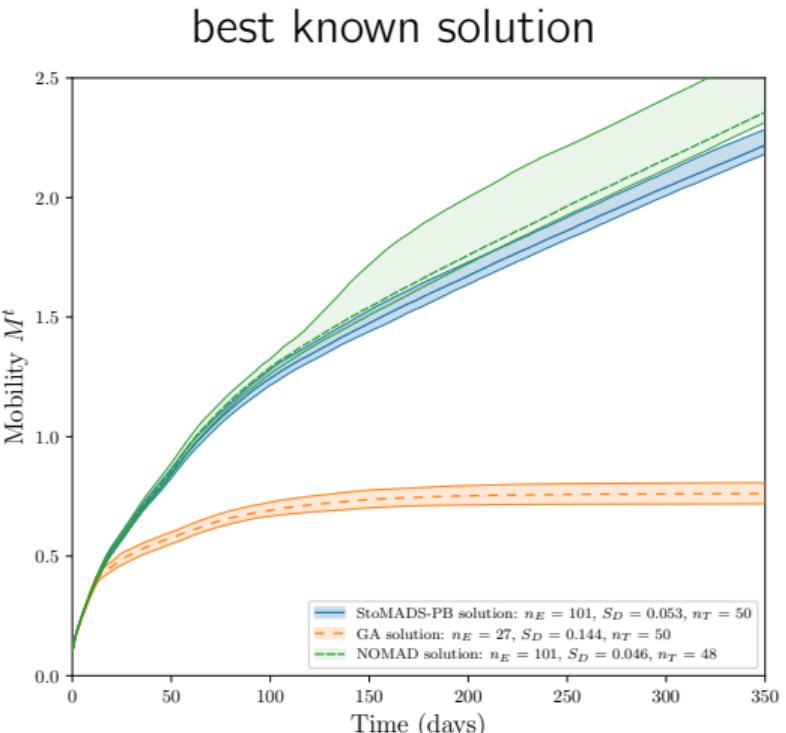
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# Conclusion

Formulated and solved public health policy-making problems

- Identified a public health policy that favored

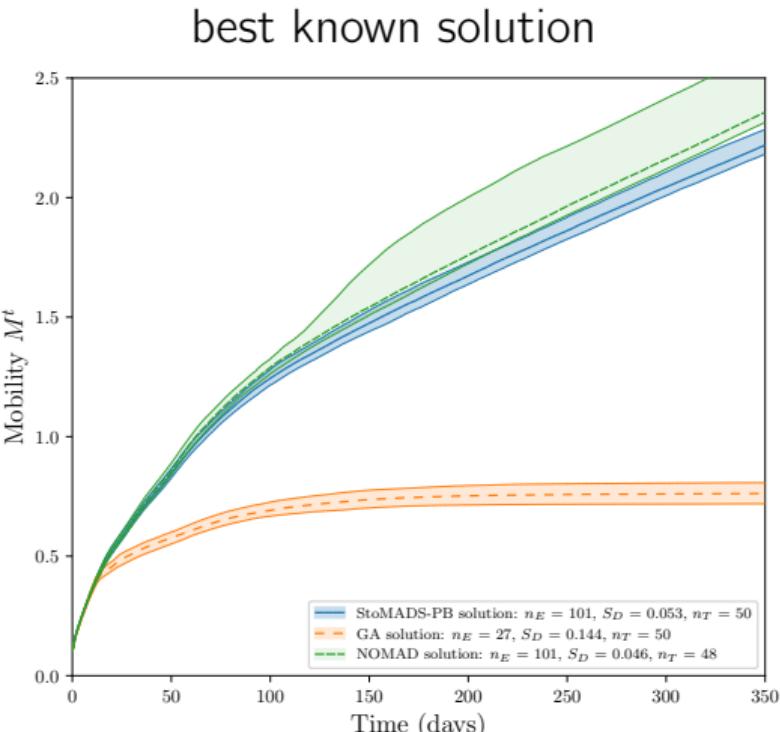




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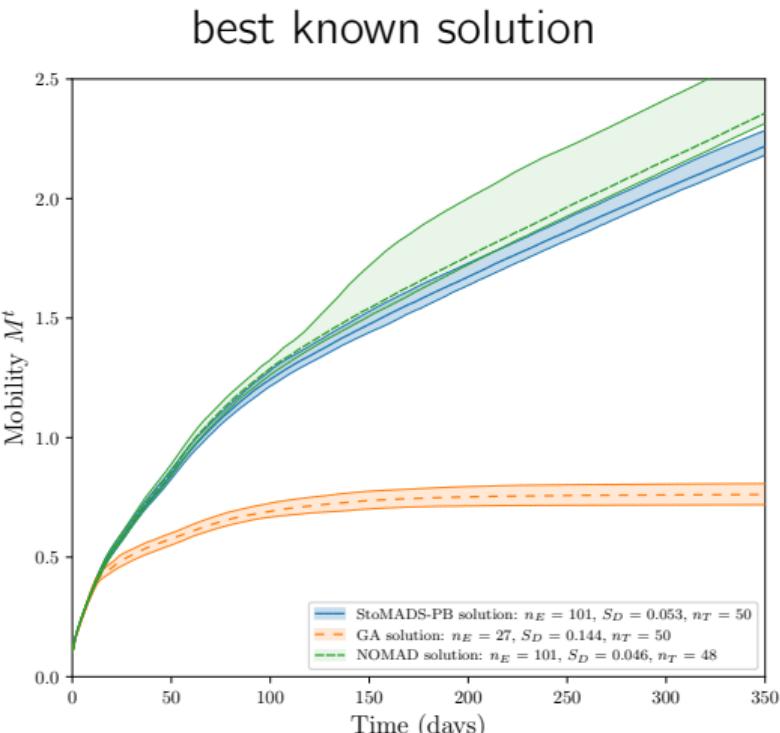




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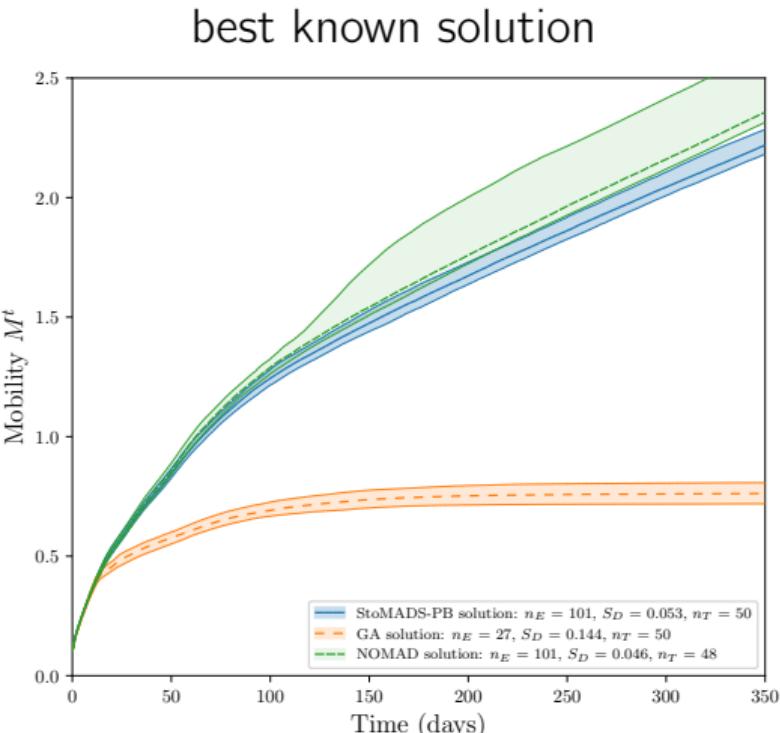




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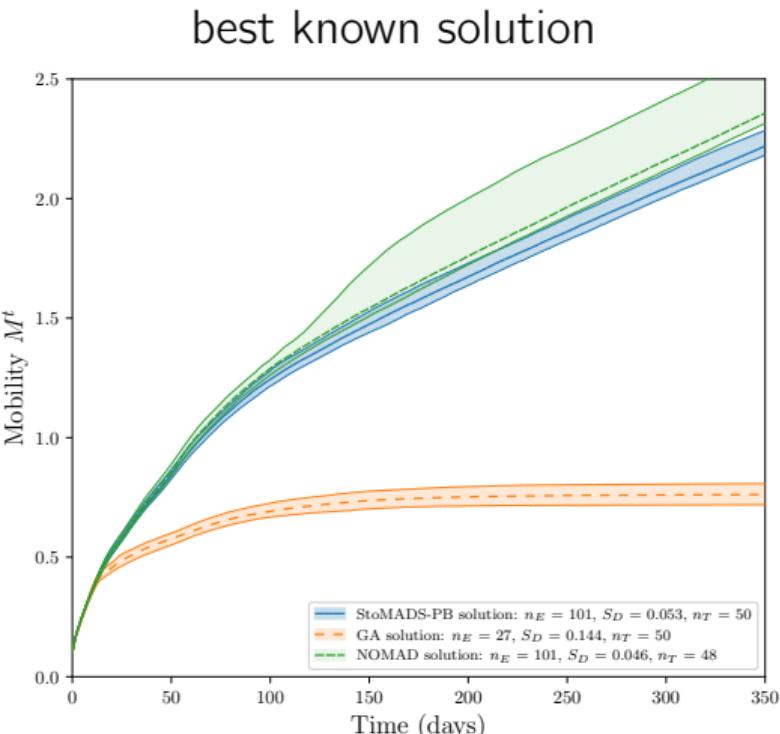




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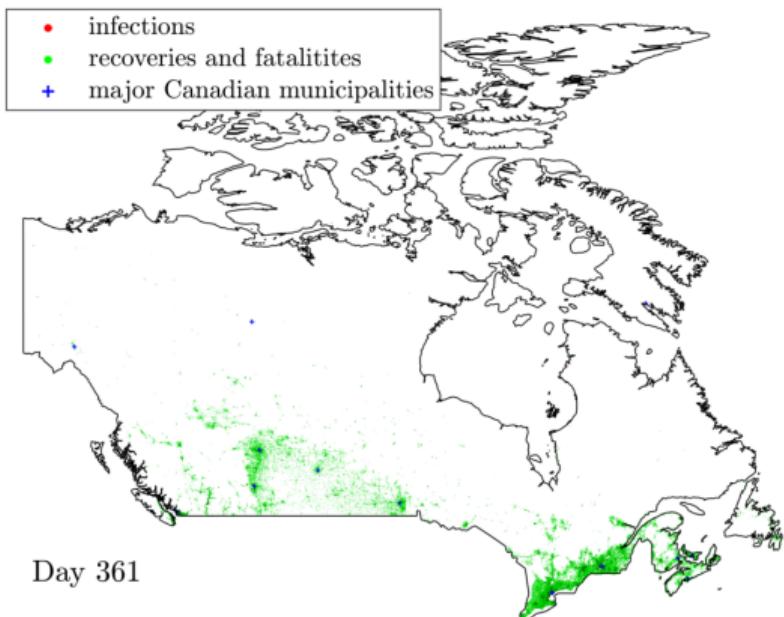
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[1] N. Ferguson et al., 2020, *Imperial College COVID-19 Response Team*

# Thank you for your time

# Open source GPU implementation of agent-based modeling<sup>1</sup>

