Computational Physics

Epidemiological simulation, CoVid19 and percolation theory

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16/06/2021

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Introduction

Motivation

- Infectious diseases spreading
  - How does a disease spread?
  - When to impose/lift lockdowns?
  - How to impose effective measures?
  - Is vaccination indeed necessary? (YES)
  - Other viruses with different lethality/infection rates
- Percolation theory has widespread applications
  - Traffic control
  - Fluid diffusion

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Percolation theory and epidemiological models

- Percolation theory:
  - Studies the behavior of a network when nodes or links are added
    - Disease spreads through this dynamical links
    - Links created between infected and susceptible people with some probability
    - Geometrical phase transition → critical probability when percolation (infinite connectivity structures) first appear

- Epidemiological models → population is classified as:
  - Susceptible Infected Recovered → SIR[1]
  - SIR + Deceased → SIRD

1. An application of the theory of probabilities to the study of a priori pathometry.—Part IProc. R. Soc. Lond. A92204–230

Methods

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Basic implementation

- People modeled as sites in a LxL grid
- SIRD model
- Basic implementation:
  - Only nearest neighbours get infected with a certain probability $P_{infection}$
  - Recovery period (R): 14 days
  - Infected population can die with a certain probability each day:

$$P_{death}^{daily} = 1 - (1 - \mathrm{P}_{\mathrm{death}}^{\mathrm{total}})^{(\frac{1}{\mathrm{R}})}$$

P_{death}^{total} = average probability of an infected person passing away

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Basic implementation

→ Further extensions

- Mobility: random long range interactions with a probability $P_{mobility}$
- Healthcare threshold: not enough medical resources
- Lockdowns
- Vaccinations

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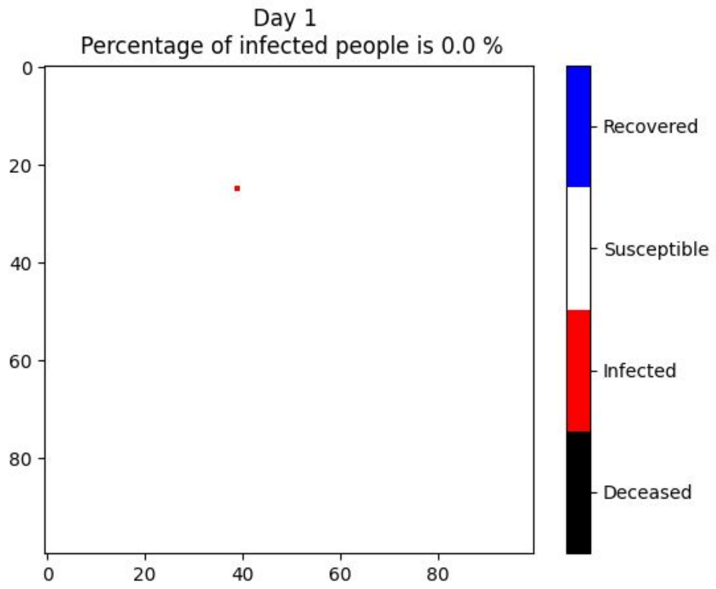
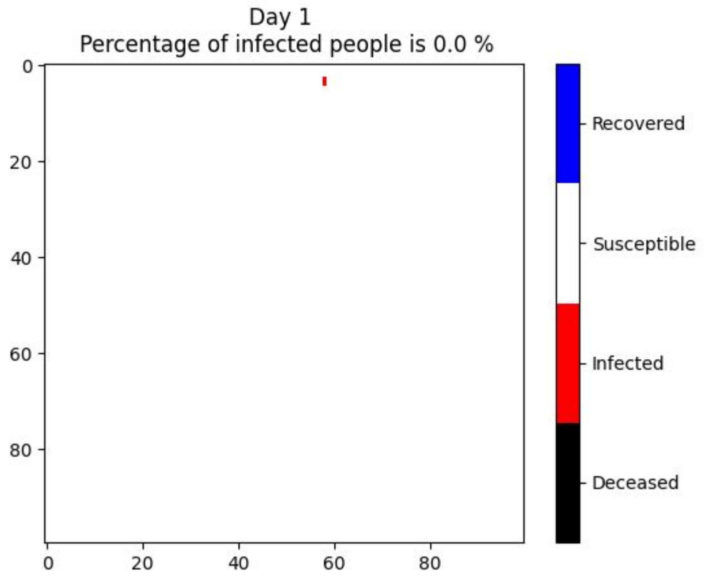
$$P_{mobility} = 0$$



$$P_{mobility} = 0.01$$



- ➔ 1 initial infected person
- ➔ 100x100 grid
- ➔ P_inf = 0.055
- ➔ P_death = 0.01

Error estimation

- Select hyperparameters
- Run the simulation ***n* = *10*** times
  - Independent results
- Obtain:
  - *Average:* $$\bar{x} = \frac{1}{n}\sum_{i=1}^{n} x_i$$
  - *Standard error of the mean:* $$\sigma_{\bar{x}} \approx \frac{\sigma_x}{\sqrt{n}}$$

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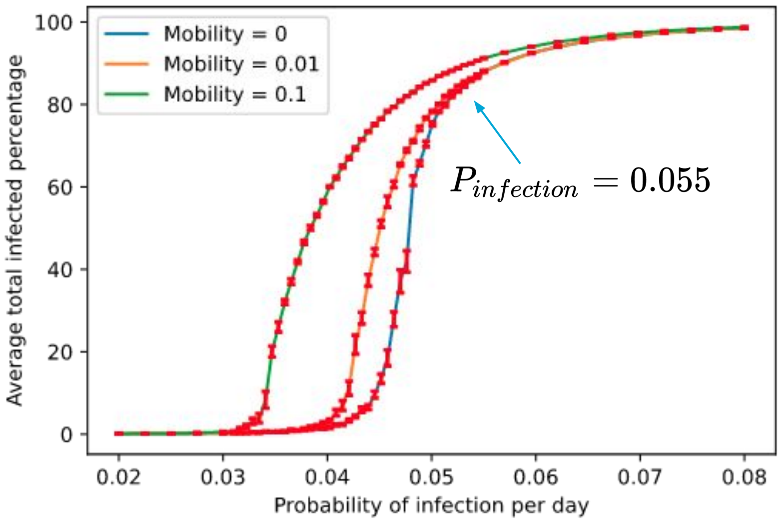
Results

Pandemic threshold

Infected population for various values of mobility



Theoretical percolation threshold probability:

$$P_{total} = \frac{1}{2} \rightarrow P_{daily} = 0.048$$

Mobility allows for a lower point of phase transition.

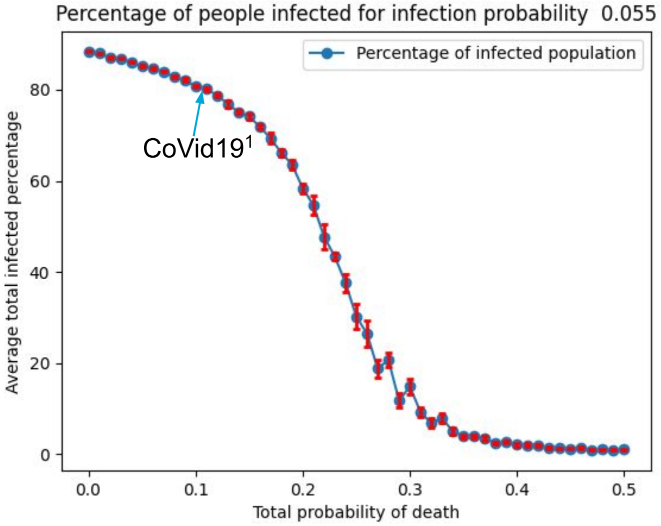
We fix $P_{infection} = 0.055$, slightly **above** the transition phase.

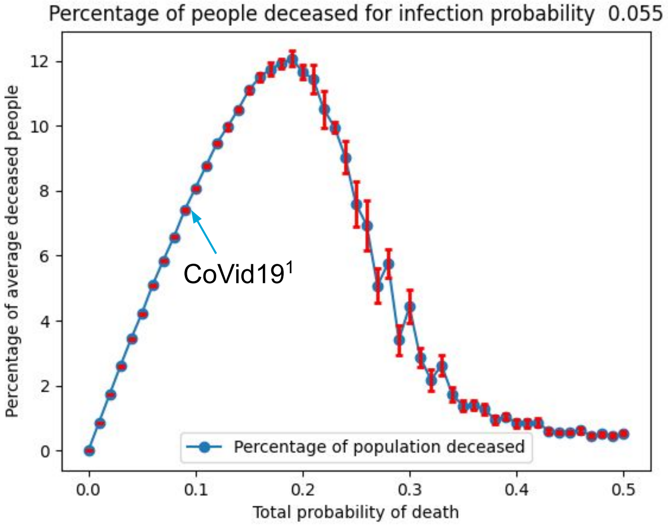
Phase transition!

Endemic → Pandemic

Do deadlier viruses kill more people?

How does the probability of passing away from the disease affects spreading?





Phase transition!

Pandemic → Endemic

1. A. C. Ghani, et. al., Methods for Estimating the Case Fatality Ratio for a Novel, Emerging Infectious Disease, *American Journal of Epidemiology*, Volume 162, Issue 5, 1 September 2005

Healthcare threshold

- The healthcare system can only support up to a percentage of active cases
- If threshold surpassed:
  - probability of death increases due to lack of medical supplies.
- Our model: $$T_H = \frac{N_{ICU\,b}}{P_h}$$

$N_{ICU\,b}$: Number of ICU beds
6 * 10^{-5} * Population

P_h: Average hospitalisation risk
0.5%

$$P_{death}^{total} = \begin{cases} 0.5\% & \text{Active cases} < T_H \\ 0.5\% \dfrac{\text{Active cases}}{T_H} & T_H < \text{Active cases} < 5\,T_H \\ 5 * 0.5\% = 2.5\% & \text{Active cases} > 5\,T_H \end{cases}$$

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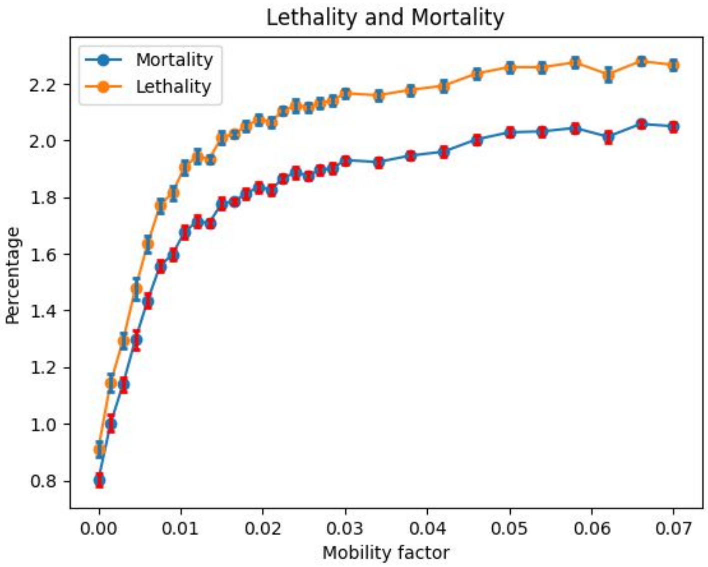
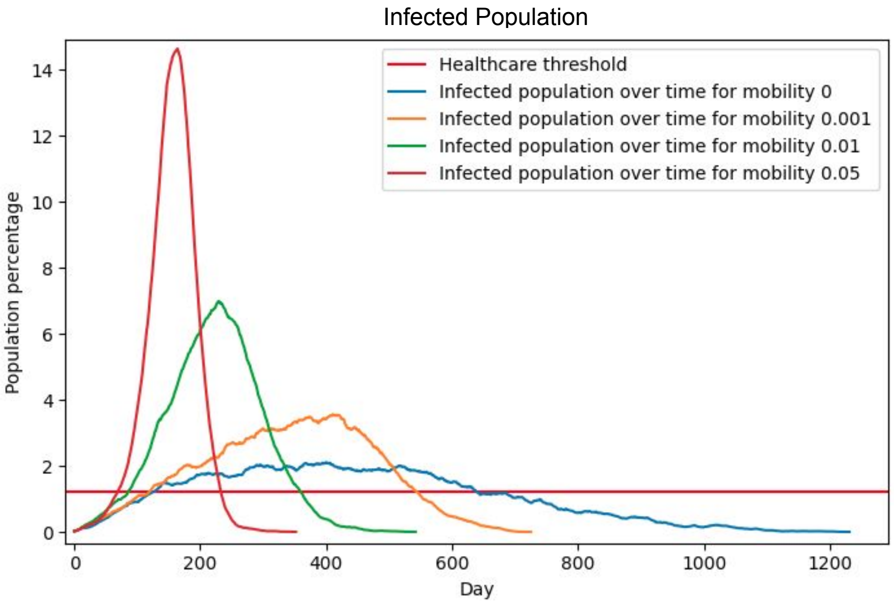
Surpassing the healthcare threshold due to mobility

Mortality = percentage of **total** people deceased
Lethality = percentage of **infected** population deceased





Flatten the curve,
don't party (without corona measures)

Lockdowns during a pandemic

- Lockdown measures:
  - Mobility is set to 0
  - Local contacts are reduced from 4 to 3 for a certain fraction of the population (50%)

Probability of infection is the same, contacts are reduced

- When to impose a lockdown?
  - Imposing threshold: 0.02% of the population is infected
  - Lifting threshold: 0.002% of population is infected

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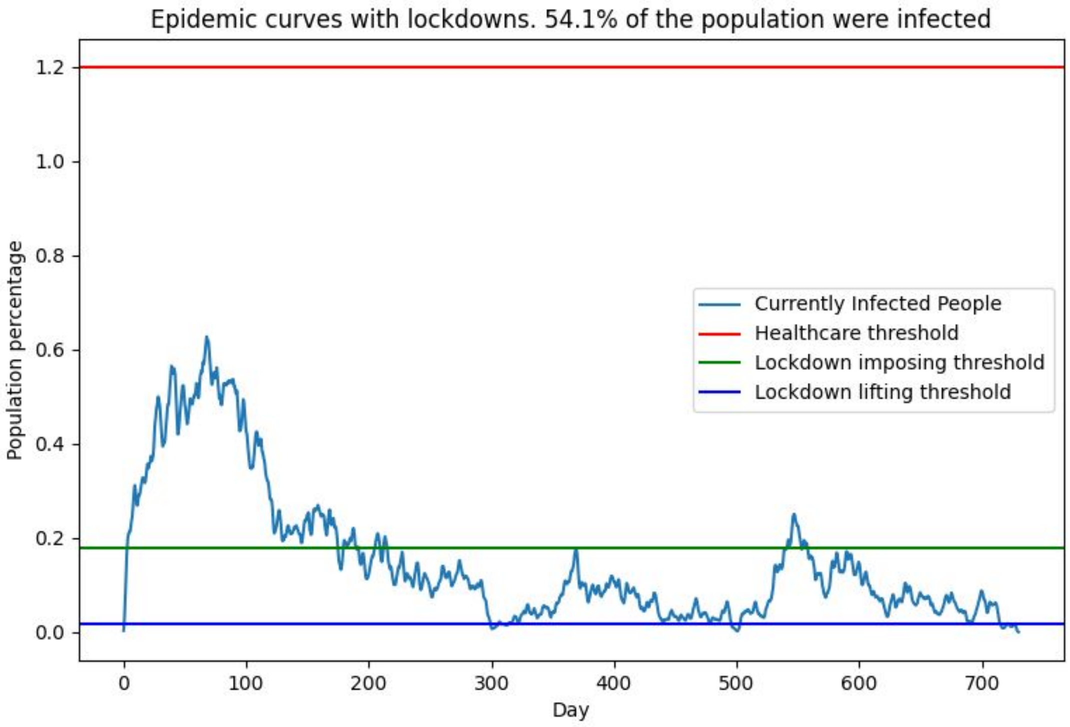
Lockdowns during a pandemic



Second and third waves!

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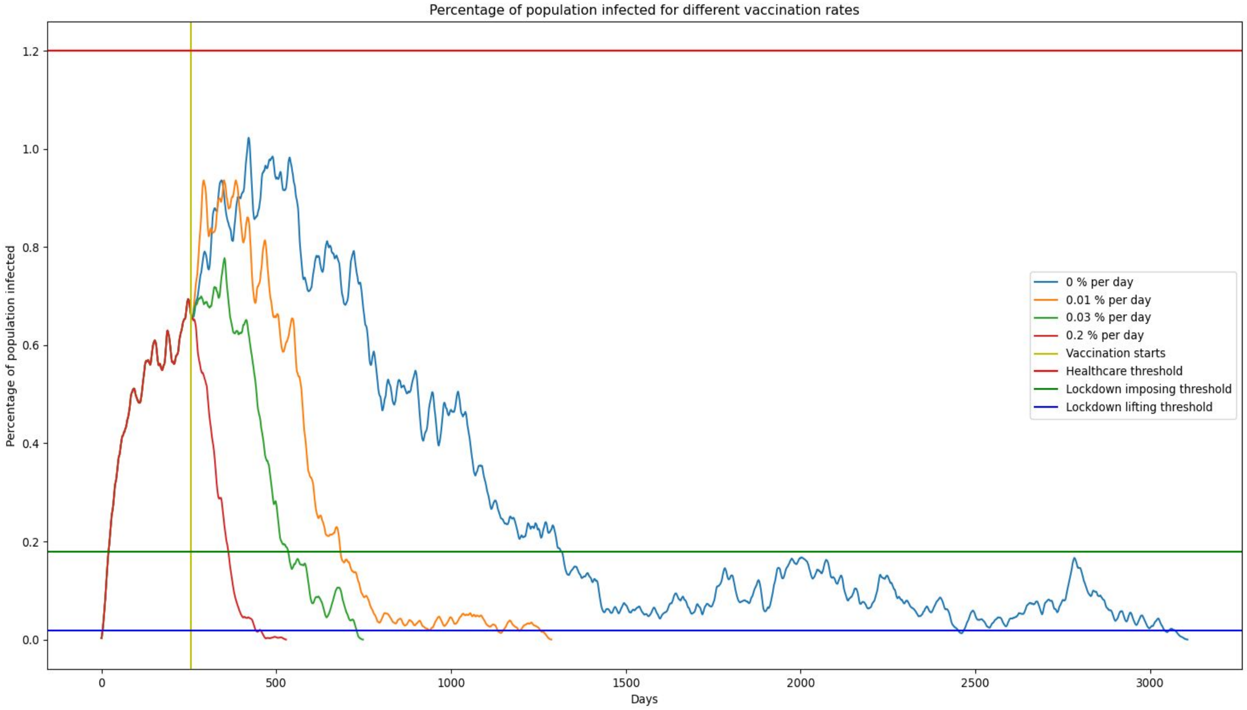
Vaccinations



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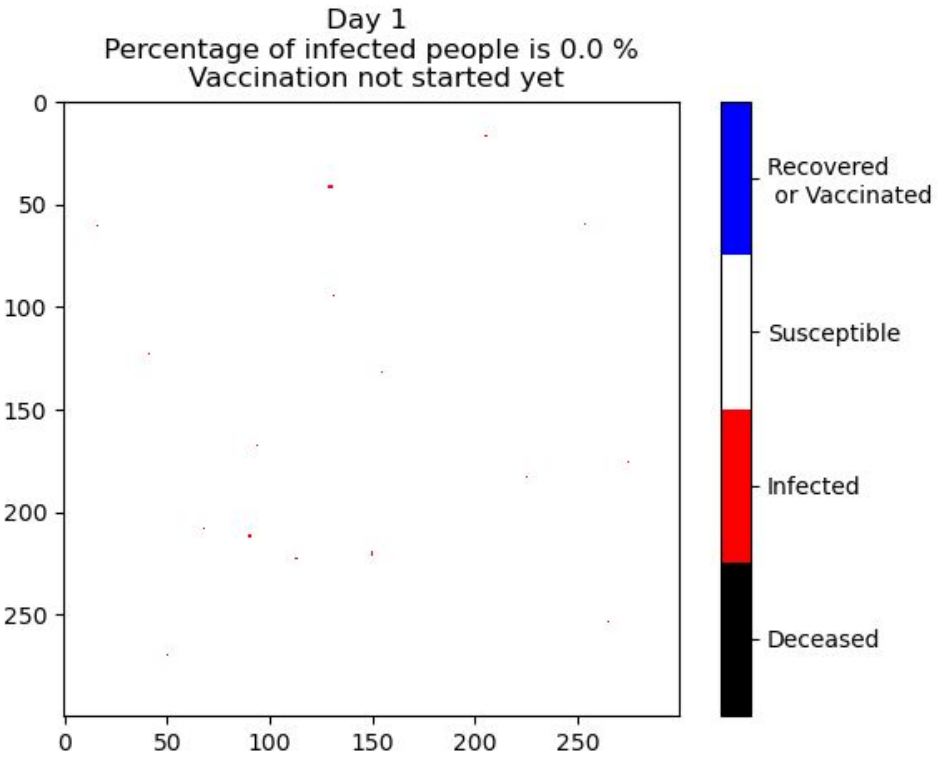
Vaccinations



Performance of the Code

- ➔ Numpy operations are used whenever possible, for plotting and visualization.
- ➔ OOP - Individuals are modeled as objects → Lists
  - ◆ Modelling potential - Performance trade-off
- ➔ For a city roughly of size of Delft ~90K, the simulation with all features (mobility, lockdowns, vaccinations etc) concludes within 1 sec on our laptops.

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Conclusions

- Virus spreading is very complex → Many hyperparameters and simulation is very sensitive to these hyperparameters.
- Exhibit phase transitions. (Endemic → Pandemic)
- The measures we considered (lockdowns and vaccinations) do work.

- Future Outlooks:
  - Age of a Person which allows for different health, mobility, etc.
  - Allow Persons to move with a certain velocity.

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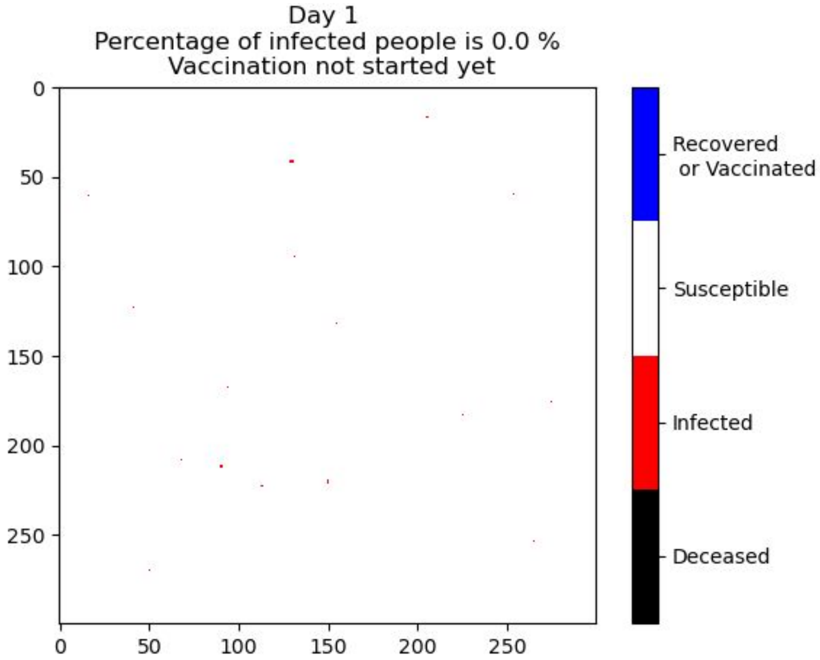
Thanks for your attention!
And get vaccinated at earliest!!



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