Early-Warning Signals of COVID-19 using Proactive Contact Tracing (PCT)

CIFAR/ELLIS Workshop

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Outline

- Motivation
- Comparison with existing methods
- Proactive Contact Tracing (PCT) framework
- Heuristic PCT - Rule based implementation of PCT
- Machine Learning enabled PCT

COVI (Source code coming soon...)

COVI White Paper - Version 1.0

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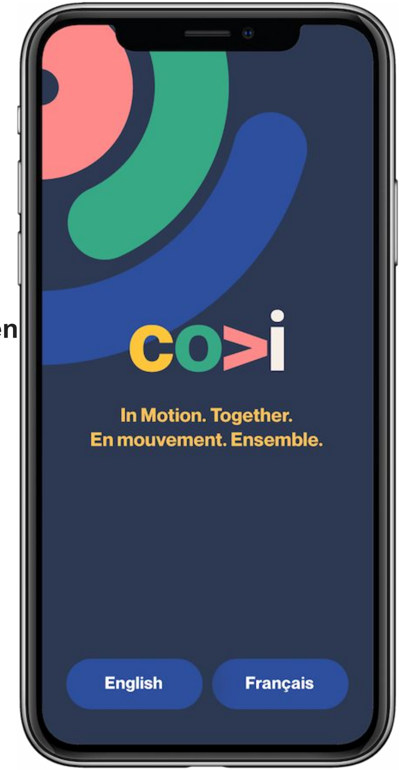

https://arxiv.org/abs/2005.08502

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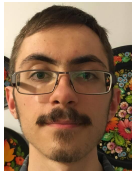
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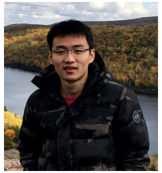
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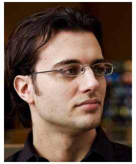
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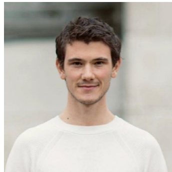
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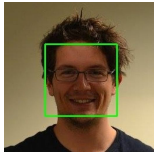
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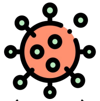
COVID -19 has posed a novel social planning problem

Health policy experts:

Min COVID-19 transmission (R_t)

S.t

- Keep society functioning
- Minimize deaths



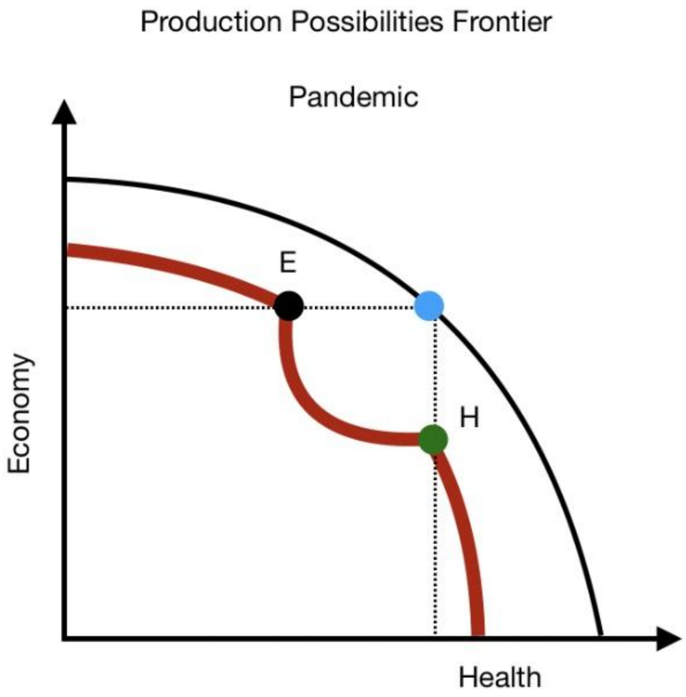
Economists:

Max Social Welfare

S.t

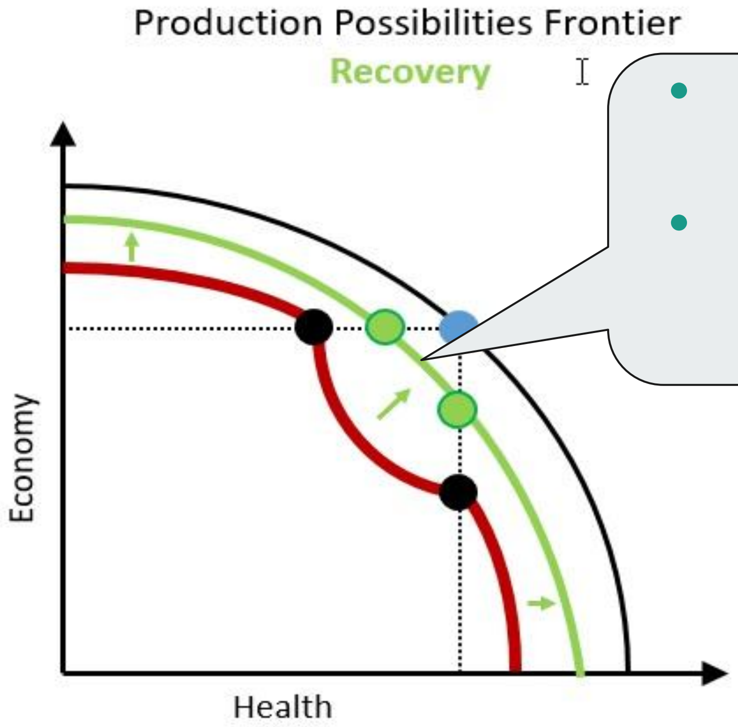
- Technological constraints
- Incentive constraints

Inefficient economic and health outcome following COVID



Source: Gans(2020), "Health Before Wealth: the Economic Logic", March 25, 2020
https://blog.usejournal.com/health-before-wealth-the-economic-logic-9c5414ae259c

How could we expand the frontier during the pandemic?



- **Public policies**
  - Public health policy
  - Monetary and fiscal policies
- **Health and technology advancement**
  - Vaccine development and health research
  - **Tracing and testing**

Optimizing policy coordination calls for advanced technology

What we observe...

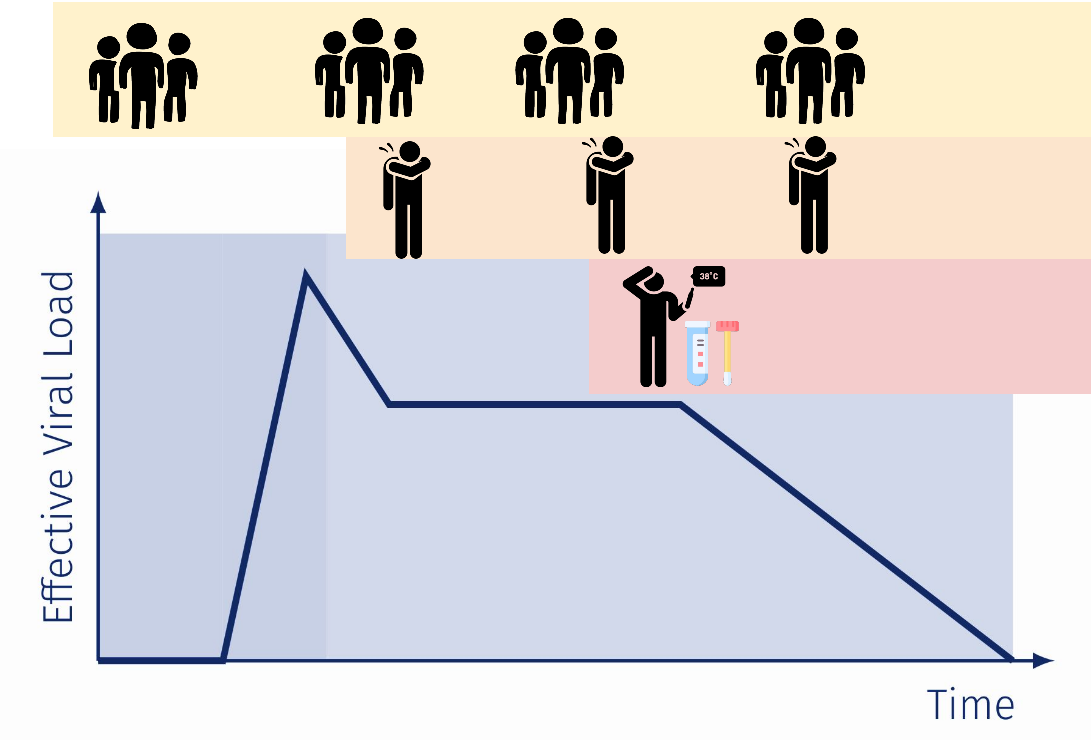
Contacts

Symptoms

Test Results

Individual Characteristics*
e.g.

- Age
- Pre-existing conditions



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Contact Tracing

Contacts

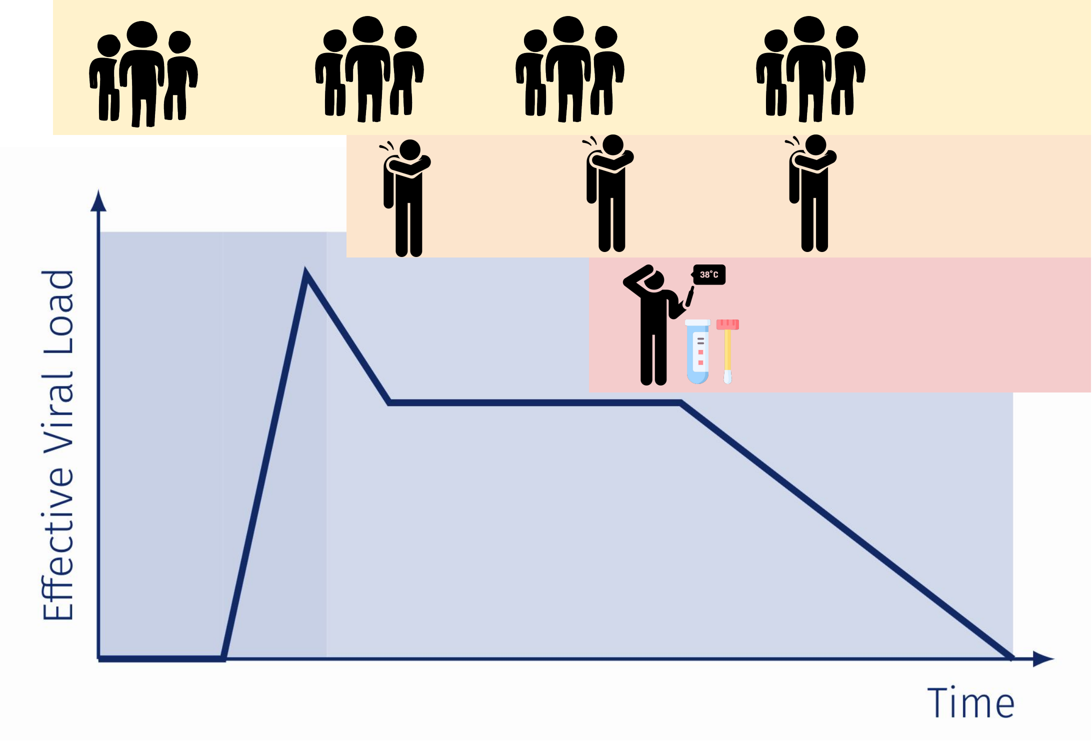
Symptoms

Test Results

Infection Events

Detection

Individual Characteristics*
e.g.
- Age
- Pre-existing conditions



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Many noisy signals...

Symptoms

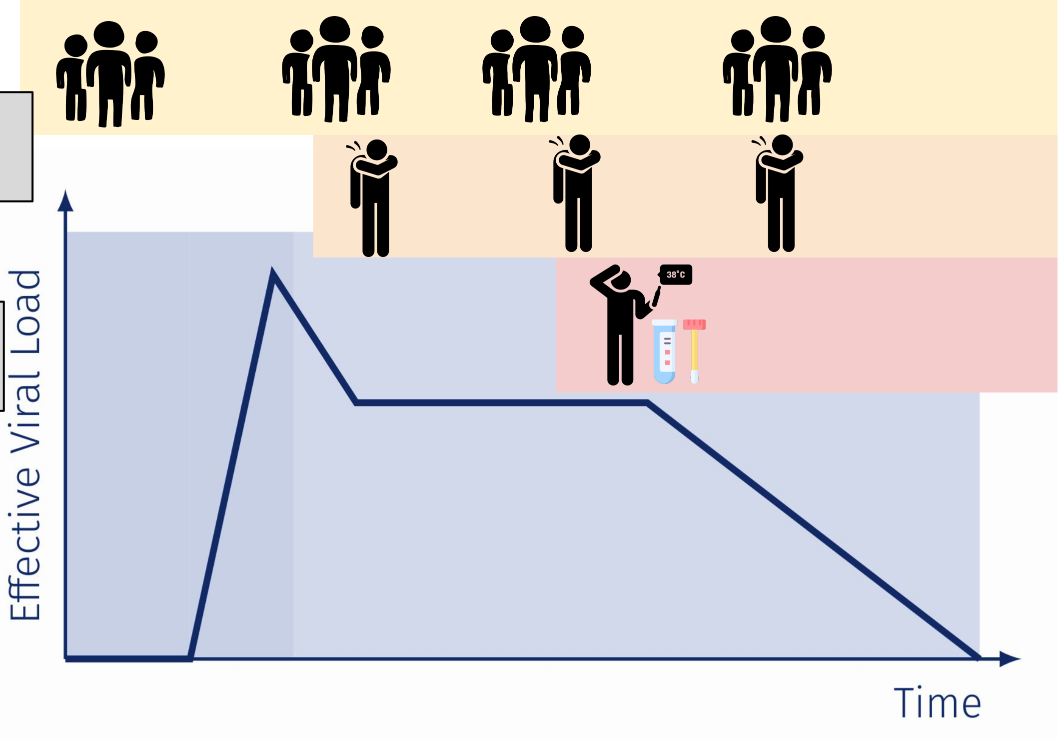
Similar to cold and flu
No symptoms in asymptomatic

Test Results

Delay
High False Negative Rates

Individual Characteristics*
e.g.

- Age
- Pre-existing conditions



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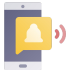
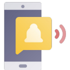
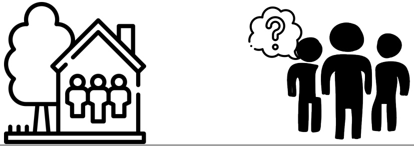
Landscape of tracing methods

	Manual Tracing	Binary Contact Tracing (BCT)	Proactive Contact Tracing (PCT)
Potential Contacts			
Clues Used			
Recommendations			

Manual Tracing is subject to memory challenges

	 Manual Tracing	Binary Contact Tracing (BCT) 	Proactive Contact Tracing (PCT) 
Potential Contacts			
Clues Used			
Recommendations			

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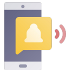
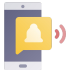
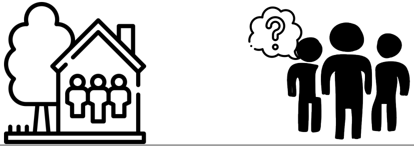
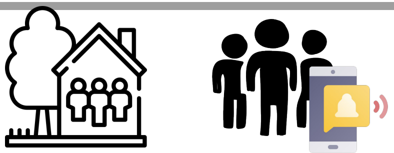
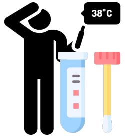
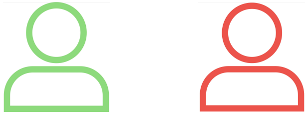
BDT provides precise contacts info, yet lacking some individual clues

	 Manual Tracing	Binary Contact Tracing (BCT) 	Proactive Contact Tracing (PCT) 
Potential Contacts			
Clues Used			
Recommendations			

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COVI encompasses BDT and profits from richer info

	Manual Tracing	Binary Contact Tracing (BCT)	Proactive Contact Tracing (PCT)
Potential Contacts			
Clues Used	38°C	38°C	38°C
Recommendations			

Example Scenario: Better Early Warning Signals

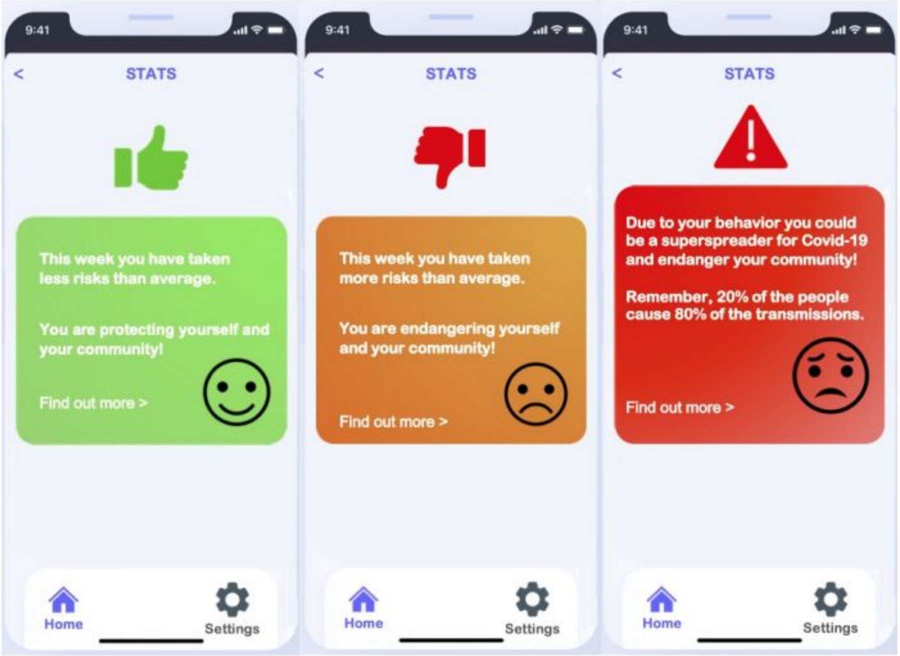
	M	T	W	T	F	S	S	M	T	W	T	F	S	S
Manual tracing only			Jim has a contact with high-risk stranger at the grocery store		Stranger starts showing symptoms		Stranger's symptoms grow worse	Jim **GOES** to work	Stranger sees doctor, gets tested	Test result comes back positive			Jim is contacted directly by public health	
Binary contact tracing	Jim installs the app		Jim has a contact with high-risk stranger at the grocery store		Stranger starts showing symptoms		Stranger's symptoms grow worse	Jim **GOES** to work	Stranger sees doctor, gets tested	Test result comes back positive			Jim is contacted directly by public health	
Our approach	Jim installs the app		Jim has a contact with high-risk stranger at the grocery store		Stranger starts showing symptoms		Stranger's symptoms grow worse	Jim **DOES NOT** go to work	Stranger sees doctor, gets tested	Test result comes back positive			Jim is contacted directly by public health	

Effectiveness of In-app notifications

How to Make COVID-19 Contact Tracing Apps work: Insights From Behavioral Economics

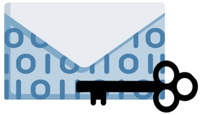
Ian Ayres,[1], Alessandro Romano[1],[2], Chiara Sotis,[3]
[1] Yale Law School, [2] Bocconi Law School, [3] London School of Economics and Political Science

A recent user-behavior research (Ayres, Ian, et al. 2020) suggests that **users respond positively to the notifications from CT apps**.

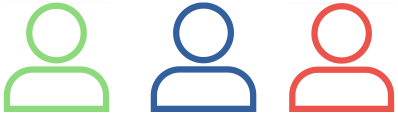


Proactive Contact Tracing (PCT): Framework

Predict **today's and past contagiousness** using all the clues

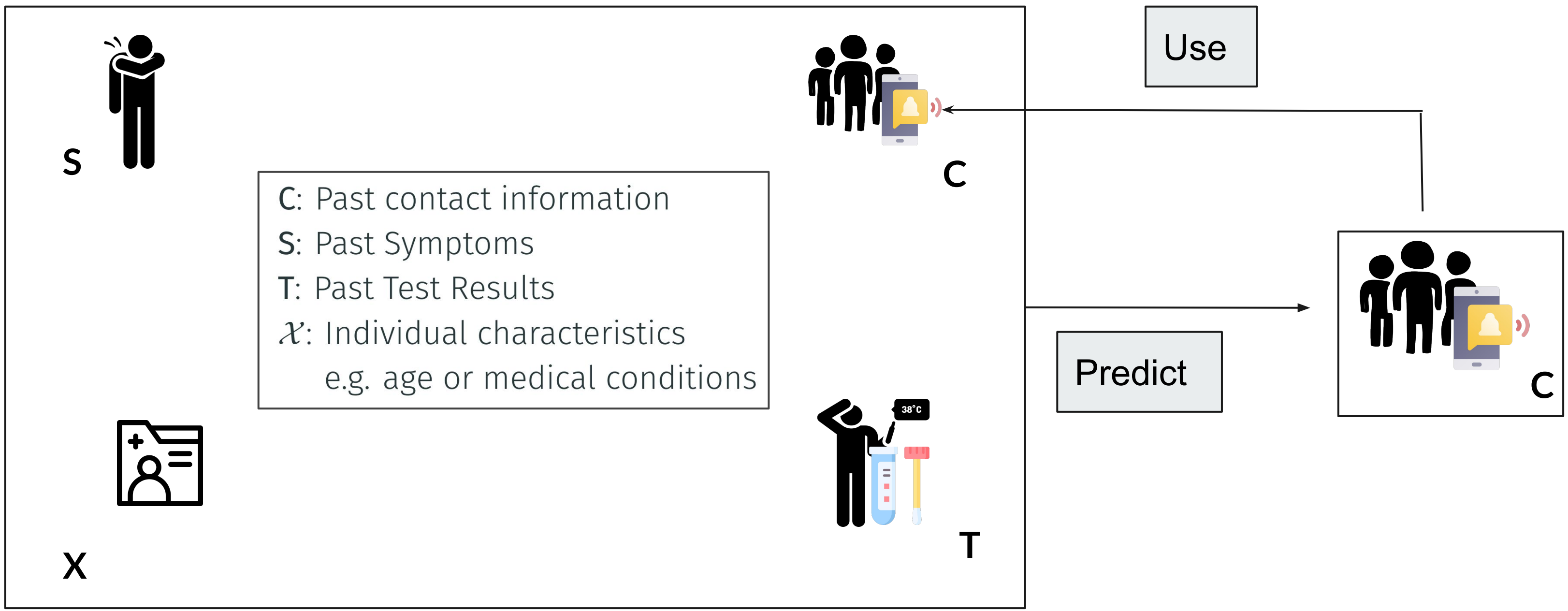


Send secure messages to previous contacts



Recommend user behavior based on **assessed risk levels**
E.g. normal (green), wear mask/self-isolate (blue), quarantine (red)

Clues used by PCT



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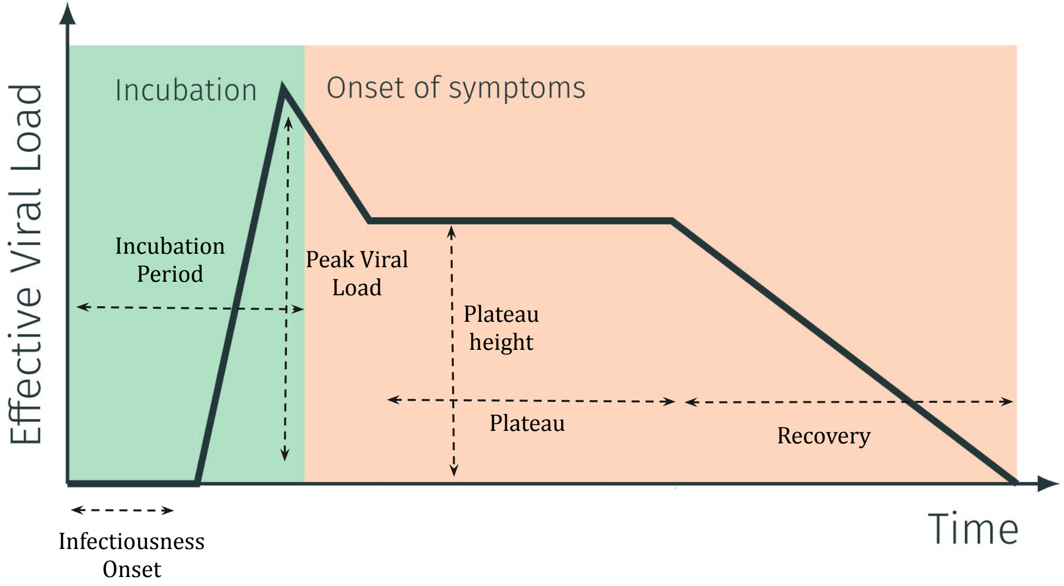
Viral Load Curve

x Individual Characteristics

$v(t)$ Functional form of Effective Viral Load (Contagiousness)
(To, Kelvin Kai-Wang, et al., 2020)



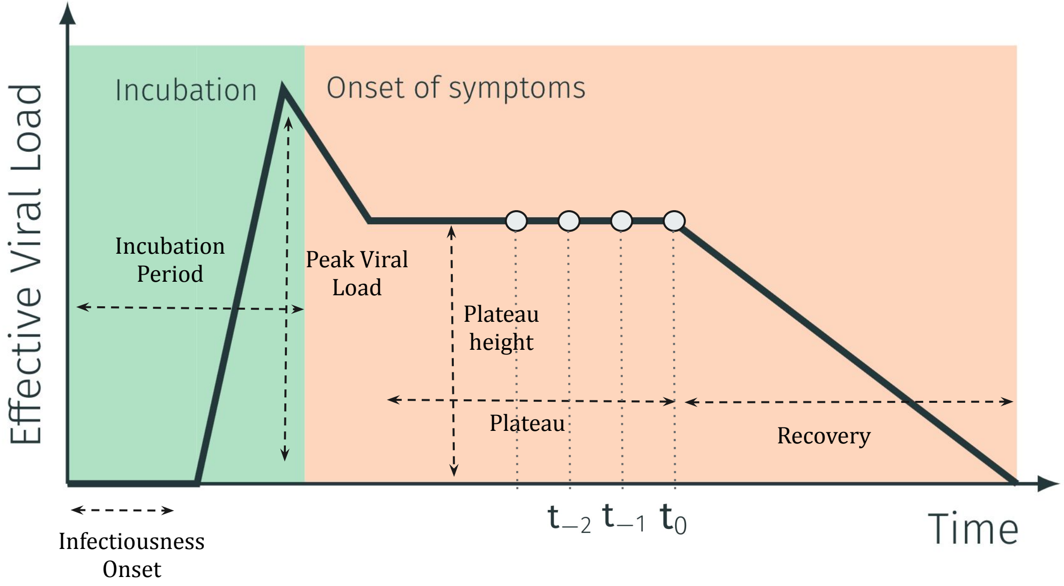
Viral Load Curve

$\mathcal{X}$ Individual Characteristics

$\mathcal{V}(t)$ Functional form of Effective Viral Load (Contagiousness)

For simplicity, we consider Effective Viral Load for each day in the past 14 days -

$$\mathcal{V}(t_{-14}, t_{-13}, \ldots, t_0)$$



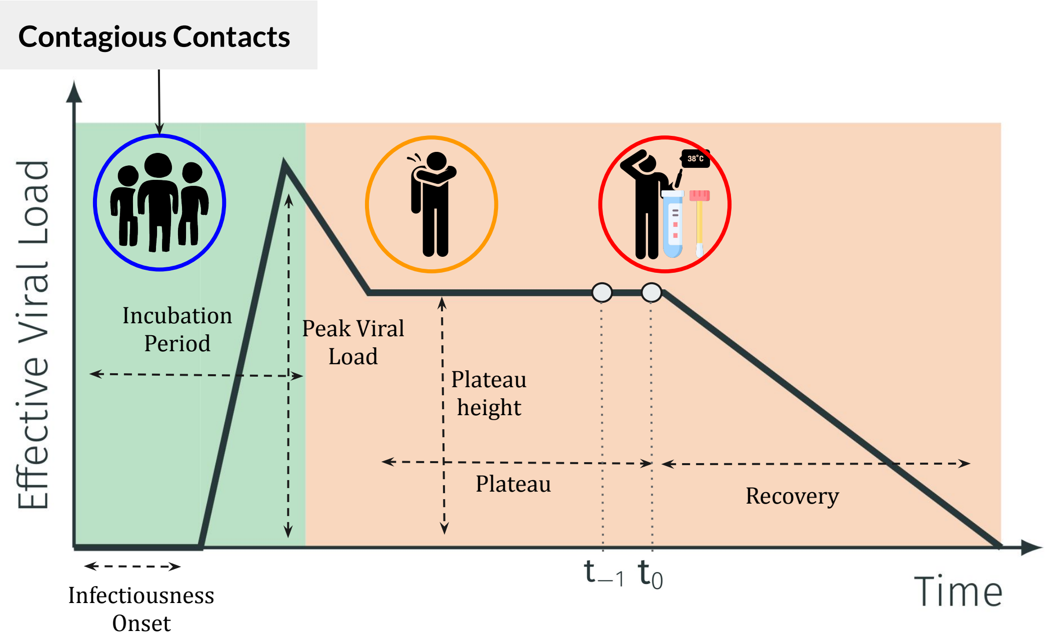
How simulated Viral Load Curve produces observables

$$\mathcal{V}(t) = f(\boxed{Contacts}, \mathcal{X})$$

$$\boxed{Symptoms}(t) = f(\mathcal{V}(t), \mathcal{X})$$

$$\boxed{TestResults} = f(\mathcal{V}, Symptoms, \mathcal{X})$$

$$\boxed{Contacts} = f(\mathcal{V}, Symptoms, TestResults, \mathcal{X})$$



What to predict?

$$\mathcal{V}(t) = f(\boxed{Contacts}, \mathcal{X})$$

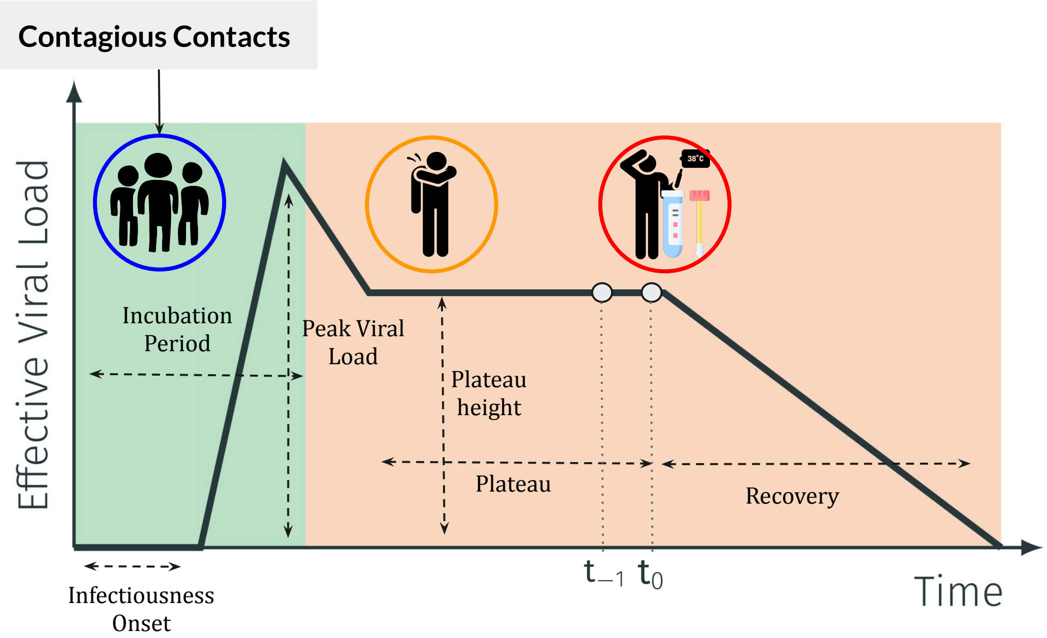
$$\boxed{Symptoms}(t) = f(\mathcal{V}(t), \mathcal{X})$$

$$\boxed{TestResults} = f(\mathcal{V}, Symptoms, \mathcal{X})$$

$$\boxed{Contacts} = f(\mathcal{V}, Symptoms, TestResults, \mathcal{X})$$

Predict Effective Viral Load as the clues are observed

$$\hat{\mathcal{V}}(t_{-14}, t_{-13}, \ldots, t_0) = g(\mathsf{C}, \mathsf{S}, \mathsf{T}, \mathcal{X})$$

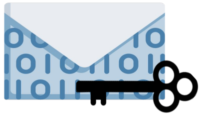


PCT: Predict - Inform - Advice

C: Past contact information
S: Past Symptoms
T: Past Test Results
$\mathcal{X}$: Individual characteristics
e.g. age or medical conditions

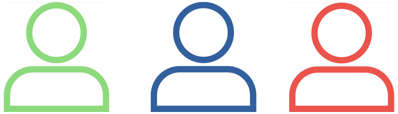
Predict **today's and past contagiousness** using all the clues i.e.

$$\hat{\mathcal{V}}(t_{-14}, t_{-13}, \ldots, t_0) = g(\mathsf{C}, \mathsf{S}, \mathsf{T}, \mathcal{X})$$



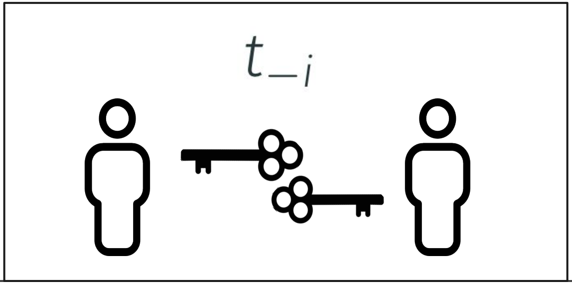
Send $\boxed{\hat{\mathcal{V}}(t_{-i})}$ to the contacts on day $\boxed{t_{-i}}$

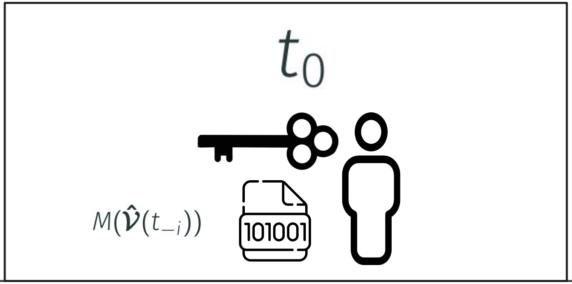
Add it to C of the **contact** and repeat



Use $\hat{\mathcal{V}}$ to **recommend user behavior**
e.g. quarantine, wear mask, self-isolate, etc.

Privacy-Preserving PCT





- A **unique key** is exchanged for every 15 minutes two apps are in proximity of 2 meters
- **Only N bits** can be sent via any key
  - **Risk Levels (R):** Quantize $\hat{\mathcal{V}}(t_{-i})$ to an integer using the map **M**

    $$\boxed{M : \mathcal{R} \rightarrow \{1, 2, 3, \ldots, 2^N\}} \qquad \boxed{R(t_{-i}) = M(\hat{\mathcal{V}}(t_{-i}))}$$

  - Simulation uses **N = 4**
  - Digital Binary Tracing (GoC), N=1 i.e only 0 or 1 is sent.
- **Send** $R(t_{-i})$ **only when it's different from the previously predicted risk level on** t_{-i}

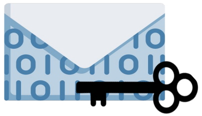
❖ Detailed discussion of privacy considerations in Alsdurf, Hannah, et al 2020.
❖ WIP - Sensitivity analysis on N bits

Privacy-Preserving PCT

C: Past contact information
S: Past Symptoms
T: Past Test Results
$\mathcal{X}$: Individual characteristics
e.g. age or medical conditions

Predict **today's and past contagiousness** using all the clues i.e.

$$\hat{\mathcal{V}}(t_{-14}, t_{-13}, ..., t_0) = g(\mathrm{C}, \mathrm{S}, \mathrm{T}, \mathcal{X})$$



Send $\boxed{R(t_{-i})}$ to the contacts on day $\boxed{t_{-i}}$

Add it to C of the **contact** and repeat

Use $\hat{\mathcal{V}}$ to **recommend user behavior**
e.g. quarantine, wear mask, self-isolate, etc.

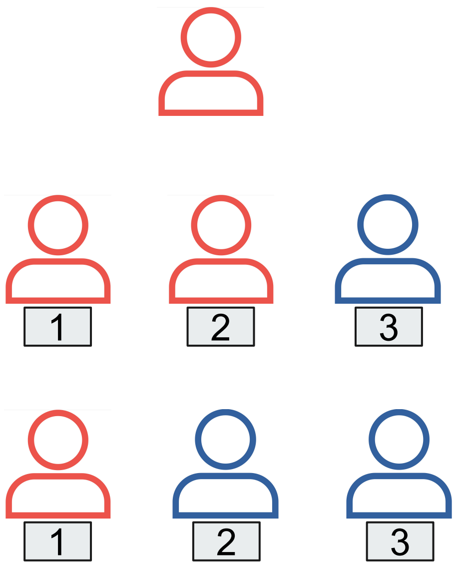
Heuristic PCT Supports Mobility of Individuals

Set Risk Levels

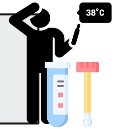
$$R(t_{-14}, t_{-13}, \ldots, t_0) = g_{Heuristic}(\mathrm{C}, \mathrm{S}, \mathrm{T})$$

T + C1. yields BCT

User Recommendations



T - If the user **reports** a **positive test result** set **R = 4 for the past 14 days**

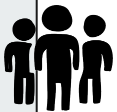


S - Depending on the **severity of reported symptom**, set R as

1. **Severe** symptoms: Set **R=3 for the past 7 days**
2. **Moderate** symptoms: Set **R = 2 for the past 7 days**
3. **Mild** symptoms: Set **R = 1 for the past 7 days**

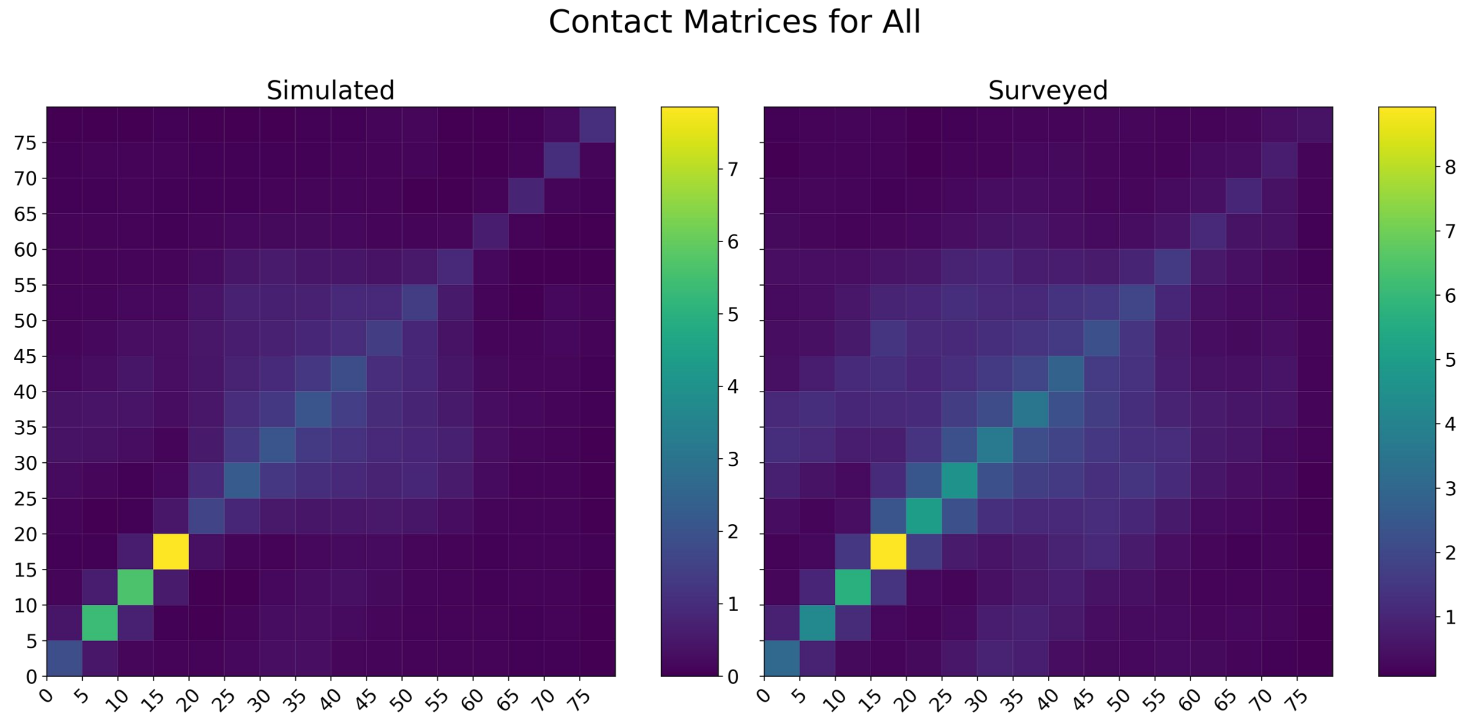
C - Break down all **received risk levels R`** into three categories

1. High (R` = 4) : Set **R =3 until the day of receipt of R`**
2. Medium (R` = 3): Set **R = 2 until the day of receipt of R`**
3. Mild (R` <= 2) : Set **R = 1 until the day of receipt of R`**

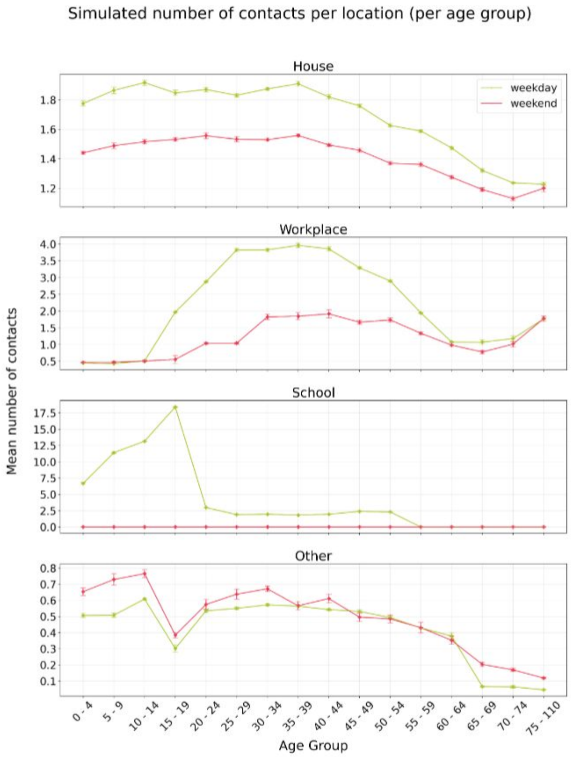


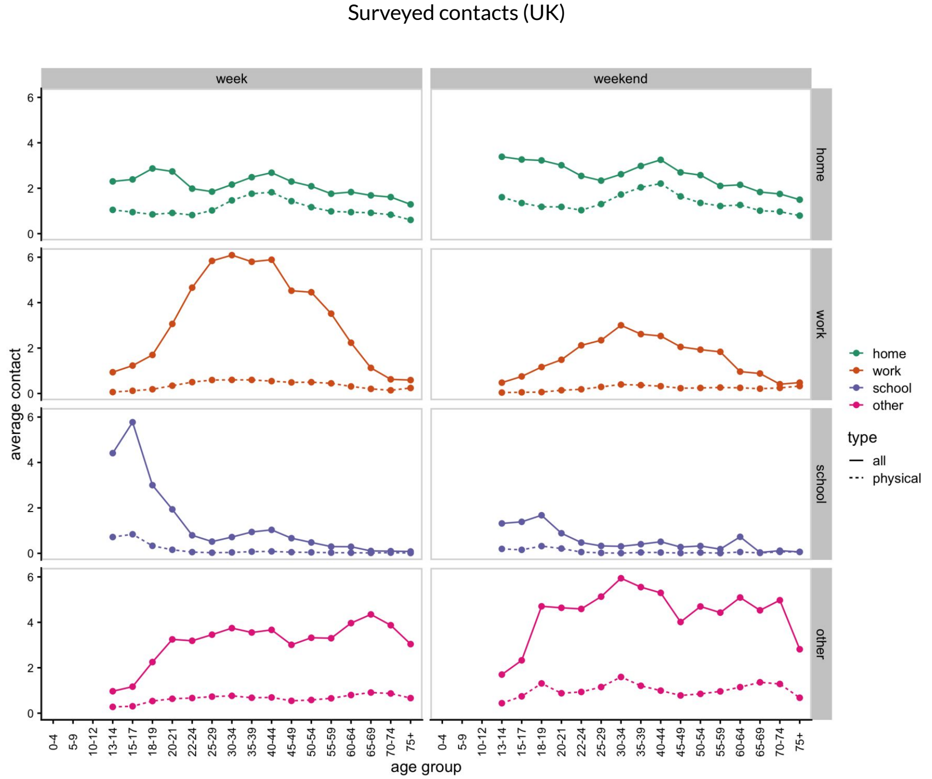
Finally, take the max of risk levels on each day obtained from above computation

Simulator: Age-stratified contact patterns



Simulator: Location dependent contact patterns



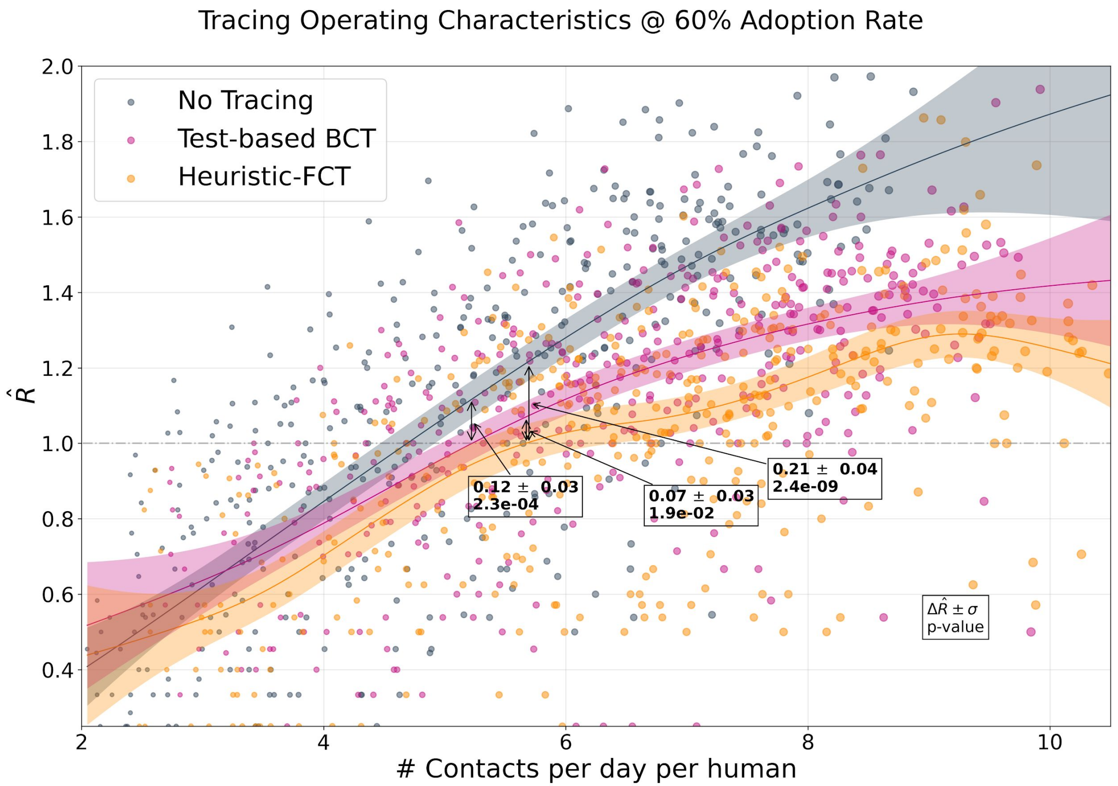


Simulations

- **Population size**: 3000
- Initial number of infected individuals: 6 (0.2% of the population)
- 25% **Asymptomatic population**
- **Number of tests per day** = 3 (0.1% of the population)
- Behavior Modifications -
  - **High Risk Agents** have 0 contacts (Quarantine)
  - **Medium-High Risk Agents** have contacts according to post-lockdown (Brisson et al. 2020)
  - **Medium Risk Agents** have half the contacts as Medium-High Risk Agents
  - **Low Risk Agents** have half the contacts as Medium Risk Agents

- **Adherence to recommendations** is modeled via dropout of 0.02 probability of following the recommendations
- **Quality of self-diagnosis** is modeled via dropout on symptoms of 0.2 i.e a user is 20% likely to not report their specific symptoms
- More details about the simulator and heuristic algorithm in Gupta et al. (2020)

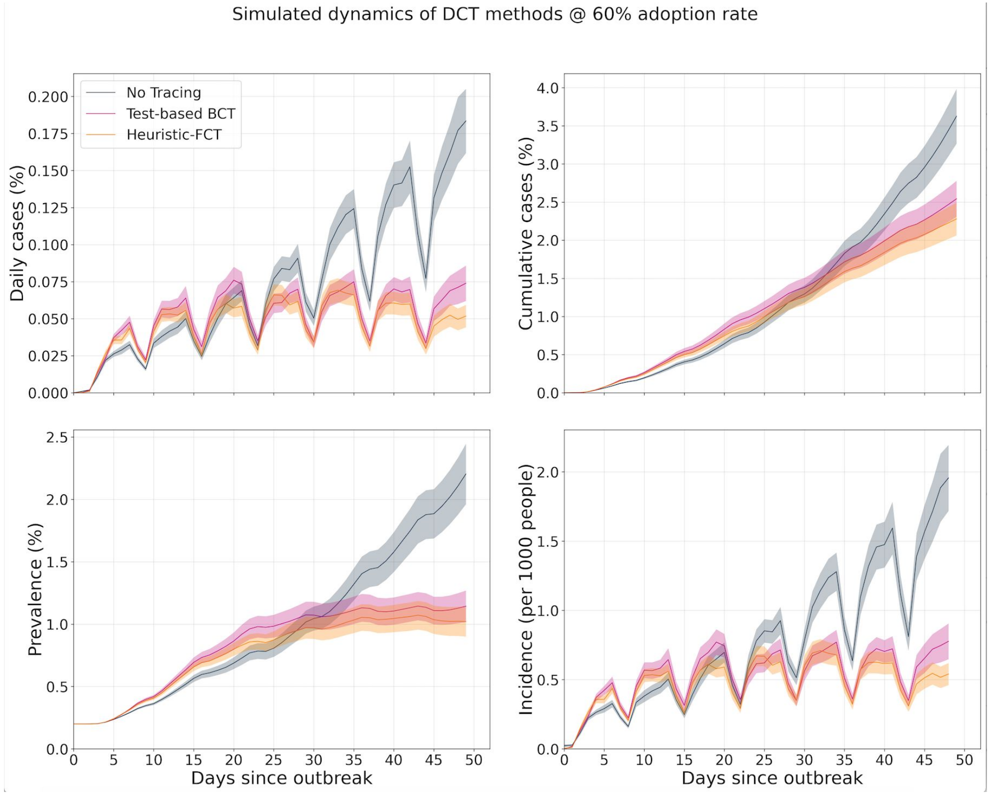
Simulation Results: Mobility vs Virus Transmission (R)



Simulation Results: Improved Case Curves Under Heuristic-PCT

Daily cases

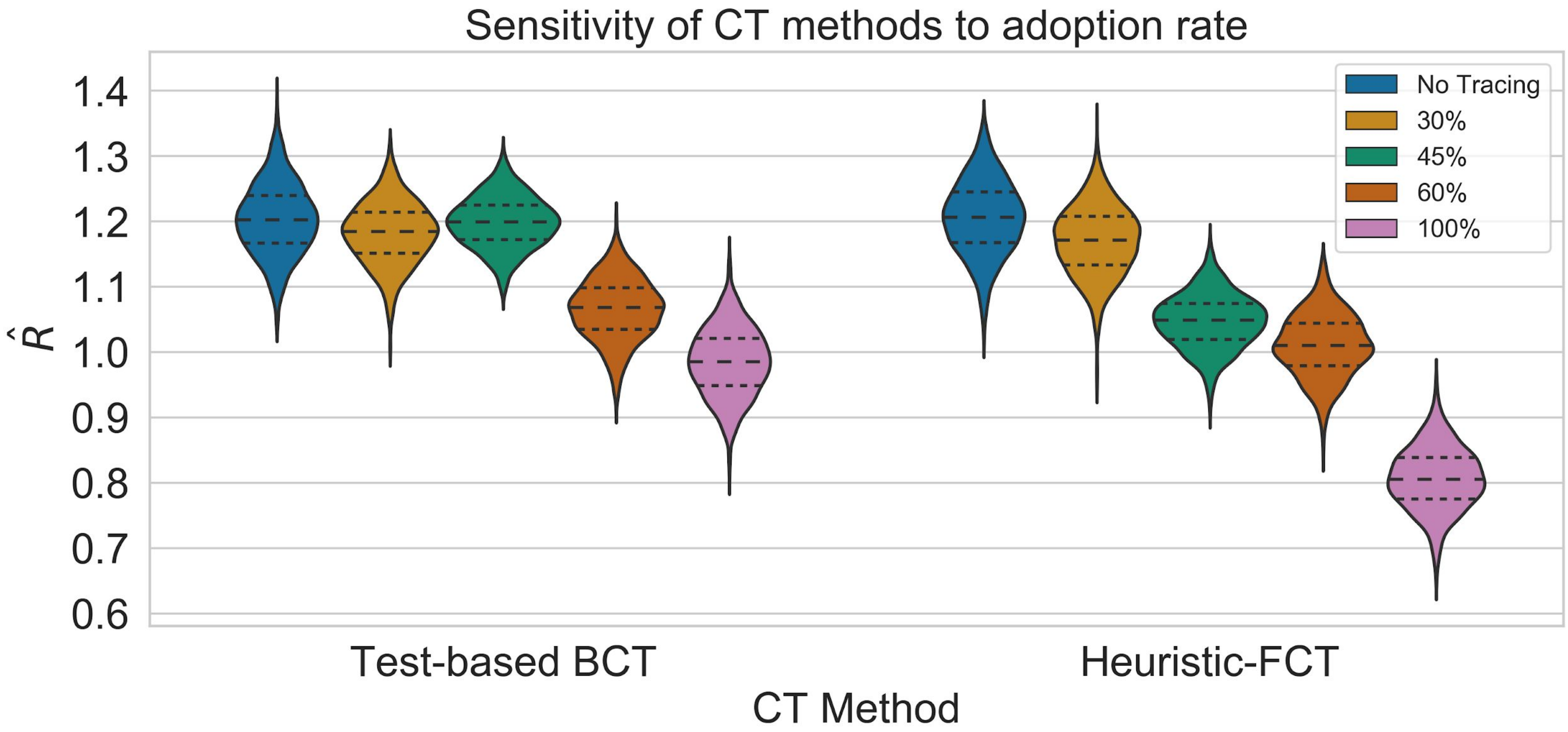
Fraction of infected population up to date



Fraction of population infected at any point in time

Average risk of infection

Simulation Results: Adoption rate sensitivity

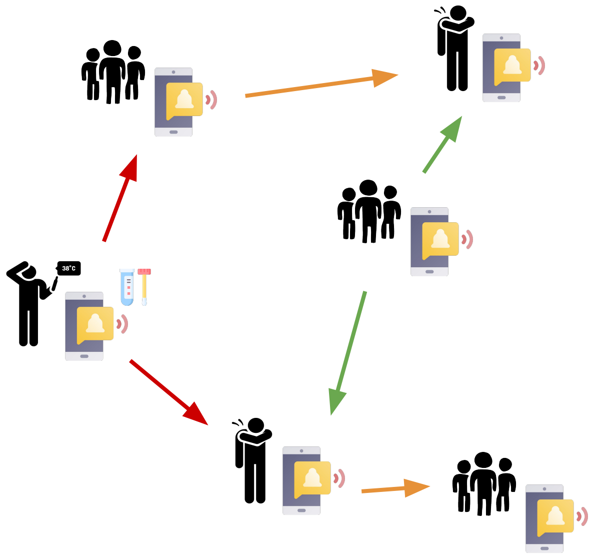


Why Machine Learning?

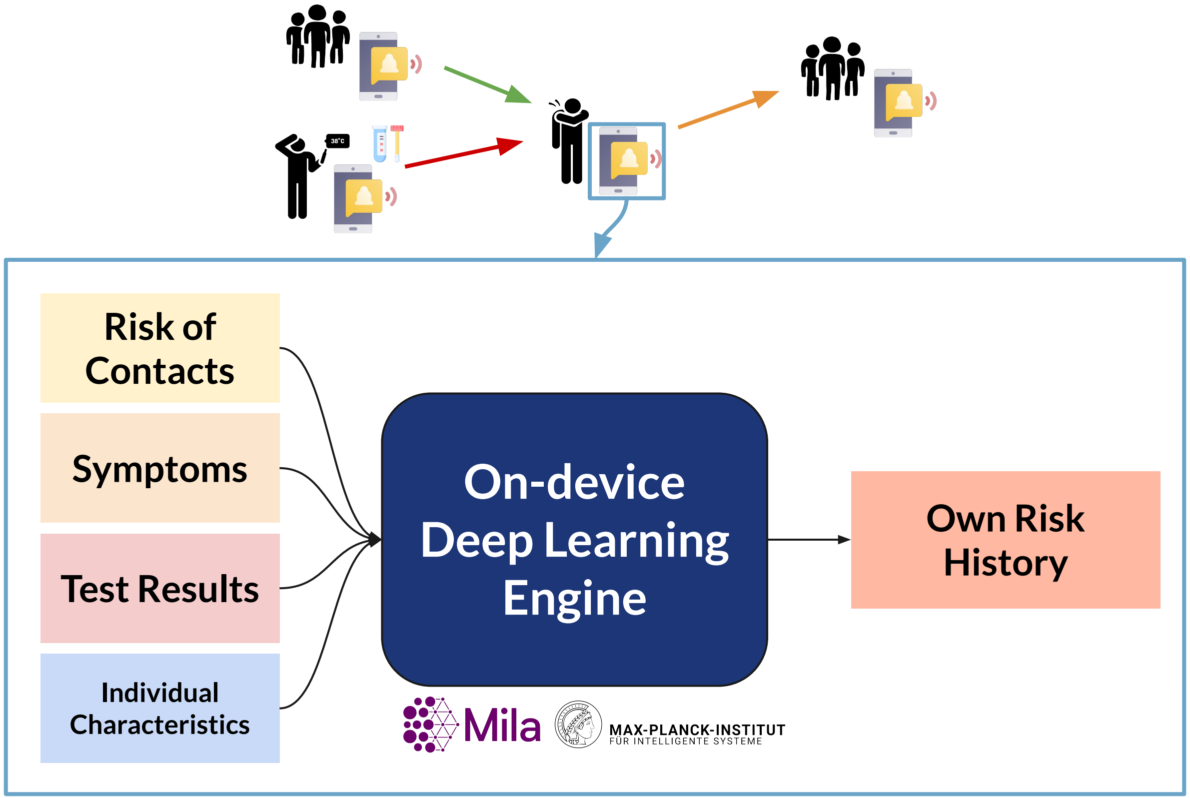
Why Machine / Deep Learning?

- It’s tricky to decide what messages one user should send to the other about its risk.
    - In Binary Contact Tracing (BCT), the decision is based on the test results.
    - But can we do better at sending early warning signals?

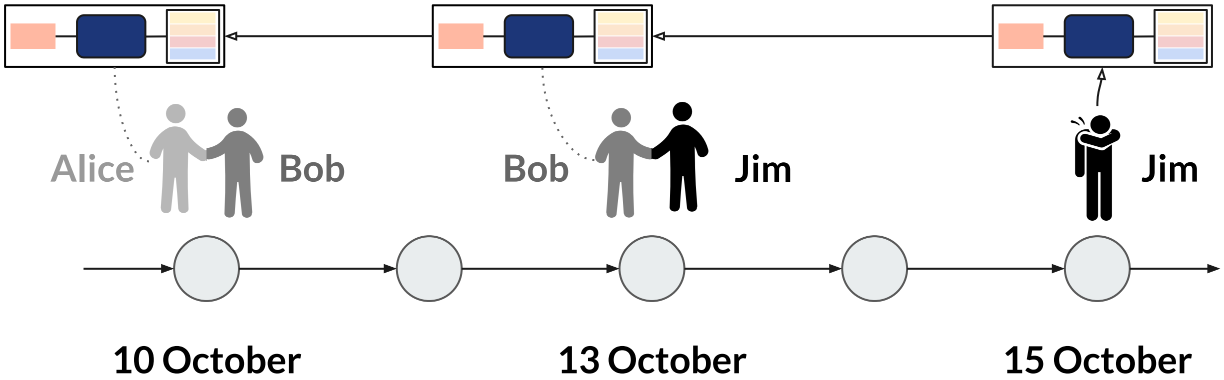
- Machine learning enables us to **learn** to decide what messages to send using real and simulation data in an automated and scalable way.



What happens on the phone?

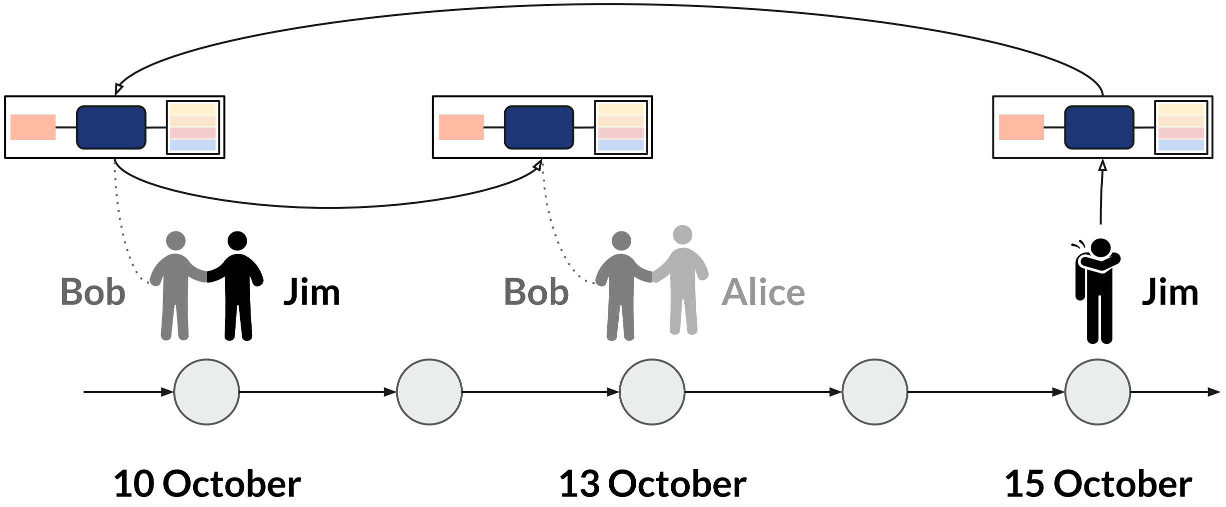


How risk messages cascade in time



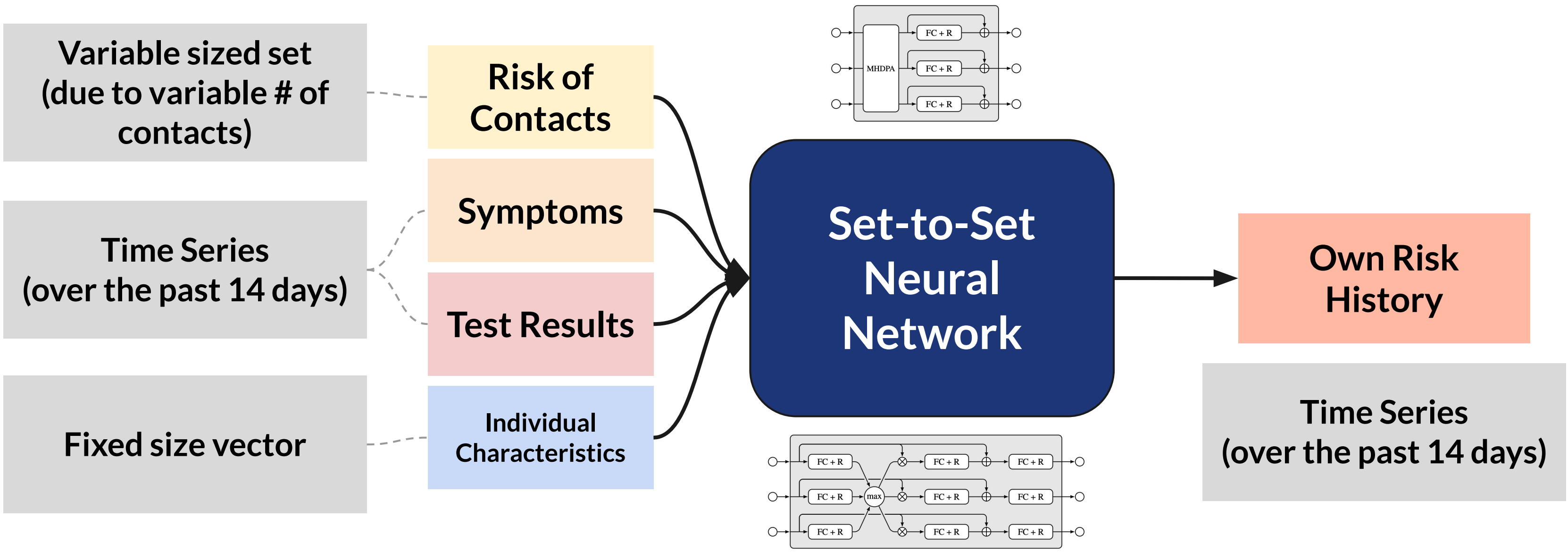
Icons made by Freepik, fjstudio, Pixel Perfect , photo3idea_studio, Gregor Cresnar, Vitaly Gorbachev from www.flaticon.com

How risk messages cascade in time

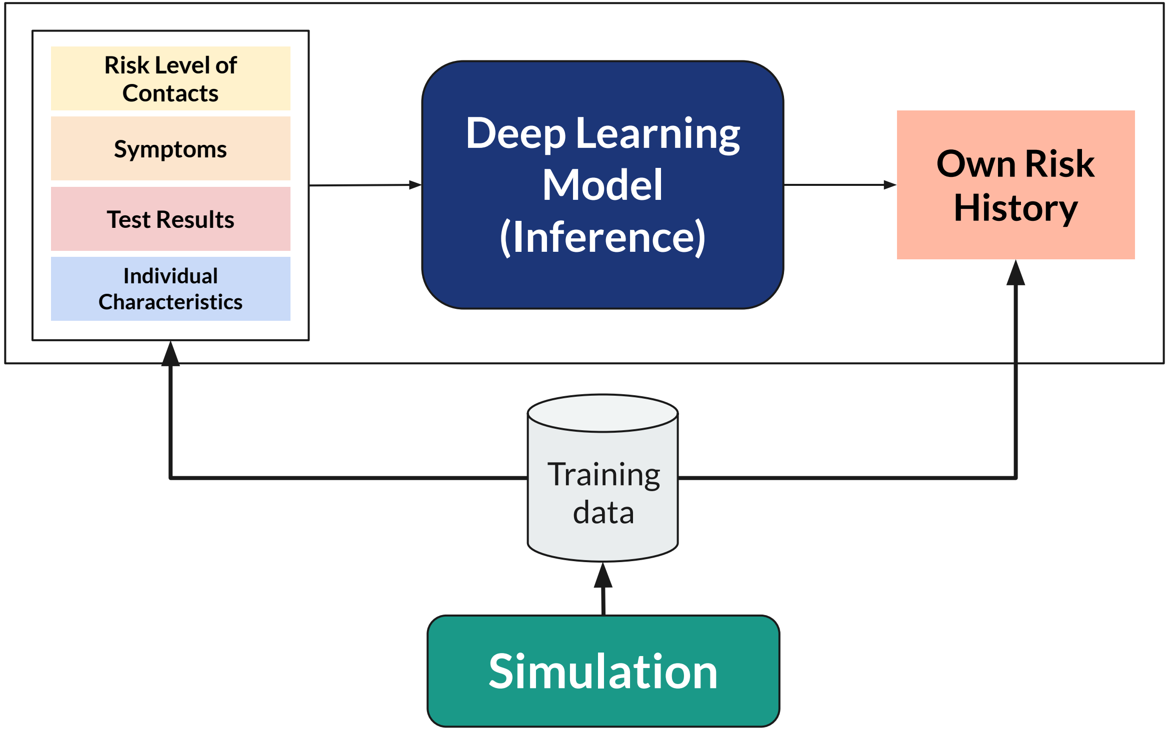


Icons made by Freepik, fjstudio, Pixel Perfect , photo3idea_studio, Gregor Cresnar, Vitaly Gorbachev from www.flaticon.com

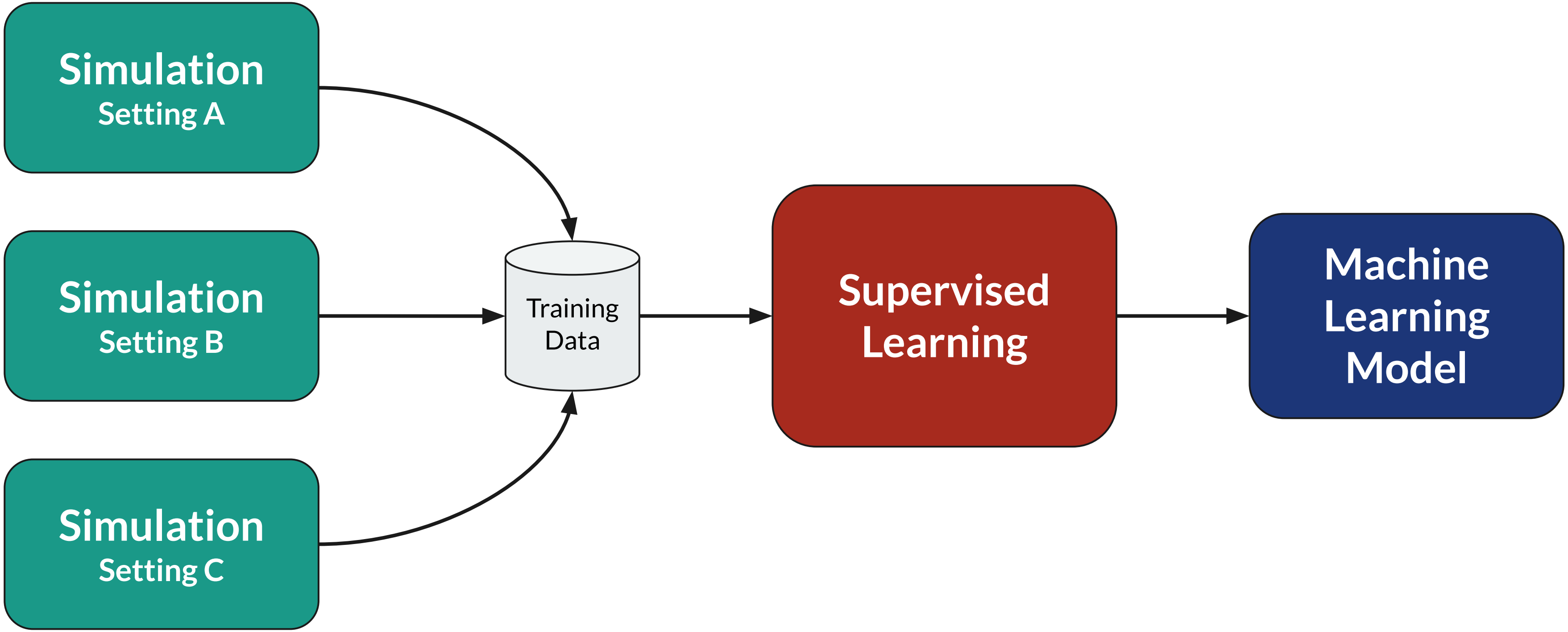
The Deep Learning Engine Unboxed



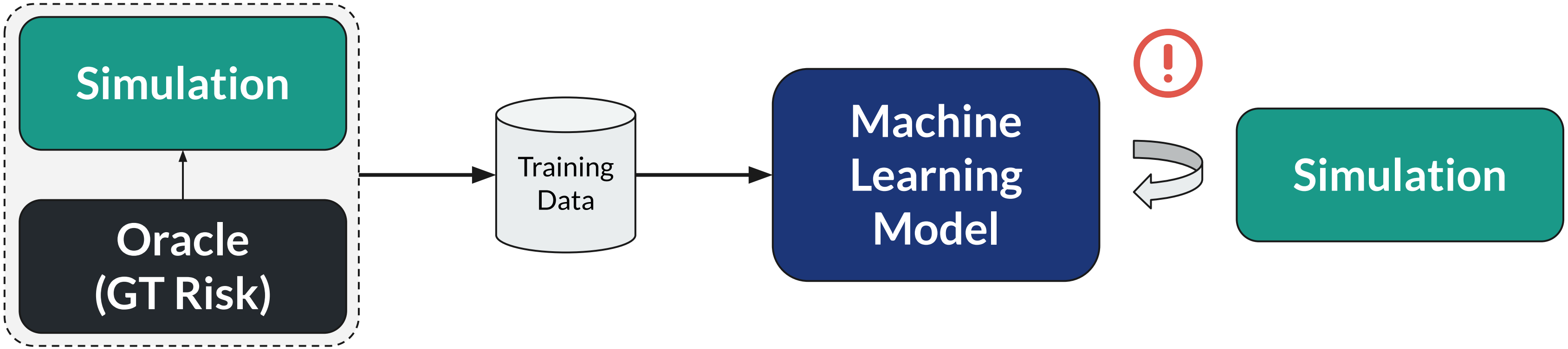
First Step: Learning from Simulations



Learning from *Domain Randomized* Data

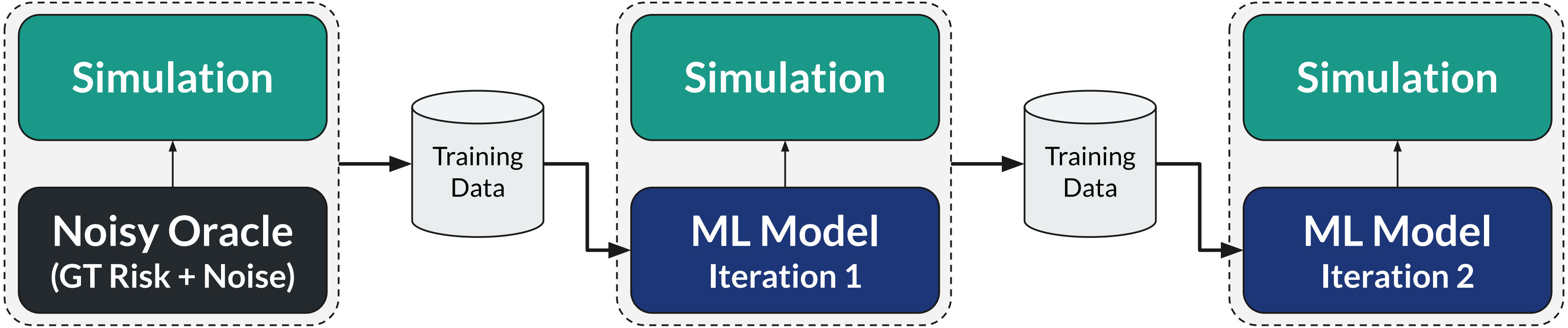


The Out-of-Distribution Problem



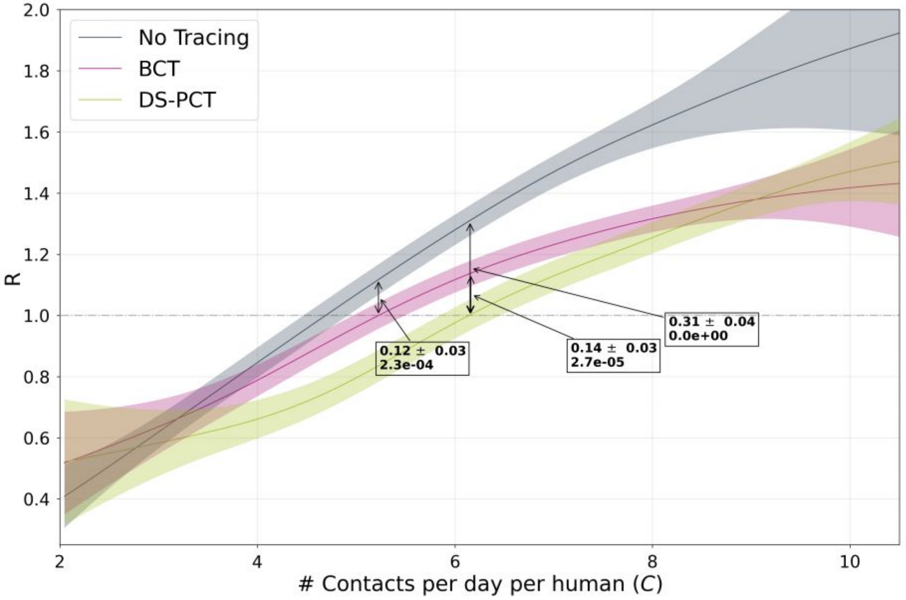
Icons made by Pixel Buddha from www.flaticon.com

Solution: Multiple iterations of training

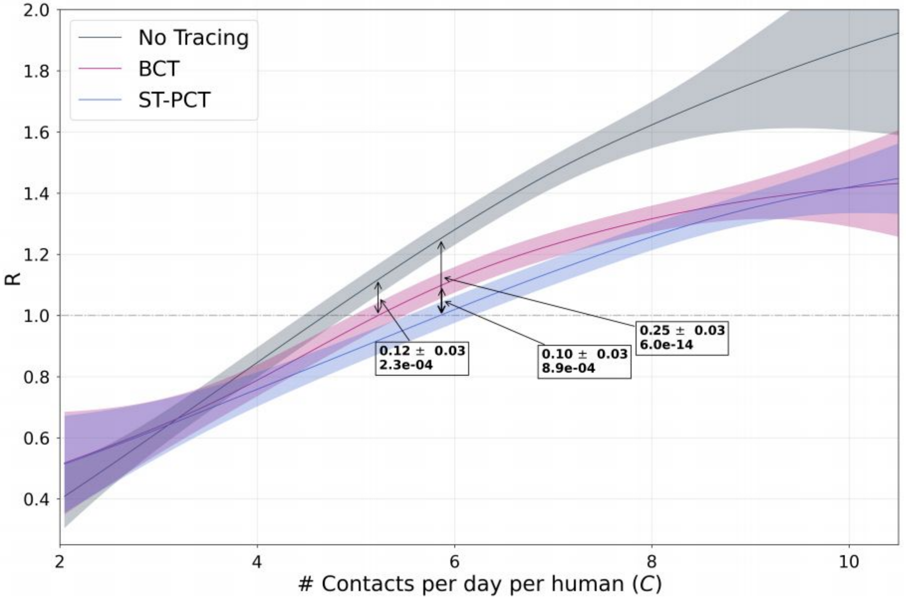


Pareto Frontier between Mobility and Spread of Disease

DeepSet (DS-PCT)



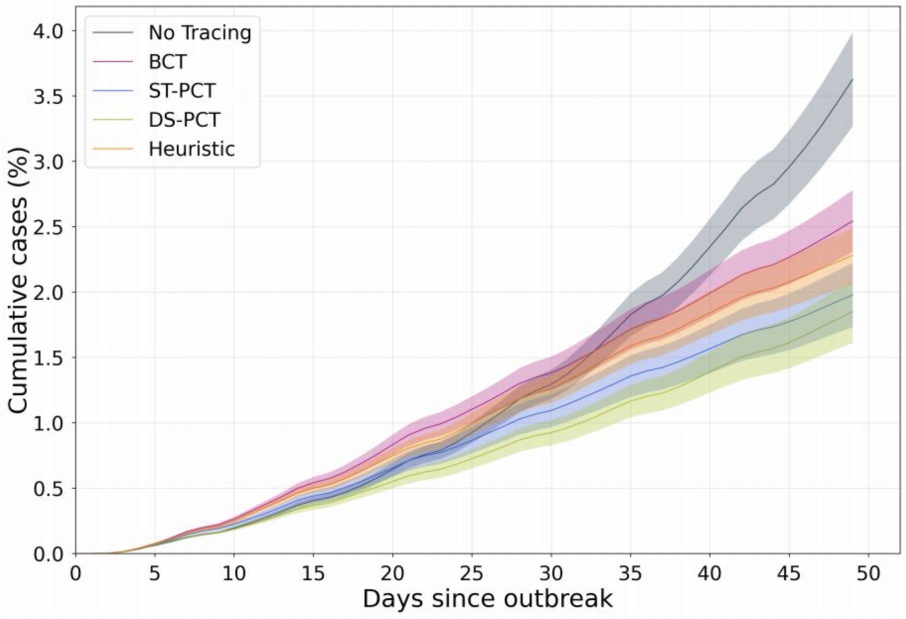
Set-Transformer (ST-PCT)



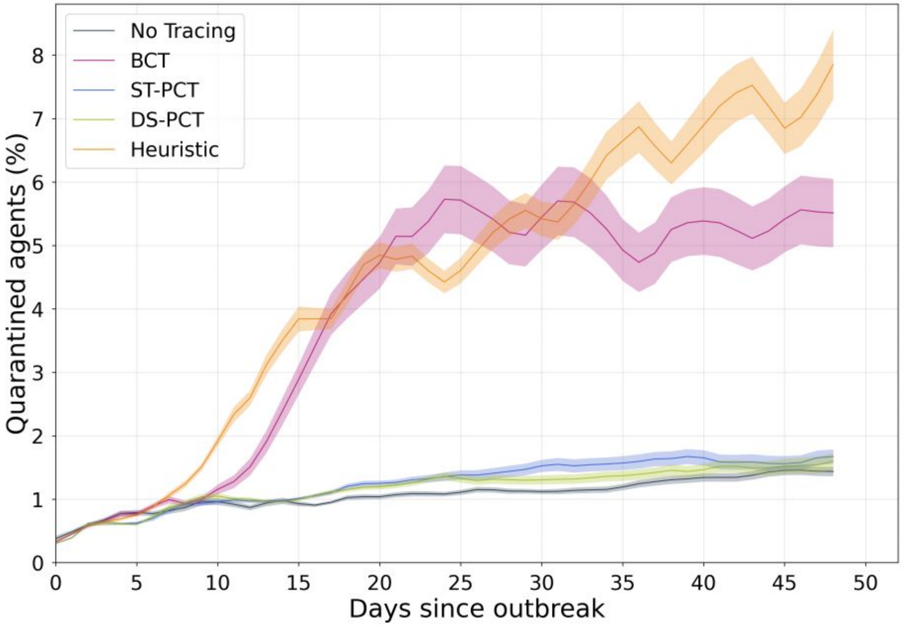
We find a better trade-off between mobility and spread of disease (R).

Case Curves and the Fraction of Quarantined Agents

Case Curves



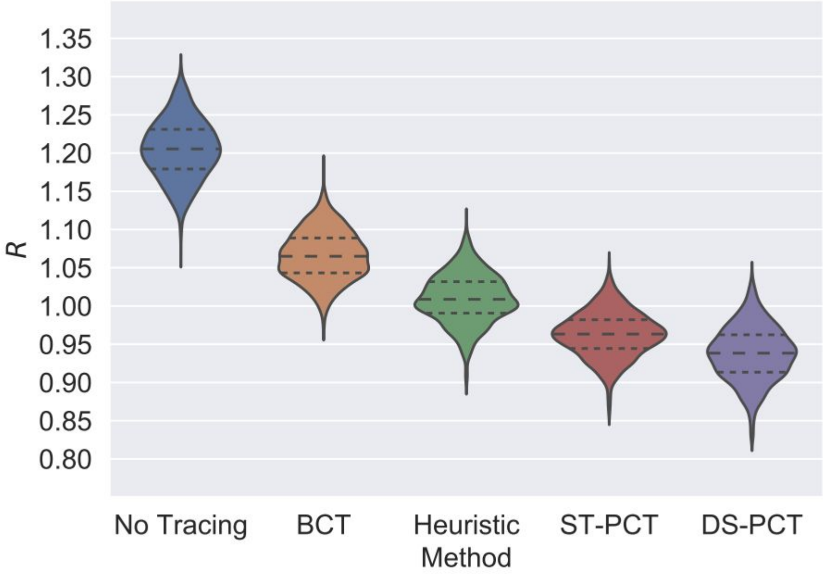
% Agents Recommended Quarantine



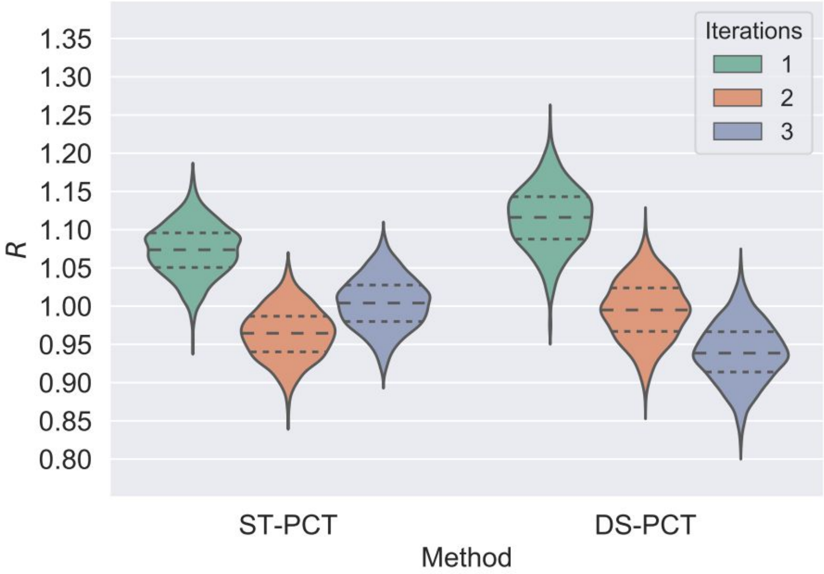
At R = 1.2 for no-tracing baseline, we recommend quarantine to the “right” agents.

Comparison with Baseline Methods

Performance w.r.t Baselines

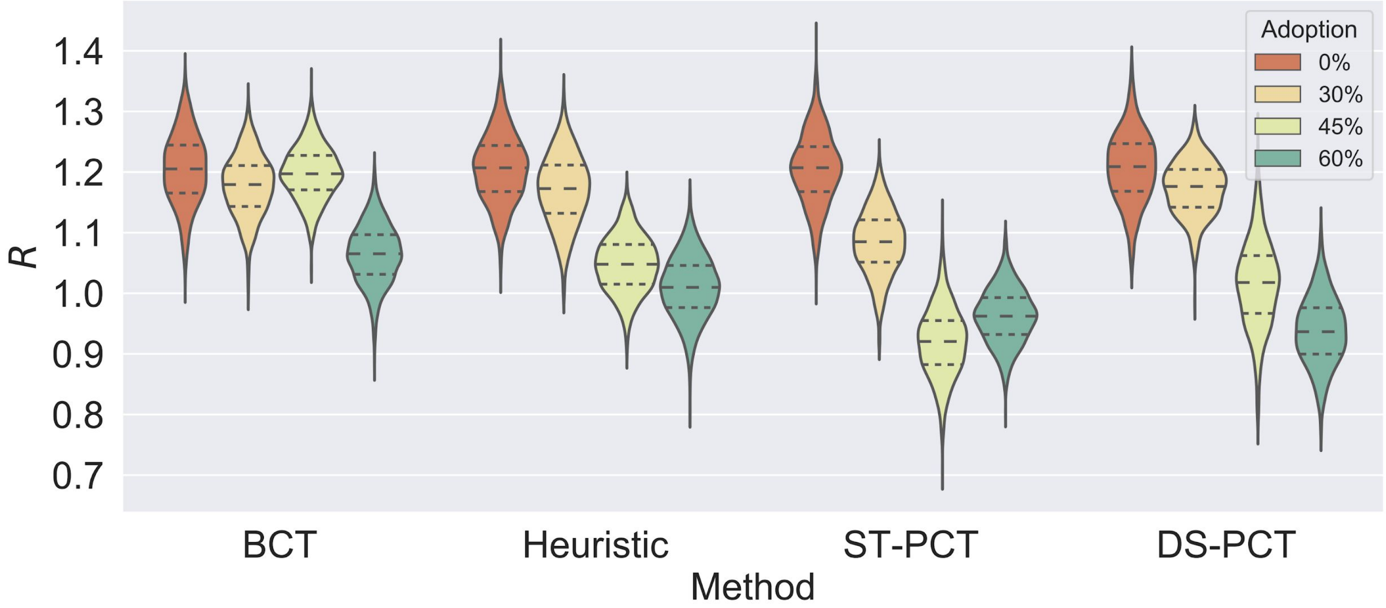


Effect of Iterative Re-training



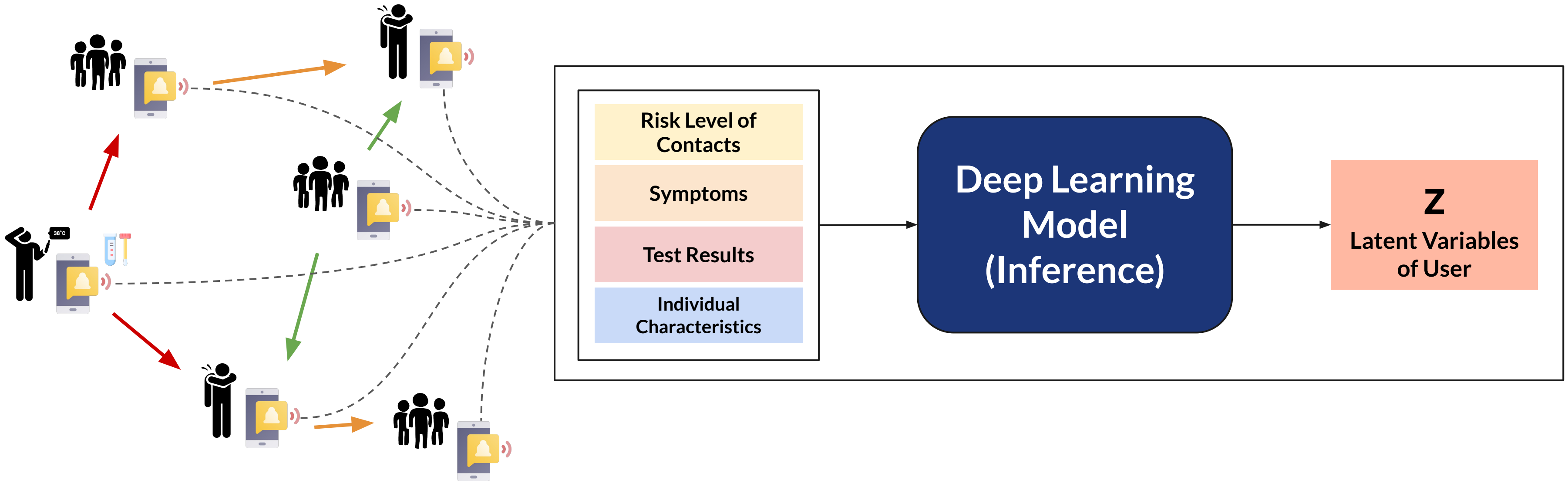
All methods work better than no-tracing, and DS-PCT works best in this setting.
Also, iterative retraining helps!

What happens when fewer people use the app?



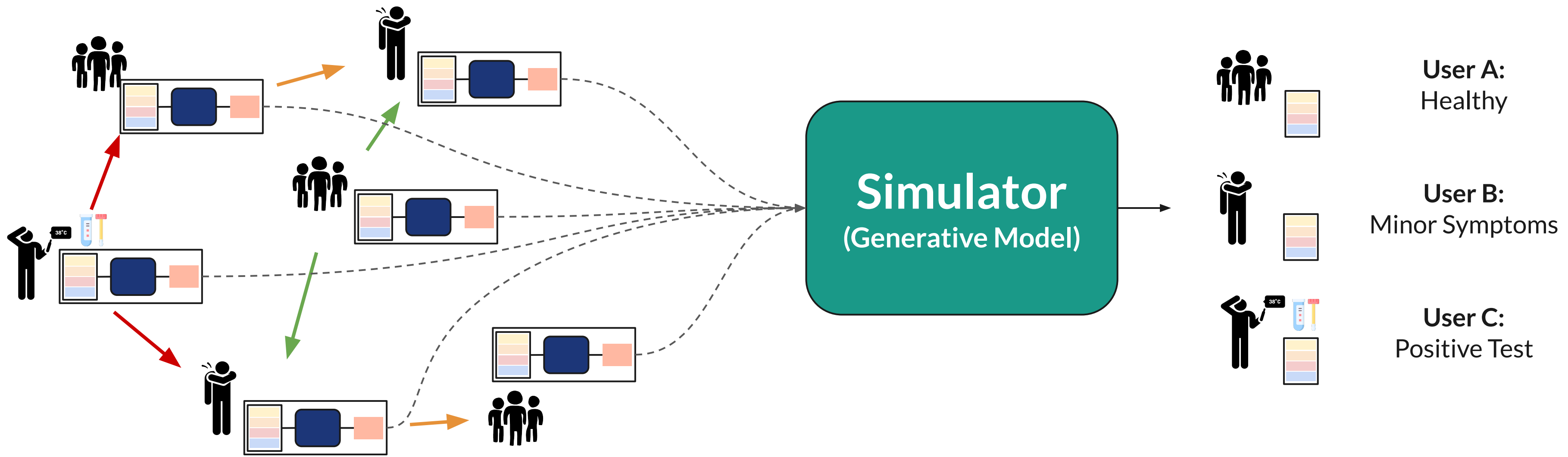
All methods work better than no-tracing, even at lower adoption rates.
ST-PCT works best at 30% and 45%, whereas DS-PCT works best at 60%.

Learning from Real World Data (Work in Progress!)



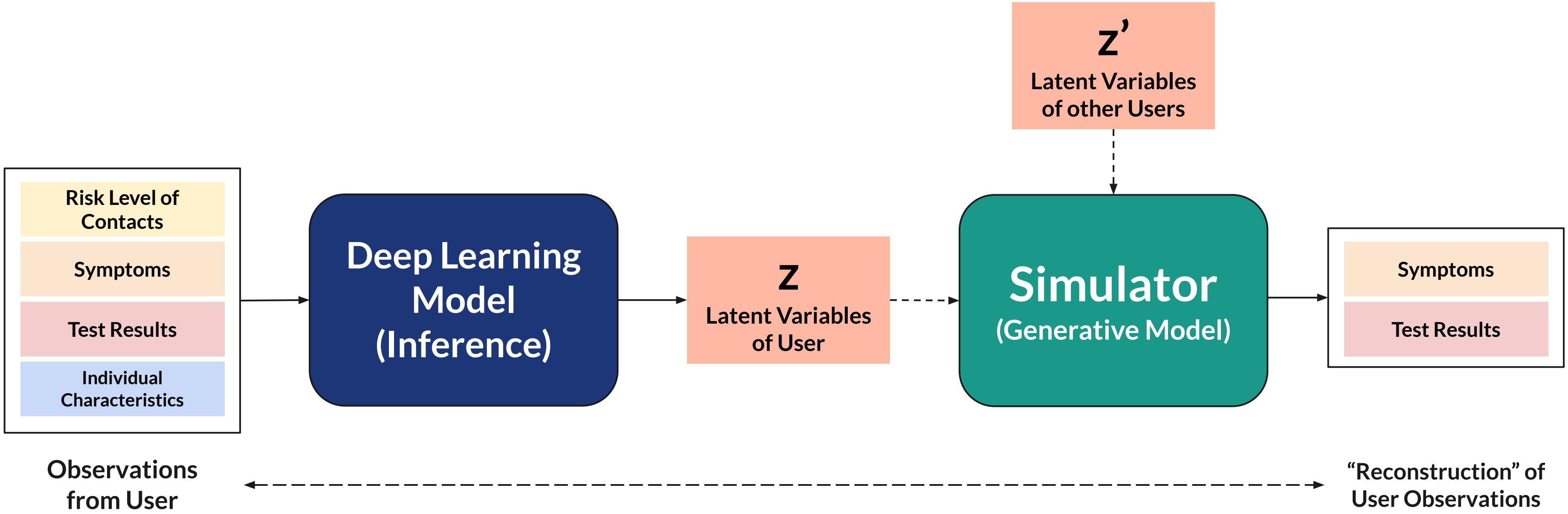
The “inference model” runs on every app-users’ phone.

Learning from Real World Data (Work in Progress!)



The “generative model” receives latent variables from every app user (who has consented), and predicts their respective states.

Learning from Real World Data (Work in Progress!)



The learning objective is to match these.

References

Ayres, Ian, Alessandro Romano, and Chiara Sotis. "How to Make COVID-19 Contact Tracing Apps work: Insights From Behavioral Economics." *Available at SSRN 3689805* (2020).

To, Kelvin Kai-Wang, et al. "Temporal profiles of viral load in posterior oropharyngeal saliva samples and serum antibody responses during infection by SARS-CoV-2: an observational cohort study." *The Lancet Infectious Diseases* (2020).

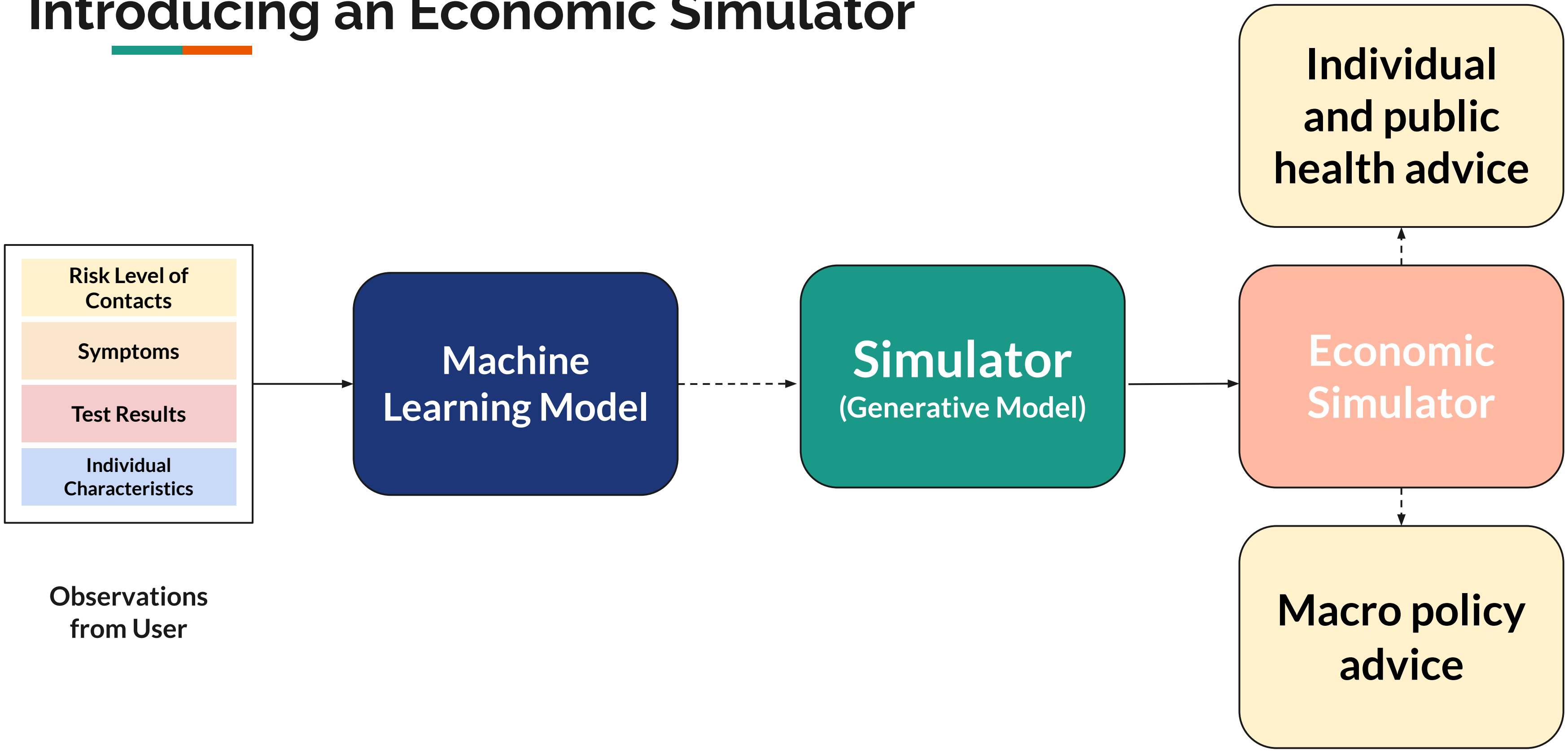
Brisson et al. “Épidémiologie et modélisation de l’évolution de la COVID-19 au Québec”. https://www.inspq.qc.ca/covid-19/donnees/projections/29-juin (2020)

Alsdurf, Hannah, et al. "COVI White Paper." *arXiv preprint arXiv:2005.08502* (2020).

Gupta et al. “COVIsim: an Agent-based Model for Evaluating Methods of Digital Contact Tracing”. OpenReview Preprint (2020)

The Health and Economic Impacts of Tracing

Introducing an Economic Simulator

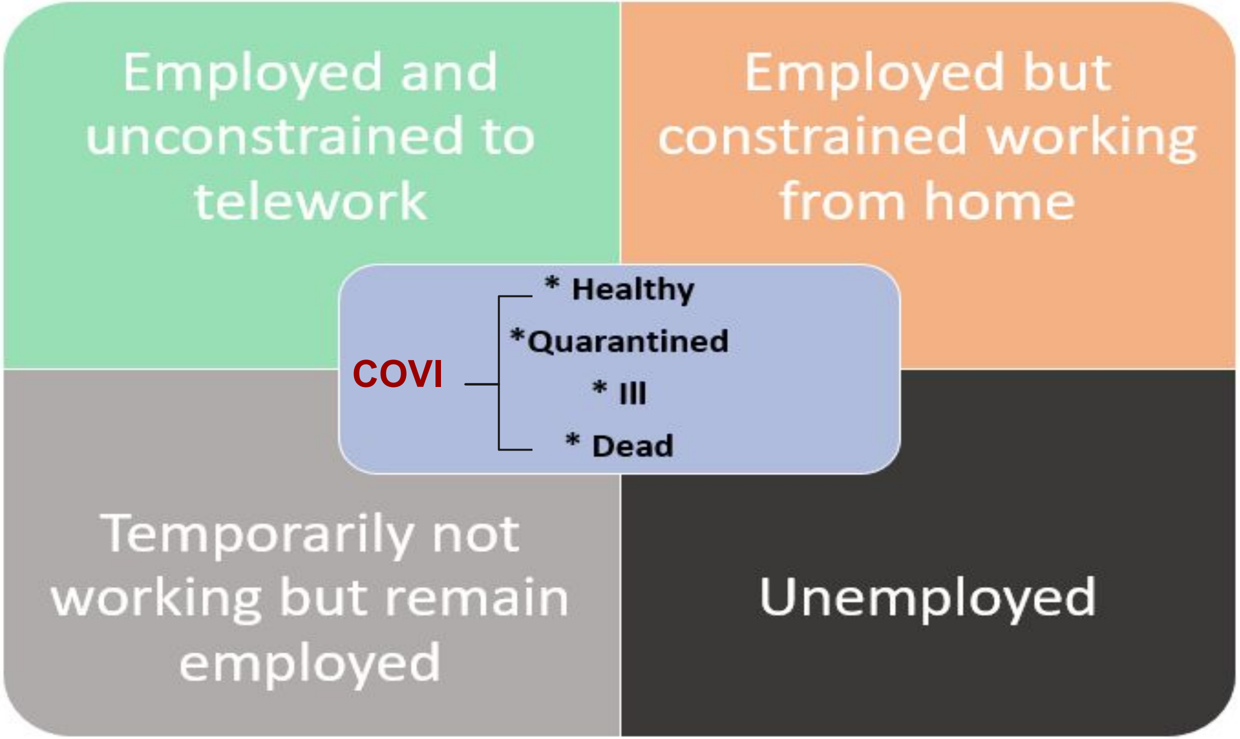


adaptER-COVID19: an application to national data

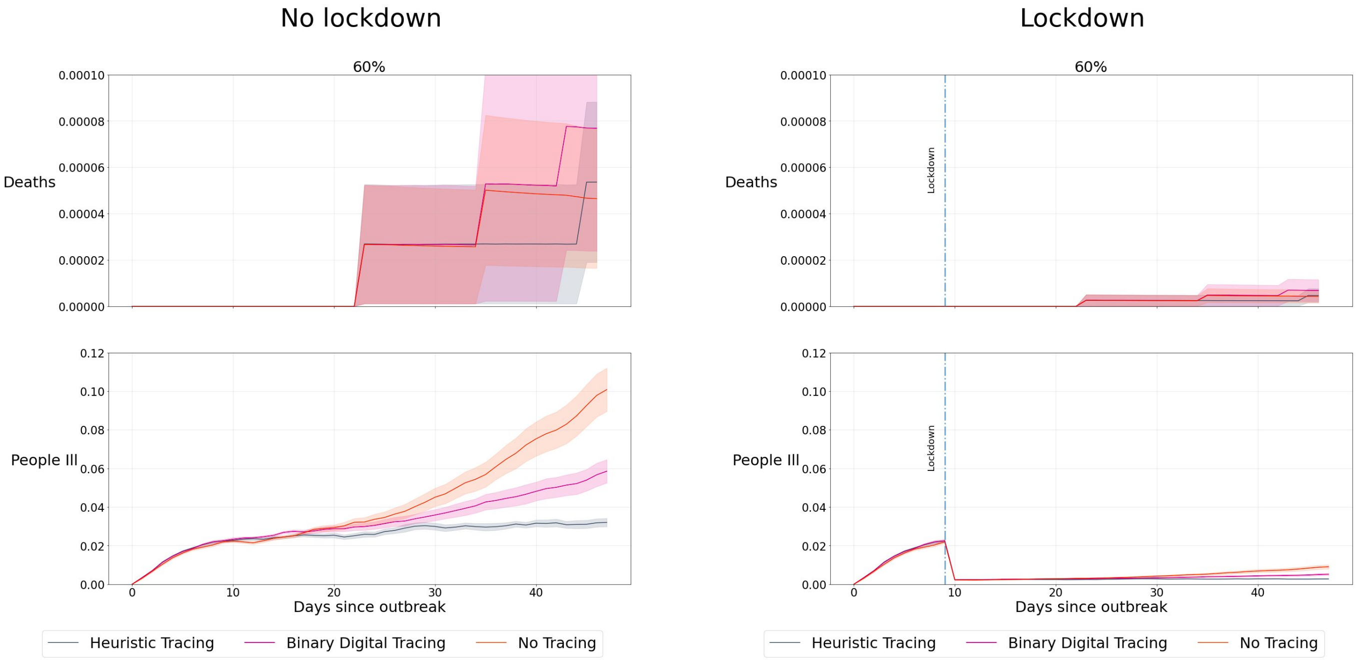
01	Input-output Model	• Labour, capital, imports as inputs for production • Consumption, investment and export sectors
02	Corporate Bankruptcy Model	• Agent-based corporate defaults • Connected to IO-Model through net operating surplus of companies
03	Individual Insolvency Model	• Model household earnings • Behavior (fear factor) determining risk of insolvency

Source: https://github.com/BDI-pathogens/OpenABM-Covid19
https://www.coronavirus-fraser-group.org/

Mapping COVI into a matrix of employment & health status

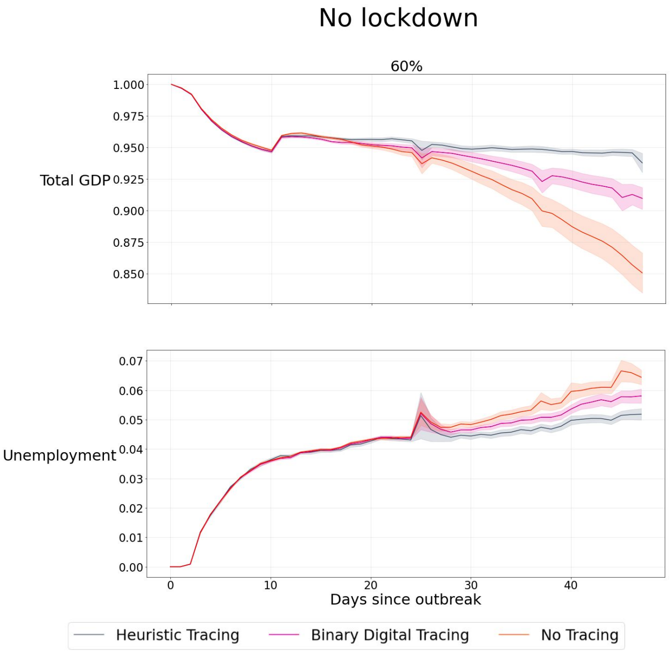


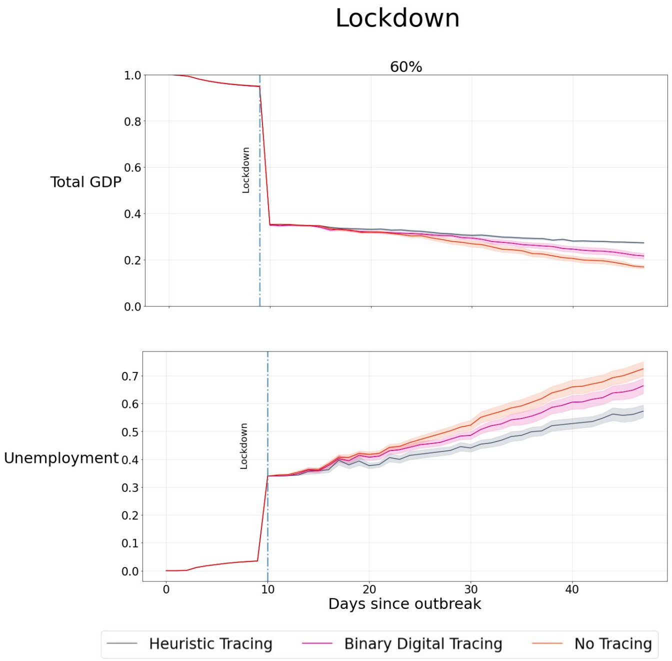
COVI improves health outcome (lower # of ill and deaths)…



Source: “The Daily - Study: Willingness of Canadians to use a contact tracing application”, Statistics Canada. July 31, 2020.
https://www150.statcan.gc.ca/n1/daily-quotidien/200731/dq200731d-eng.htm

… while incurring smaller economic cost (higher GDP & lower U rate)





Data source: Pathogen Dynamics group, University of Oxford, IBM UK. Data collection for Canada is underway.

Some limitations in adapterER - COVID19

- **I-O model uses accounting identity, no pricing optimization**
  - Switching to realistic production function considering input substitutability

- **Modelling labour and capital market may benefit from general equilibrium models**
  - Workers don’t have the ability to switch jobs
  - No part-time, self-employment

- **Don’t account for interest payments and leverage of firms**

ACTION: Expand the Health-Economic Frontier with Technology!

	No Tracing	Digital Binary Tracing	PRA (COVI)
Individual mobility (social wellbeing)	High, but at risk of forced lockdown	Low	Intermediate
Infection Transmission rate (R0)	High	Intermediate	Low
Economic impact (GDP, jobs)	Poor	Intermediate	Improved

Icons made by Freepik, fjstudio, Pixel Perfect , photo3idea_studio, Gregor Cresnar, Vitaly Gorbachev from www.flaticon.com

Appendix

Future Work & Limitations & Challenges

- Scalability of simulations
- Sensitivity Analysis on privacy parameters / economical scenarios / (WIP)
- Pilot cohort study
- Deployment in developing countries
- Evaluation of risk of getting infected
- Running AdaptER-Covid19 on Canadian Datasets with support mechanisms

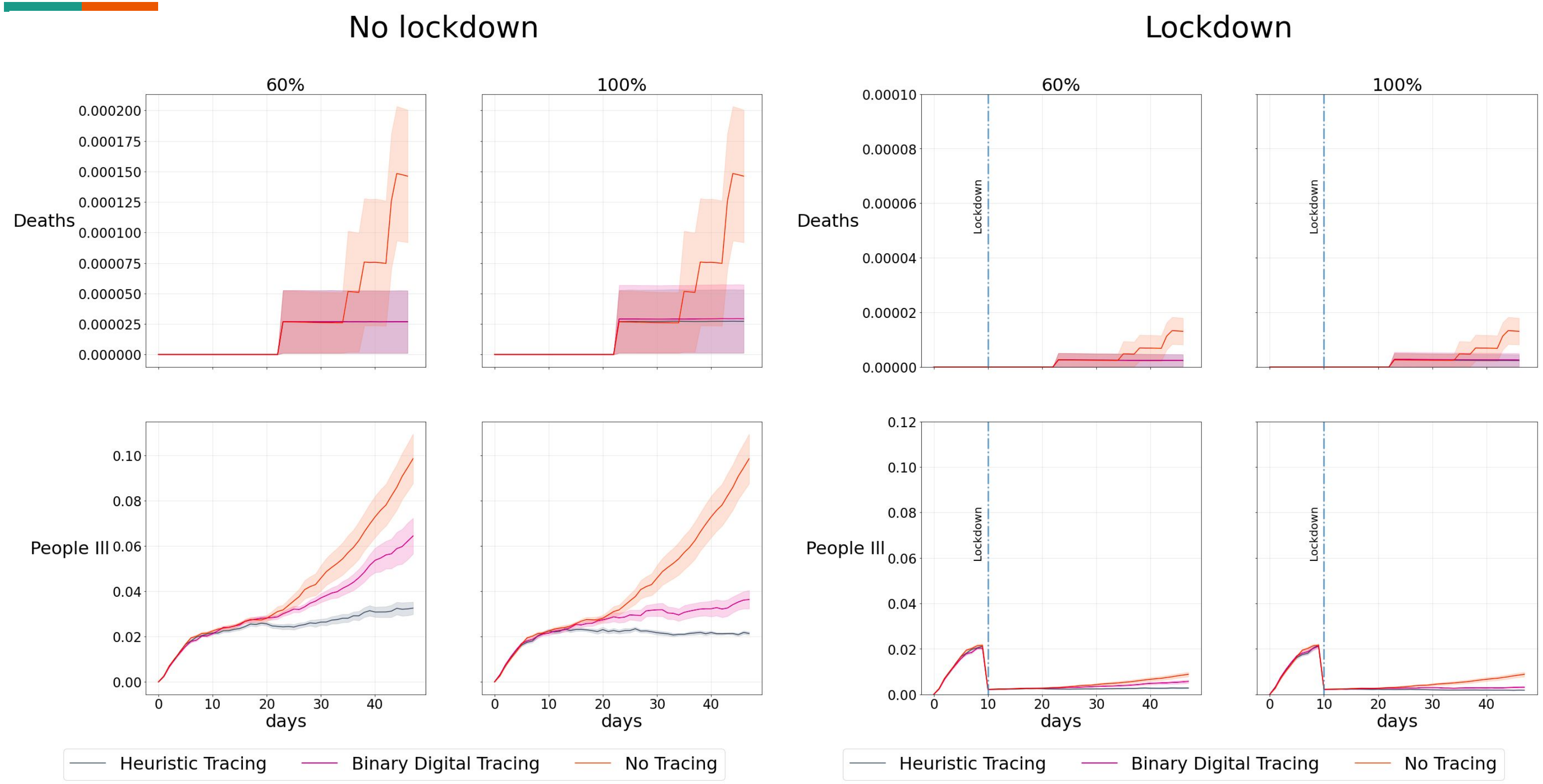
Ethical considerations

- Ensured privacy based on decentralized approach to data
- Cryptographic technology for risk information notification
- Pseudonymized nature of optional volunteered data
- Governance and inclusivity

Preliminary Simulations

- Population size: 3000
- Initial number of infected individuals: 6 (0.2% of the population)
- 25% Asymptomatic population
- Number of tests per day = 3 (0.1% of the population)
- Behavior Modifications -
  - Low Risk Agents have 1/8th of the contacts as compared to pre COVID-19 contacts
  - Medium Risk Agents have 1/4th of the contacts as compared to pre-COVID-19 contacts
  - High Risk Agents have 0 contacts (Quarantine)
- Adherence to recommendations is modeled via dropout of 0.02 probability of following the recommendations
- Quality of self-diagnosis is modeled via dropout on symptoms of 0.2 i.e a user is 20% likely to not report their specific symptoms

100% adoption rate comparison



100% adoption rate comparison