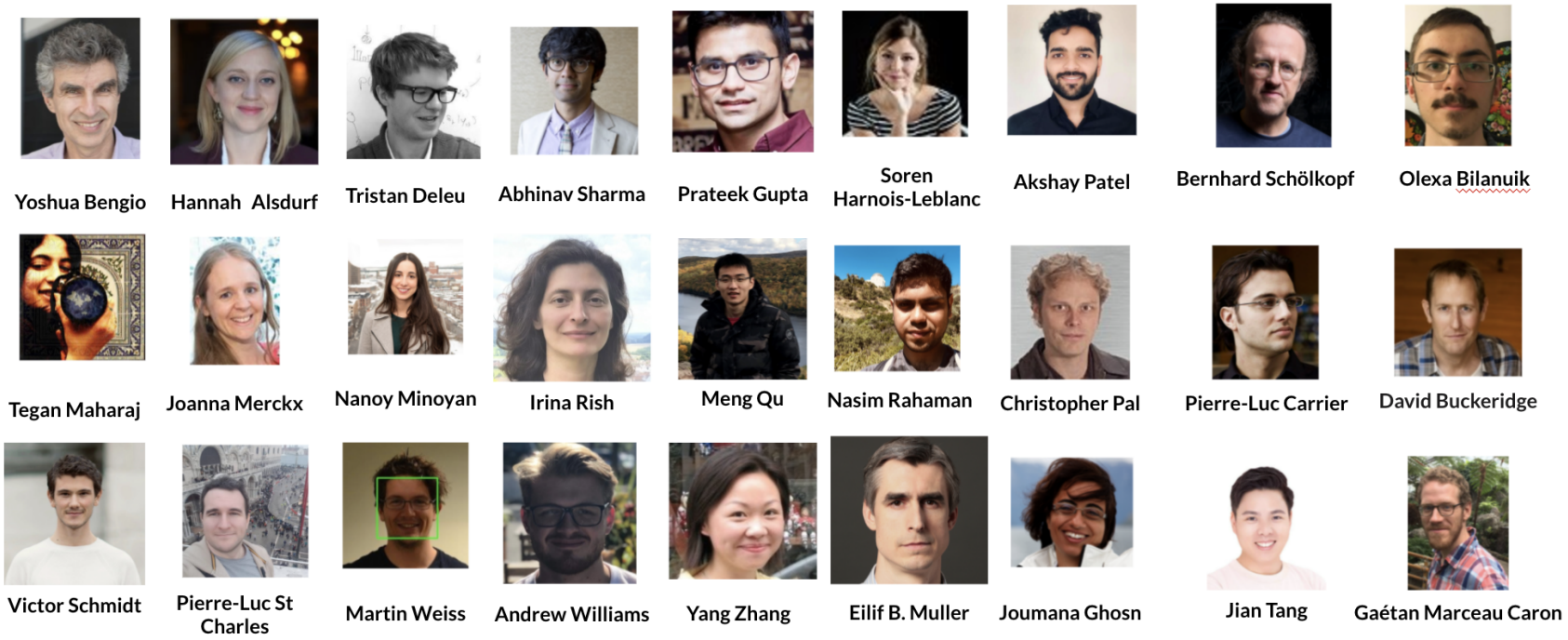
Proactive Contact Tracing

Prateek Gupta

10th Doctoral Researcher Award
Sept. 11th 2021

Epi/ML/Econ/Privacy Team Members



To

To **improve digital contact tracing apps** via

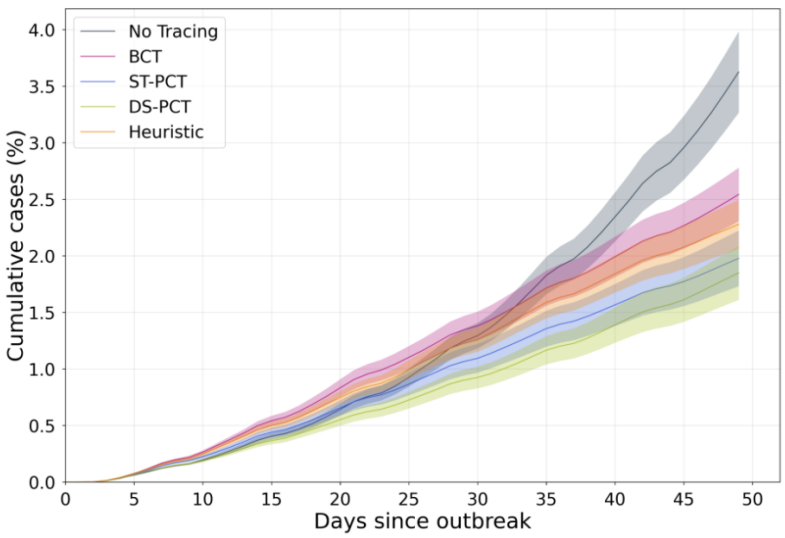
To **improve digital contact tracing apps** via **risk assessment mechanism** yielding

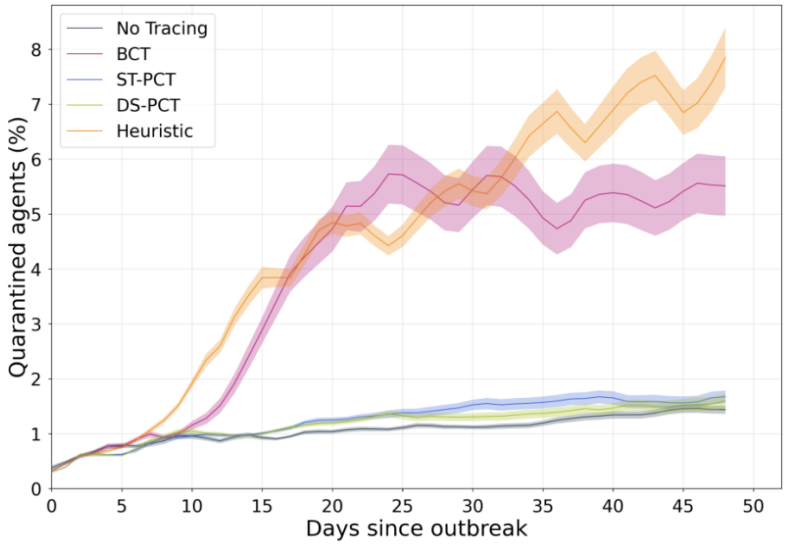
To **improve digital contact tracing apps** via **risk assessment mechanism** yielding **reduction in viral spread** and

To **improve digital contact tracing apps** via **risk assessment mechanism** yielding **reduction in viral spread** and **reduced false positives** while

To **improve digital contact tracing apps** via **risk assessment mechanism** yielding **reduction in viral spread** and **reduced false positives** while preserving the **user privacy**

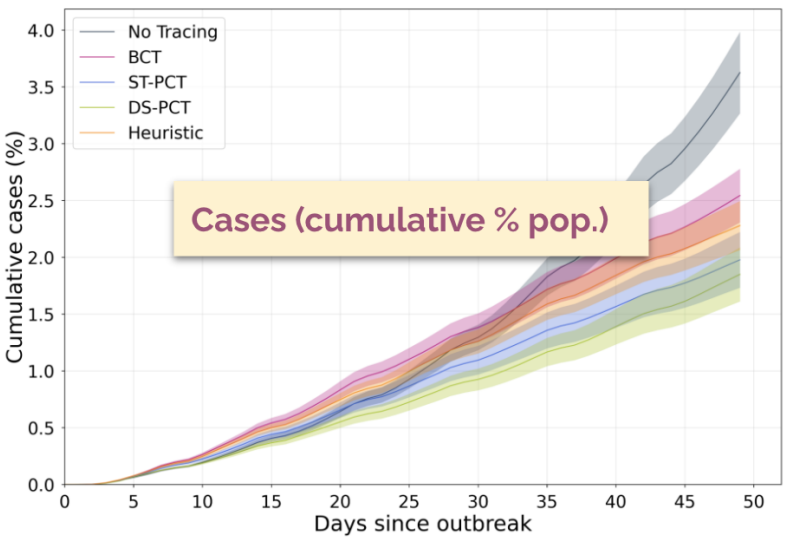
To **improve digital contact tracing apps** via **risk assessment mechanism** yielding **reduction in viral spread** and **reduced false positives** while preserving the **user privacy**

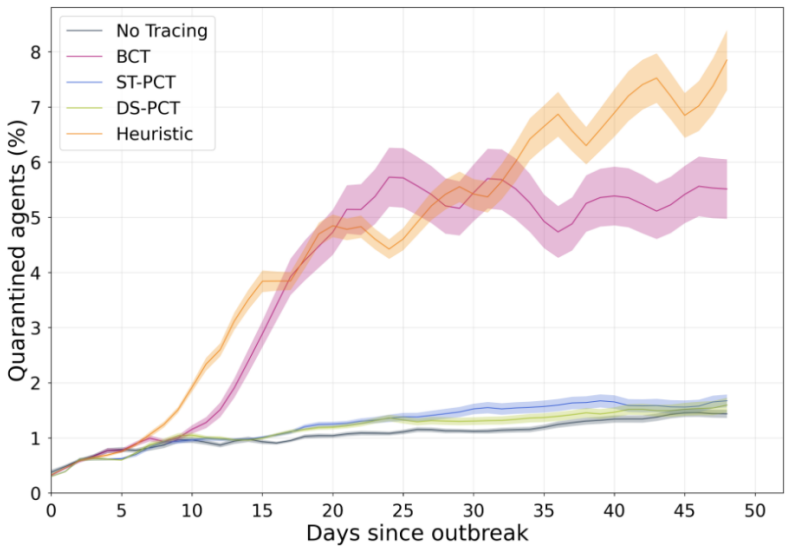




Simulated results on 3000 agents

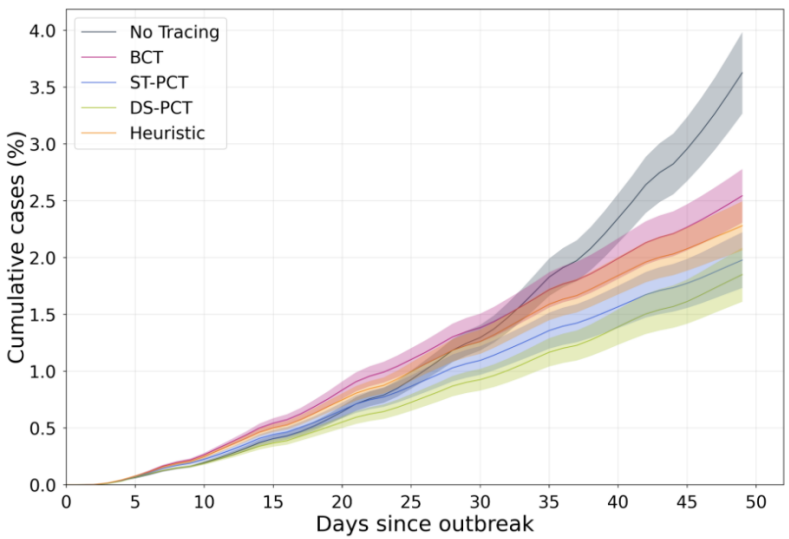
To **improve digital contact tracing apps** via **risk assessment mechanism** yielding **reduction in viral spread** and **reduced false positives** while preserving the **user privacy**

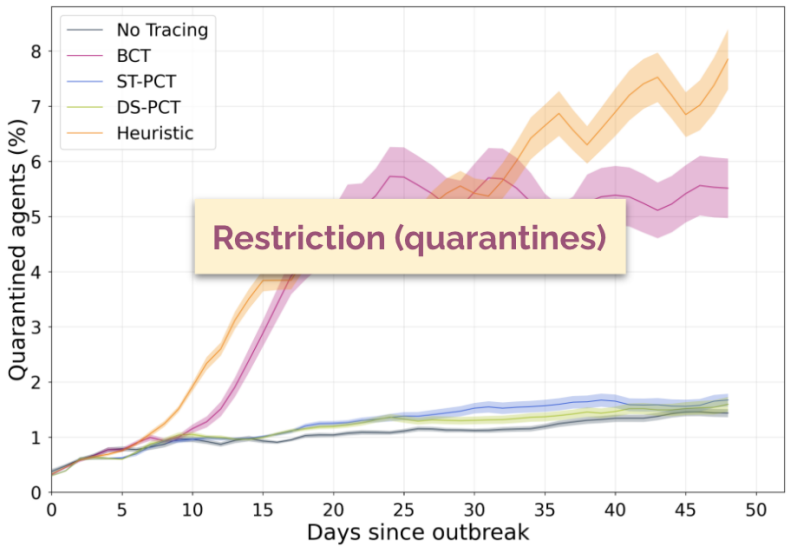




Simulated results on 3000 agents

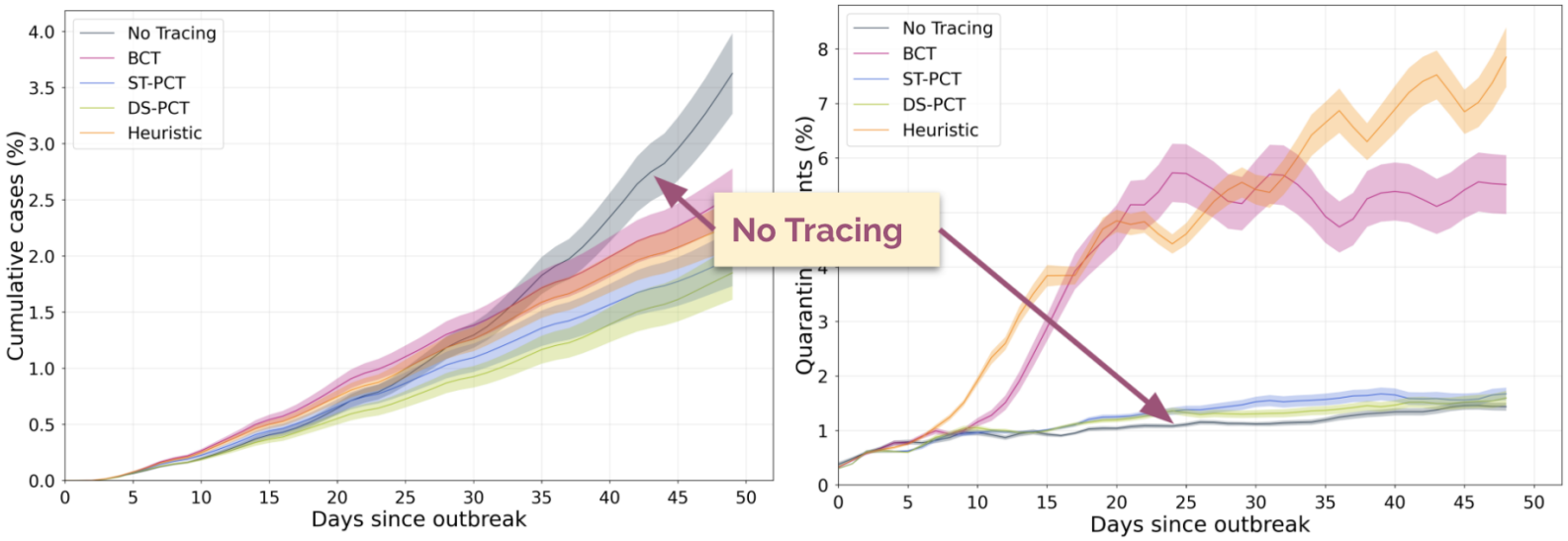
To **improve digital contact tracing apps** via **risk assessment mechanism** yielding **reduction in viral spread** and **reduced false positives** while preserving the **user privacy**





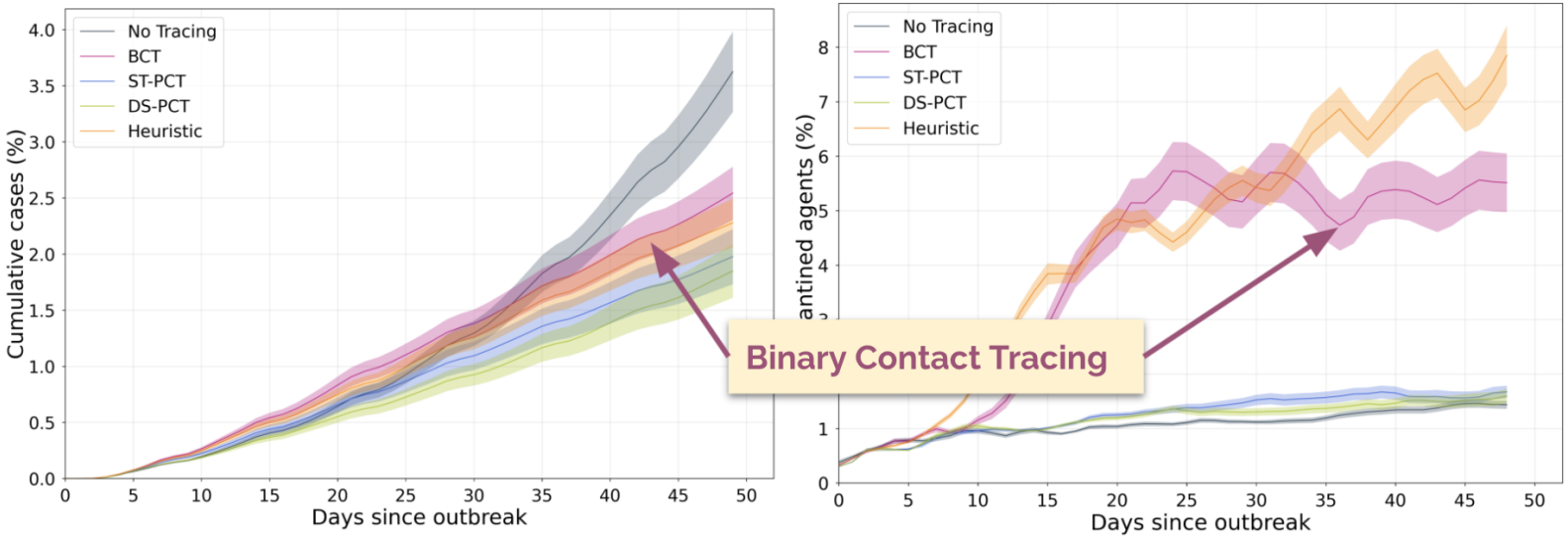
Simulated results on 3000 agents

To **improve digital contact tracing apps** via **risk assessment mechanism** yielding **reduction in viral spread** and **reduced false positives** while preserving the **user privacy**



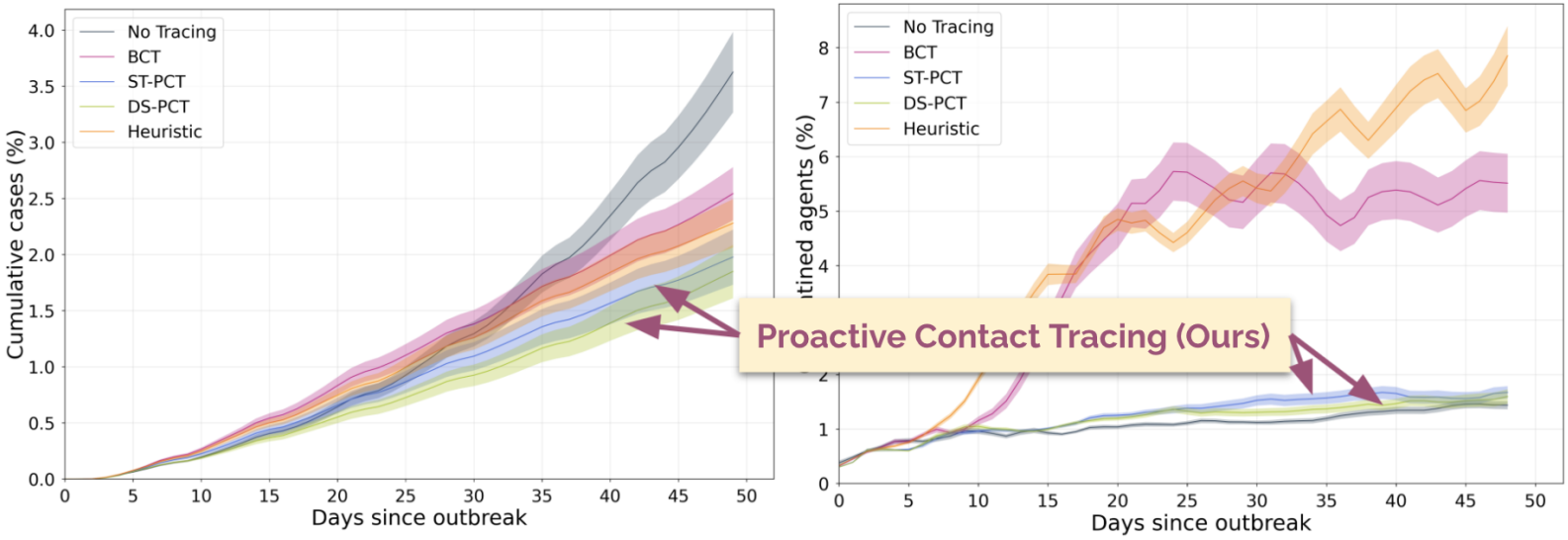
Simulated results on 3000 agents

To **improve digital contact tracing apps** via **risk assessment mechanism** yielding **reduction in viral spread** and **reduced false positives** while preserving the **user privacy**



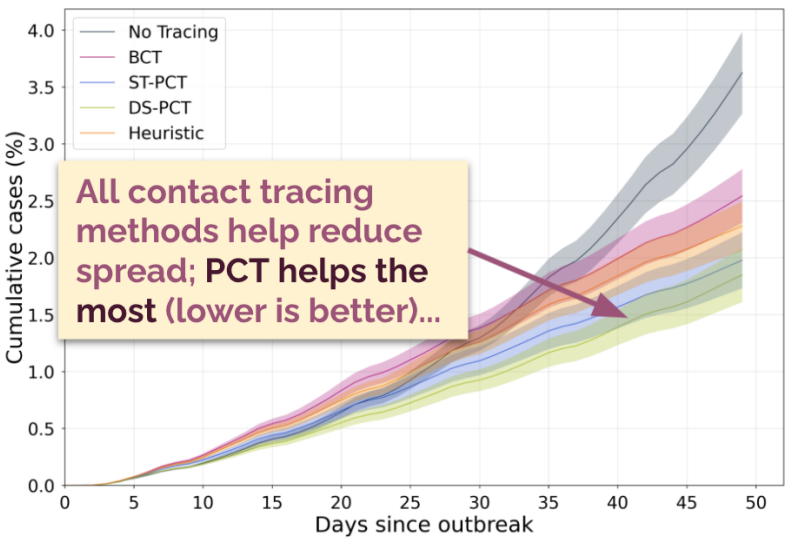
Simulated results on 3000 agents

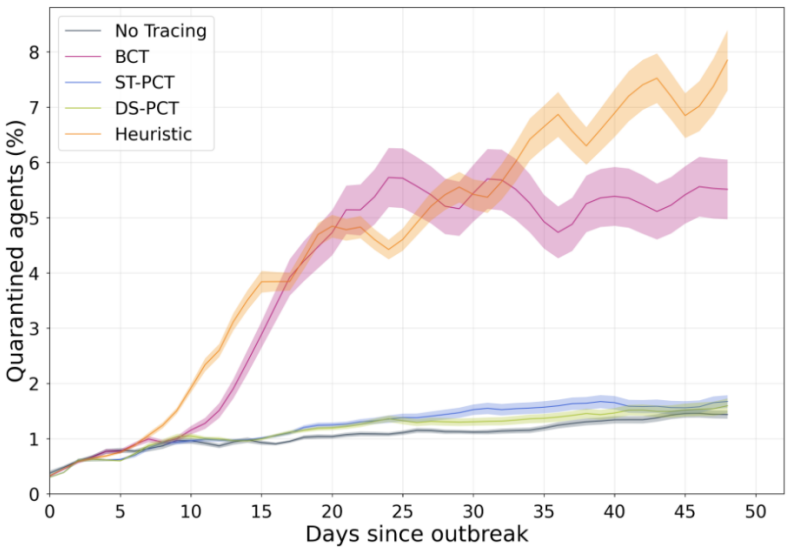
To **improve digital contact tracing apps** via **risk assessment mechanism** yielding **reduction in viral spread** and **reduced false positives** while preserving the **user privacy**



Simulated results on 3000 agents

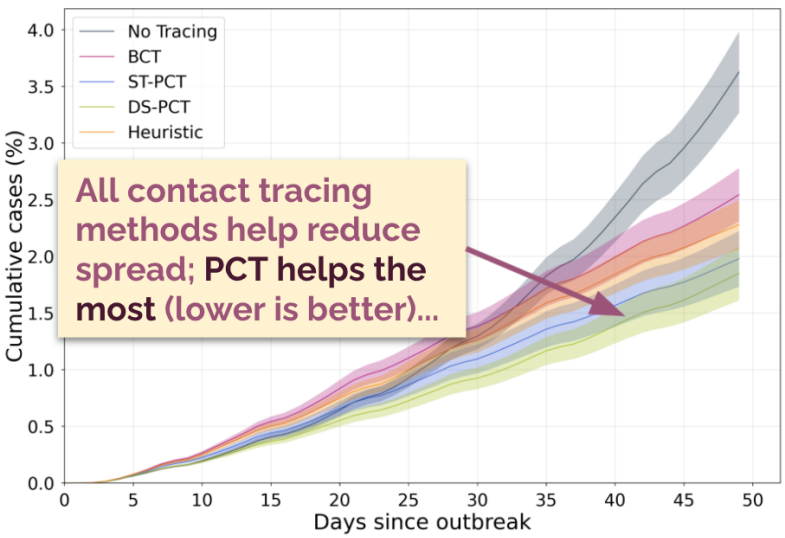
To **improve digital contact tracing apps** via **risk assessment mechanism** yielding **reduction in viral spread** and **reduced false positives** while preserving the **user privacy**

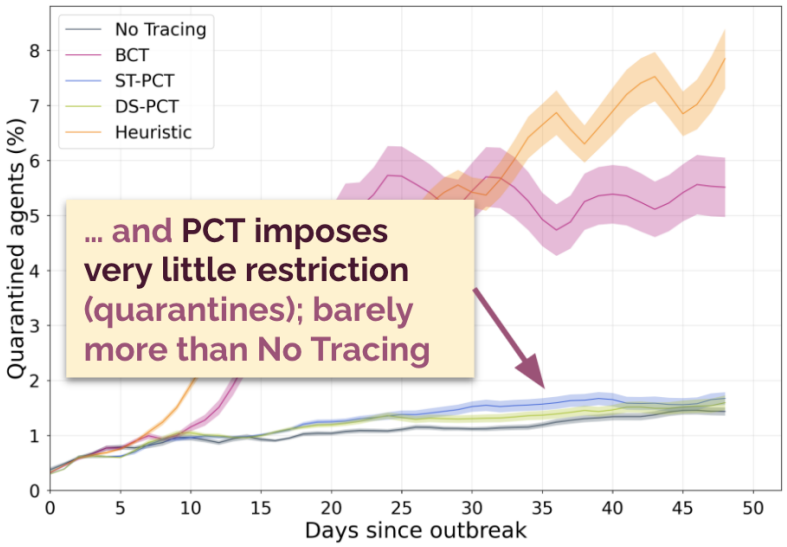




Simulated results on 3000 agents

To **improve digital contact tracing apps** via **risk assessment mechanism** yielding **reduction in viral spread** and **reduced false positives** while preserving the **user privacy**





Simulated results on 3000 agents

Outline

Problem formulation

Our approach: Proactive Contact Tracing (PCT)

Deep Learning for PCT

Conclusion

Outline

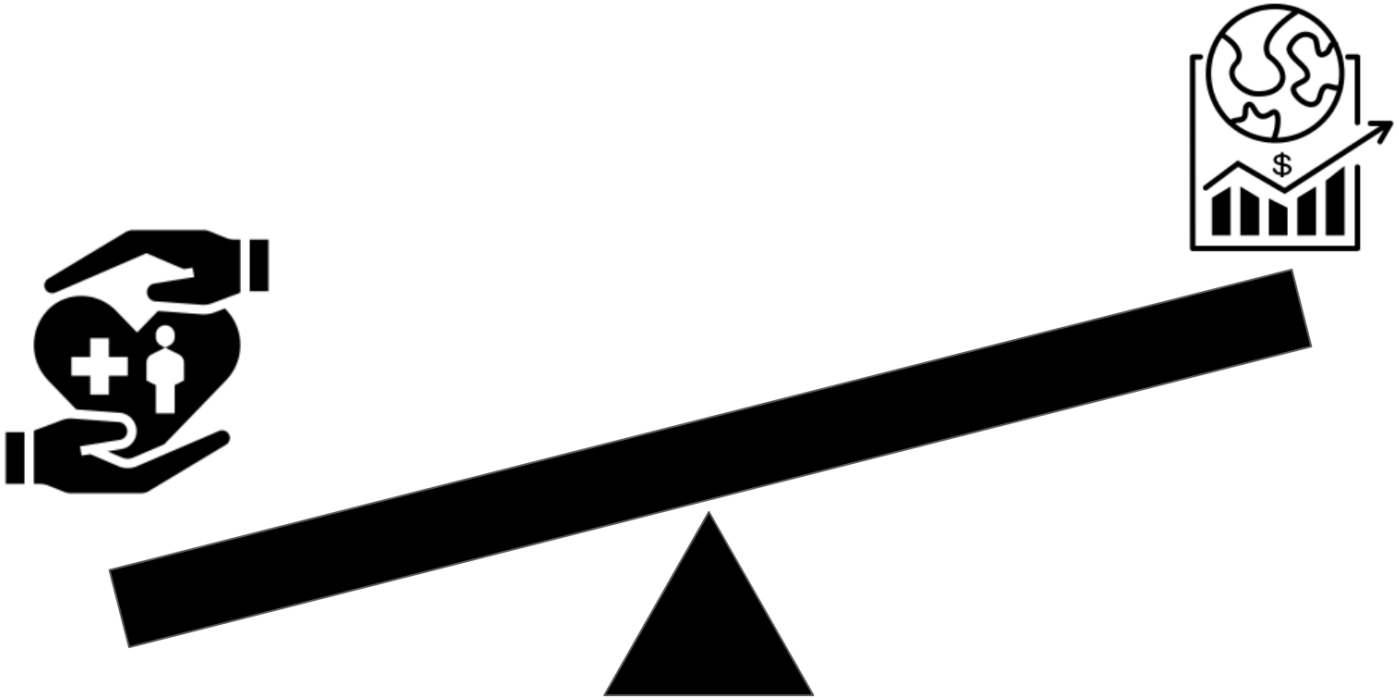
Problem formulation

Our approach: Proactive Contact Tracing (PCT)

Deep Learning for PCT

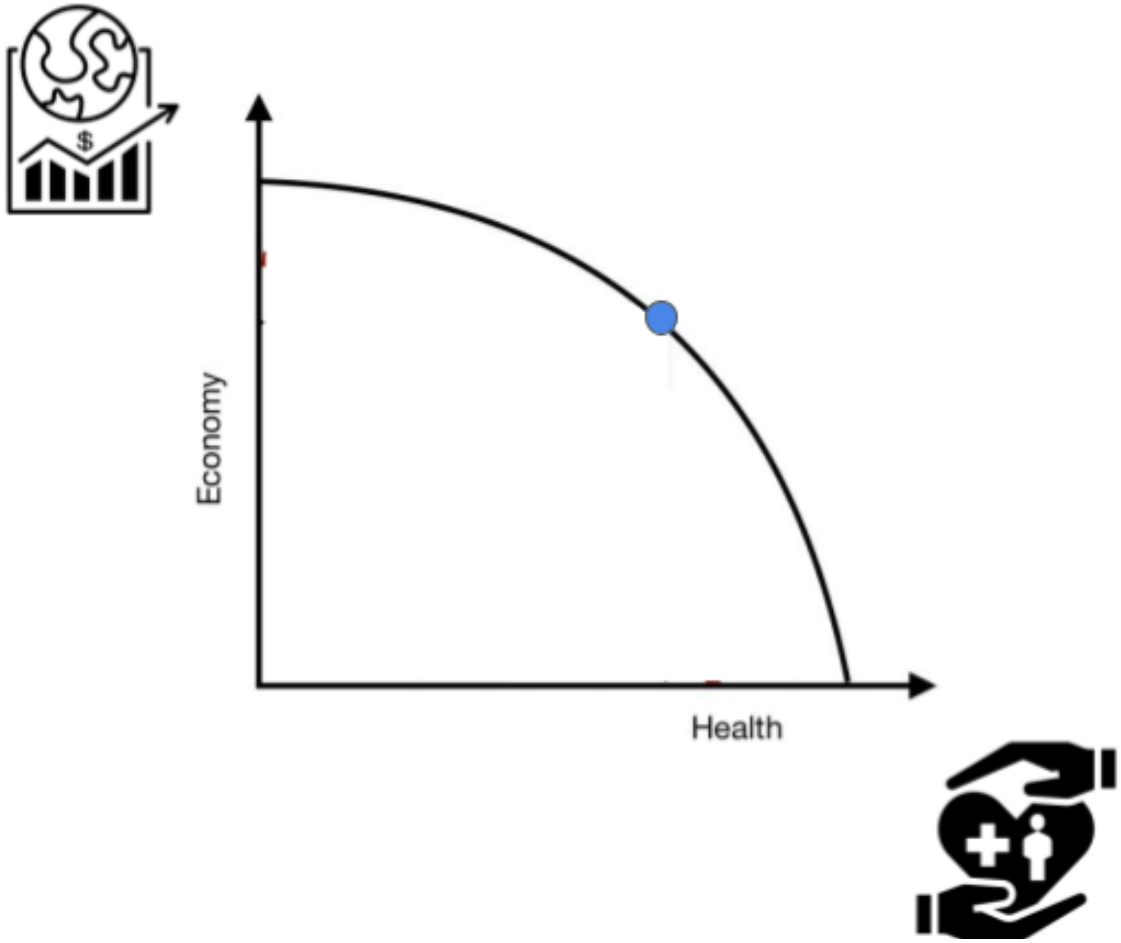
Conclusion

Health vs. Economy



Source: Gans(March 25, 2020), "Health Before Wealth: the Economic Logic"

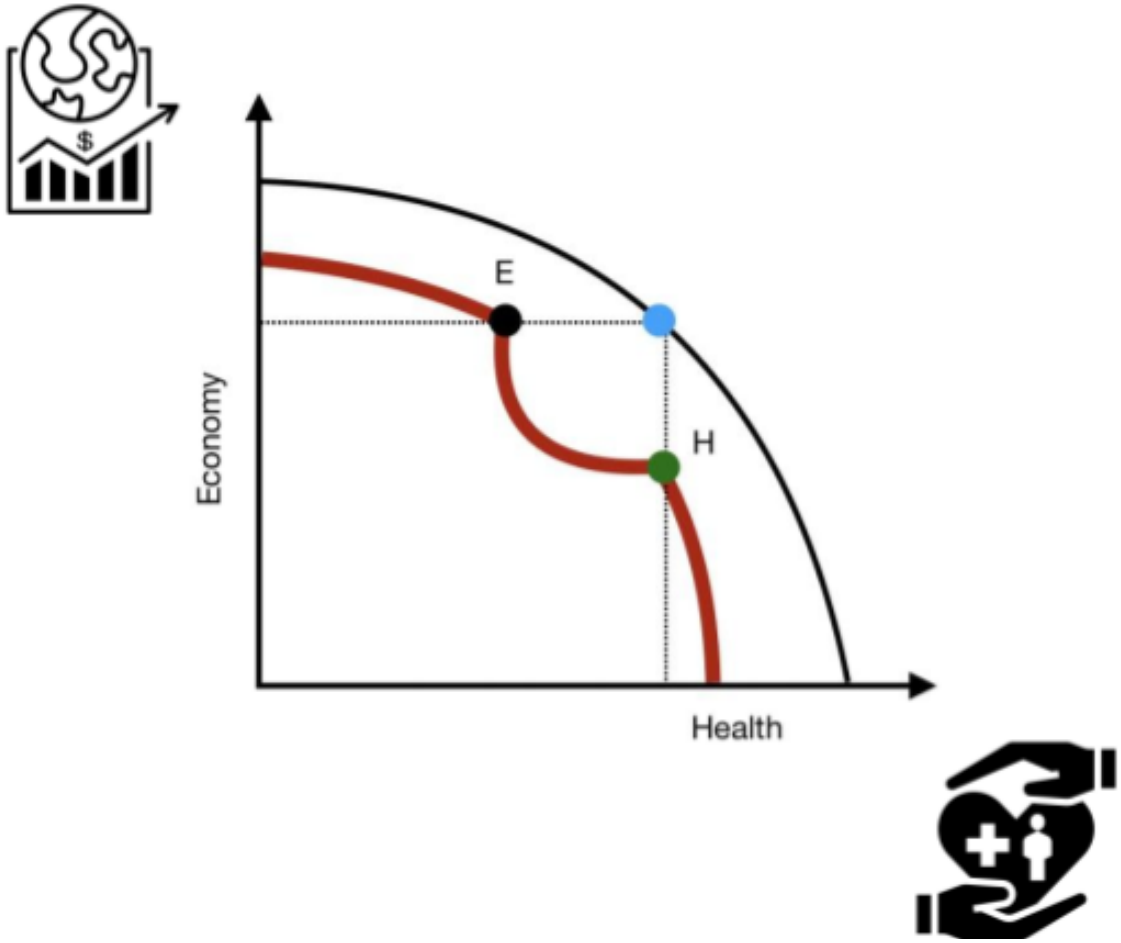
Health vs. Economy



Trade-off during the normal (pre-pandemic) times

Source: Gans(March 25, 2020), "Health Before Wealth: the Economic Logic"

Health vs. Economy



Trade-off during the pandemic times

Source: Gans(March 25, 2020), "Health Before Wealth: the Economic Logic"

Health vs. Economy

Trade-off during recovery using various public health interventions like contact tracing, social distancing measures, etc.

Source: Gans(March 25, 2020), "Health Before Wealth: the Economic Logic"

Contact Tracing

- **Manual Contact Tracing**: Uses public health experts (PHE) to **phone/email** contacts
  - Classic epidemic management
  - Overwhelmed by scale of pandemic

Contact Tracing

- **Manual Contact Tracing**: Uses public health experts (PHE) to **phone/email** contacts
  - Classic epidemic management
  - Overwhelmed by scale of pandemic
- **Digital Contact Tracing**: Uses Bluetooth enabled **smartphone apps** to notify contacts

Contact Tracing

- **Manual Contact Tracing**: Uses public health experts (PHE) to **phone/email** contacts
  - Classic epidemic management
  - Overwhelmed by scale of pandemic
- **Digital Contact Tracing**: Uses Bluetooth enabled **smartphone apps** to notify contacts
  - **Binary Contact Tracing**:
    - Uses positive/negative test results
    - Recommends Quarantine/No-Quarantine to the users

Contact Tracing

- **Manual Contact Tracing**: Uses public health experts (PHE) to **phone/email** contacts
  - Classic epidemic management
  - Overwhelmed by scale of pandemic
- **Digital Contact Tracing**: Uses Bluetooth enabled **smartphone apps** to notify contacts
  - **Binary Contact Tracing**:
    - Uses positive/negative test results
    - Recommends Quarantine/No-Quarantine to the users
  - **Proactive Contact Tracing**:
    - Uses individual-features, test results, symptoms, "risk-messages"
    - Recommends Quarantine/reduced contacts/regular contacts

Outline

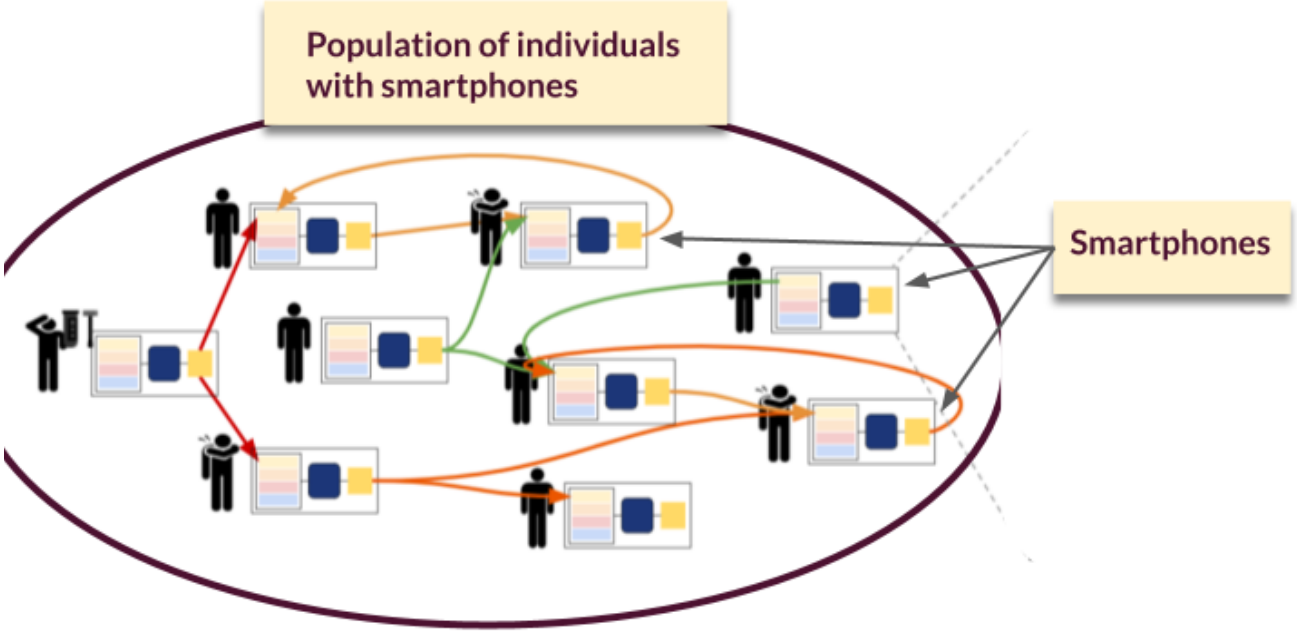
Problem formulation

Our approach: Proactive Contact Tracing (PCT)
- Framework
- Privacy Constraints

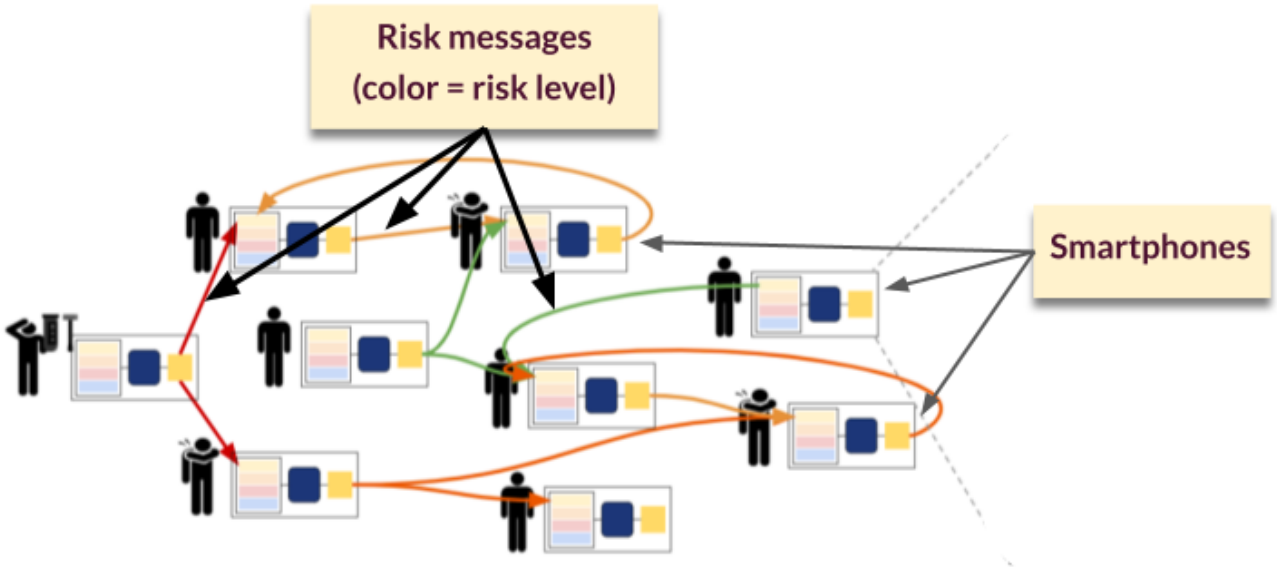
Deep Learning for PCT

Conclusion

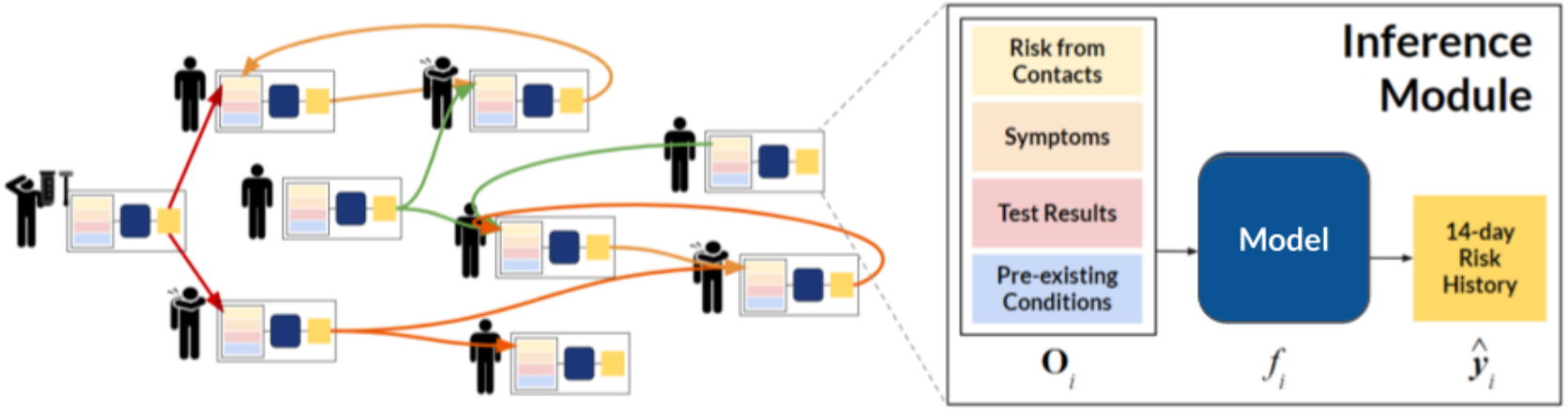
PCT Framework



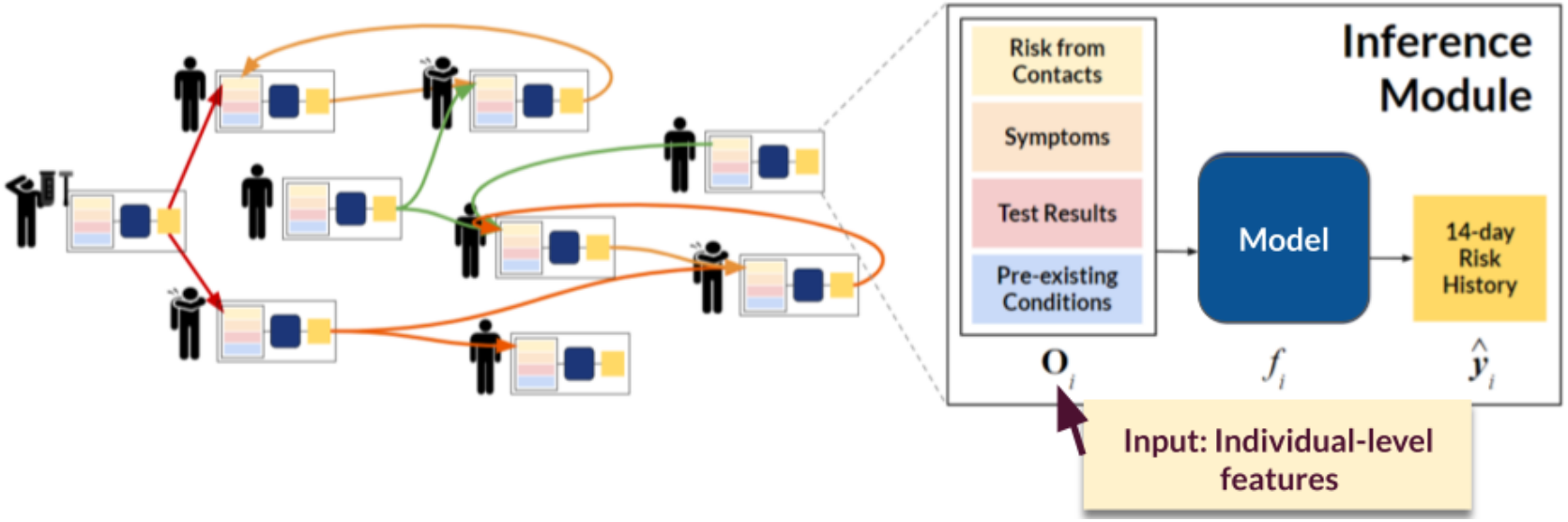
PCT Framework



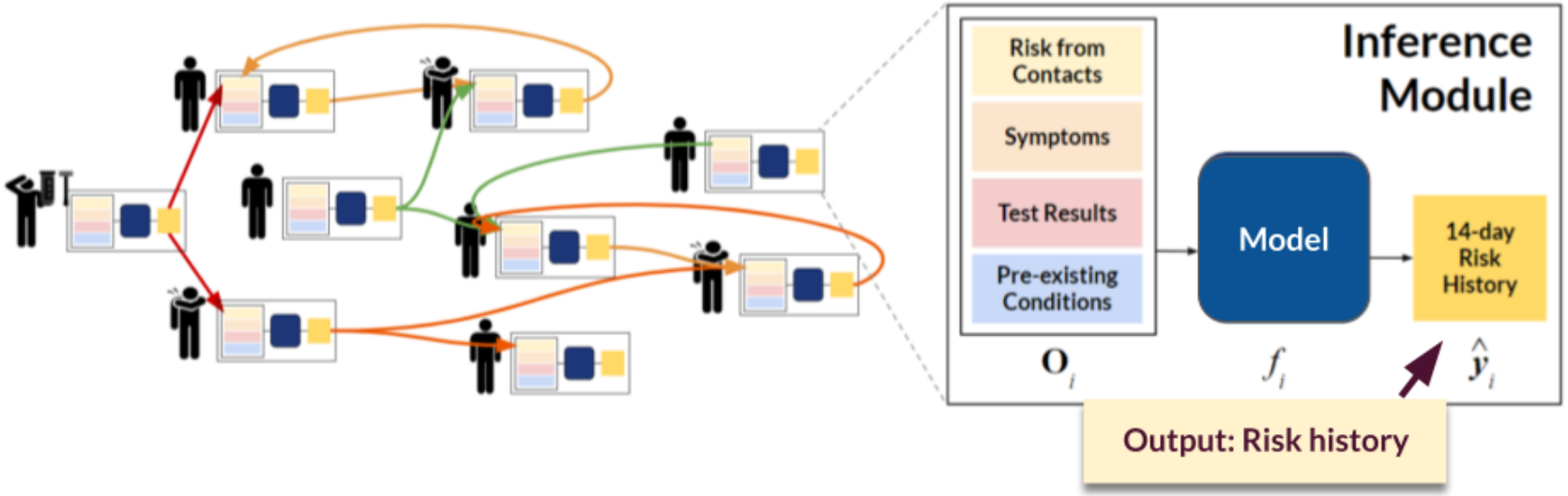
PCT Framework



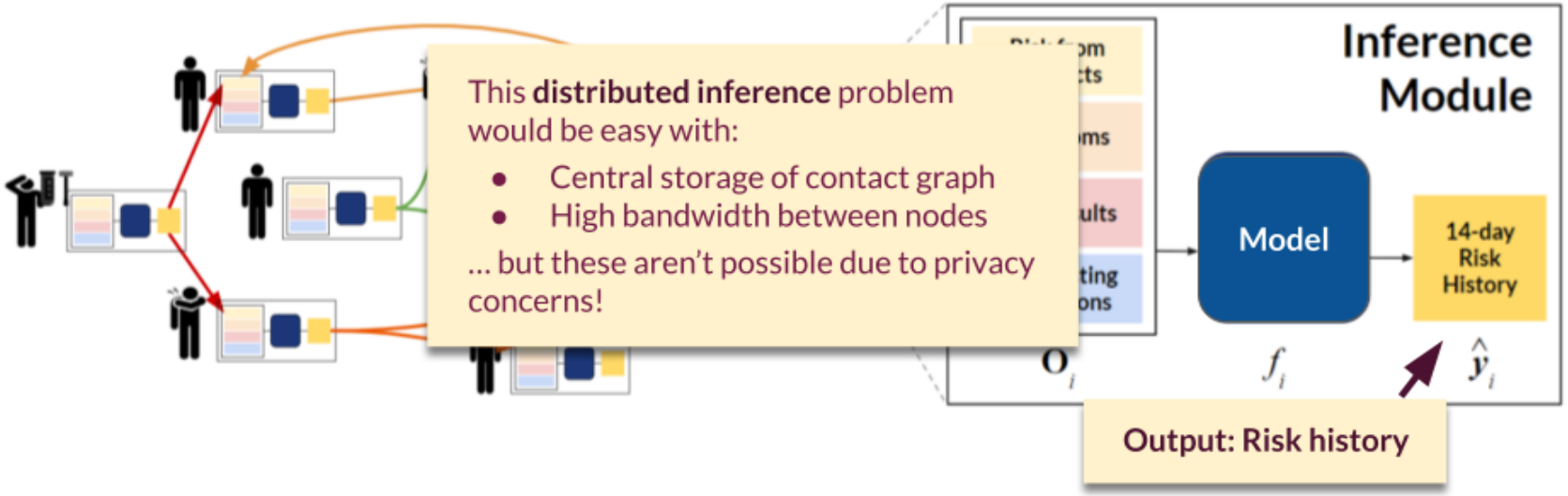
PCT Framework



PCT Framework



PCT Framework



This **distributed inference** problem would be easy with:

- Central storage of contact graph
- High bandwidth between nodes

... but these aren't possible due to privacy concerns!

PCT: Addressing Privacy

- No central storage of the contact graph

PCT: Addressing Privacy

- No central storage of the contact graph
- De-identification and encryption of all data

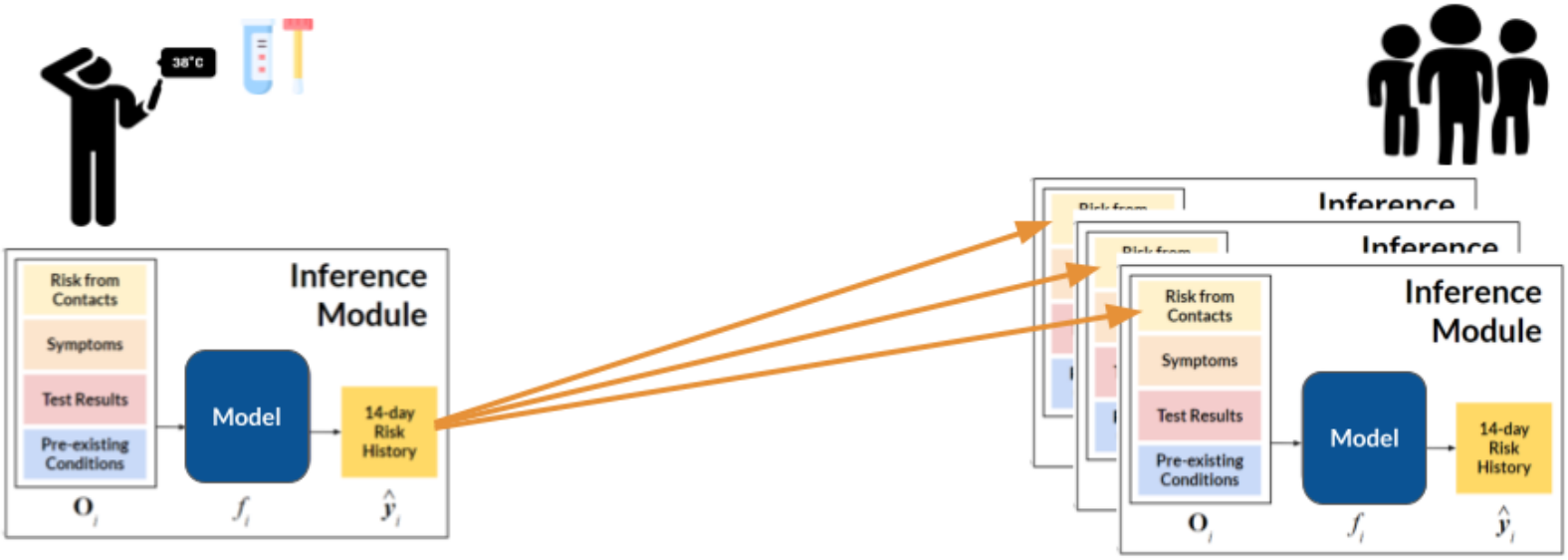
PCT: Addressing Privacy

- No central storage of the contact graph
- De-identification and encryption of all data
- User consent to share information

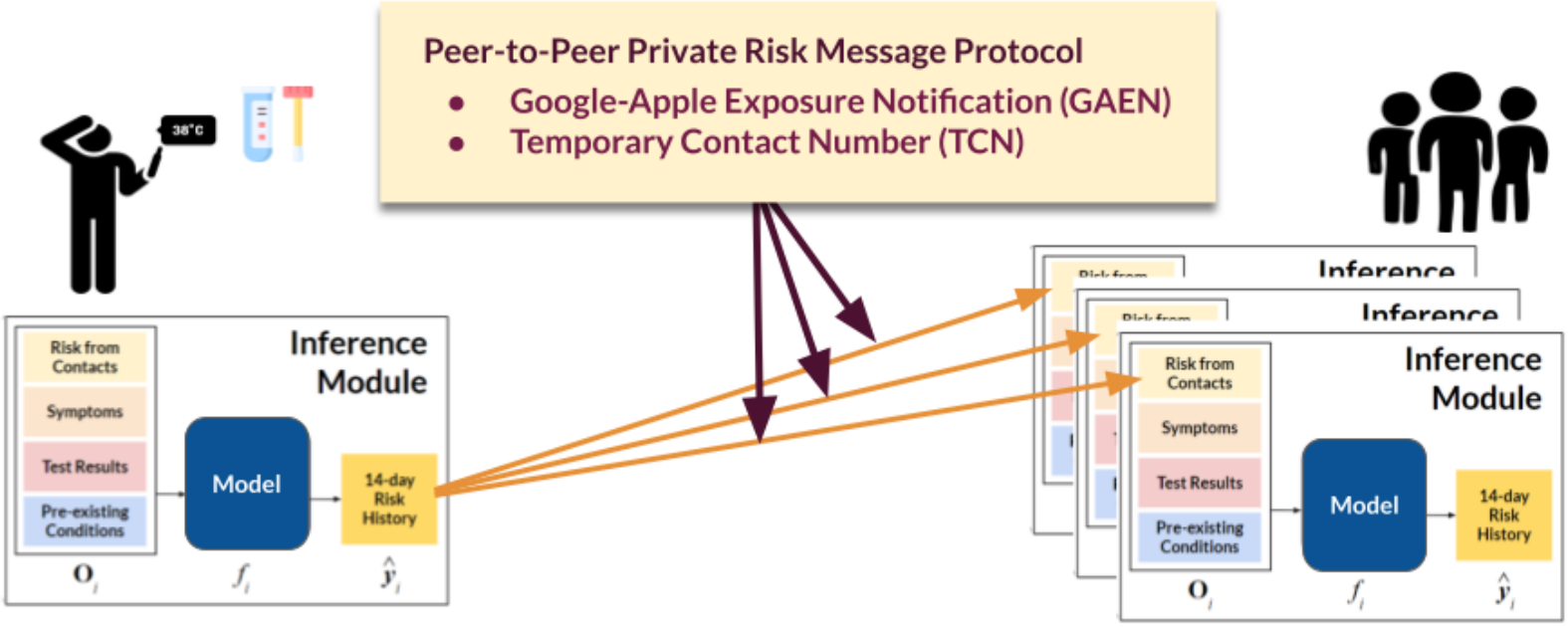
PCT: Addressing Privacy

- No central storage of the contact graph
- De-identification and encryption of all data
- User consent to share information
- User information never leaves the phone

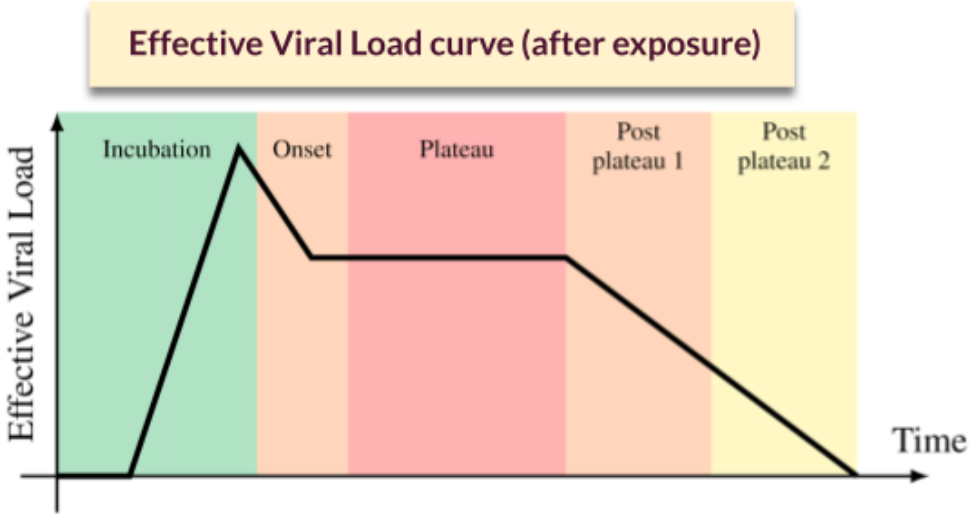
PCT: Risk Messages between phones



PCT: Risk Messages between phones

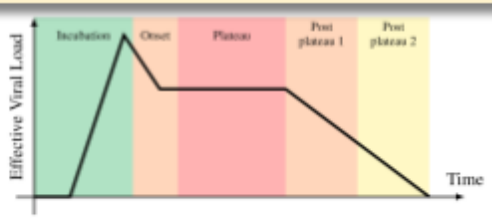


PCT: Risk Messages and Infectiousness



PCT: Risk Messages and Infectiousness

Effective Viral Load curve (after exposure)



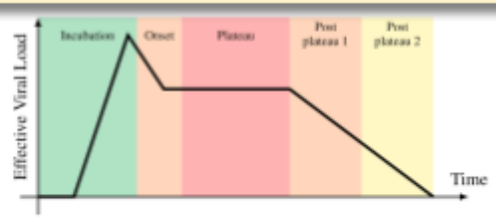
Example of target from curve

$\mathbf{y}_i$ Infectiousness over 14 days

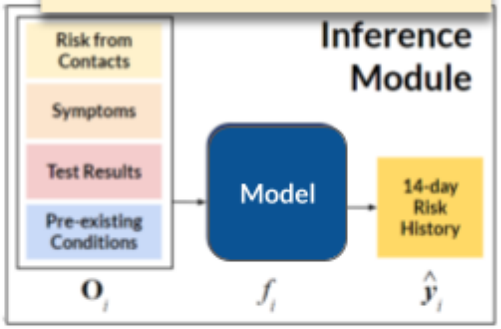
.00	.00	.08	.93	.75	.75	.75	.75	.75	.52	.37	.20	.12	.05

PCT: Risk Messages and Infectiousness

Effective Viral Load curve (after exposure)



Inference module on each phone



Example of target from curve

$\mathbf{y}_i$ Infectiousness over 14 days

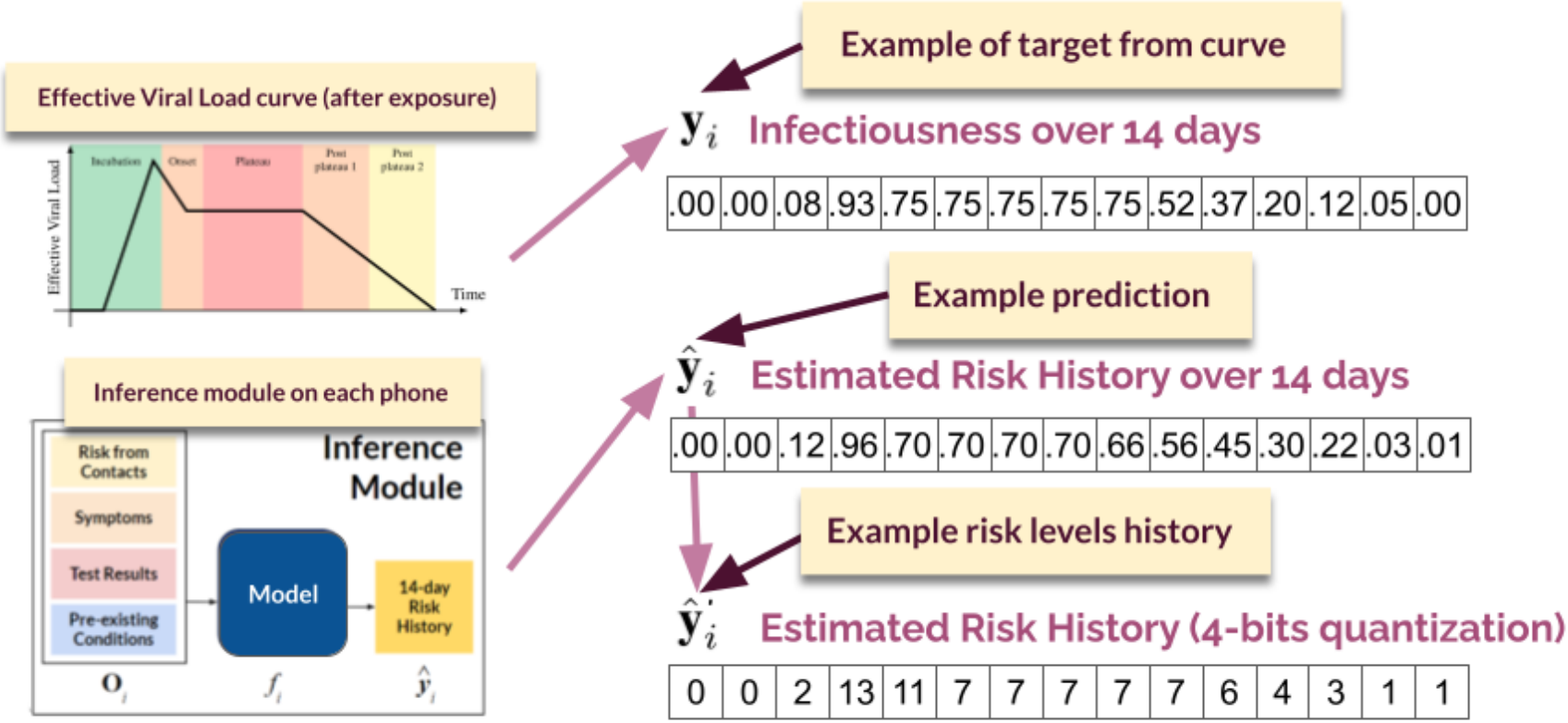
.00	.00	.08	.93	.75	.75	.75	.75	.75	.52	.37	.20	.12	.05	.00

Example prediction

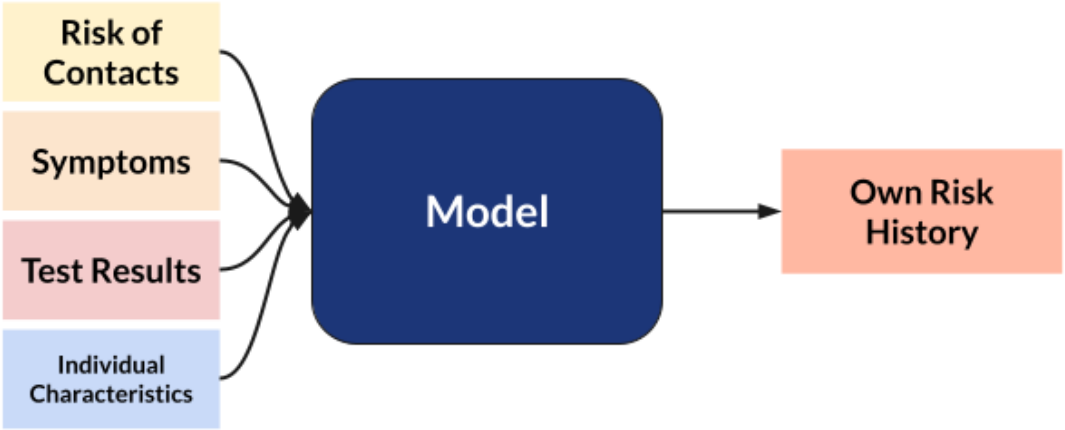
$\hat{\mathbf{y}}_i$ Estimated Risk History over 14 days

.00	.00	.12	.96	.70	.70	.70	.70	.66	.56	.45	.30	.22	.03	.01

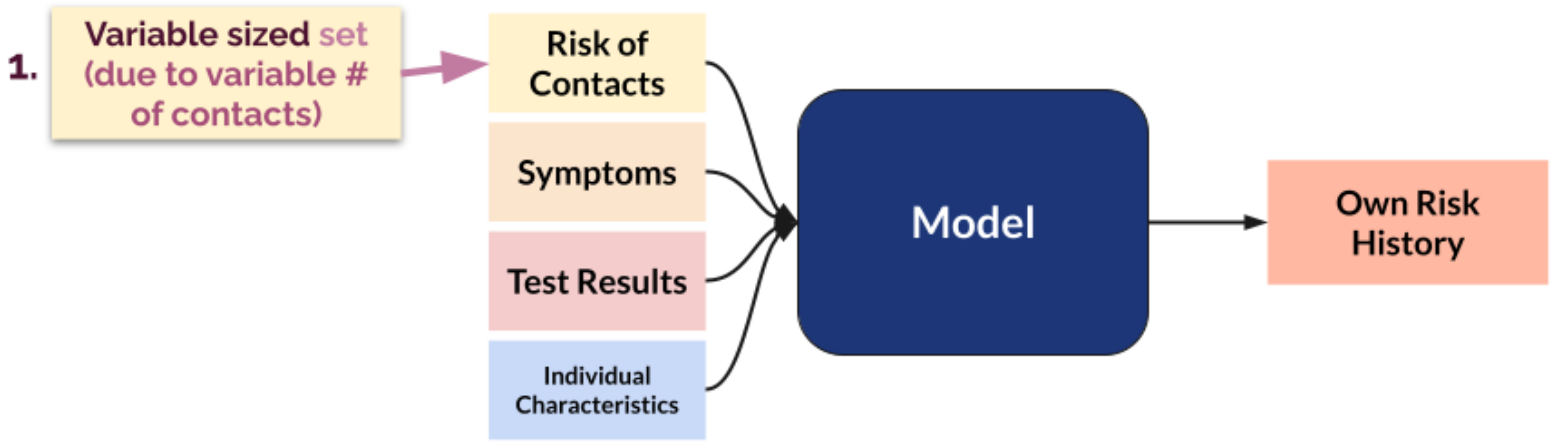
PCT: Risk Messages and Infectiousness



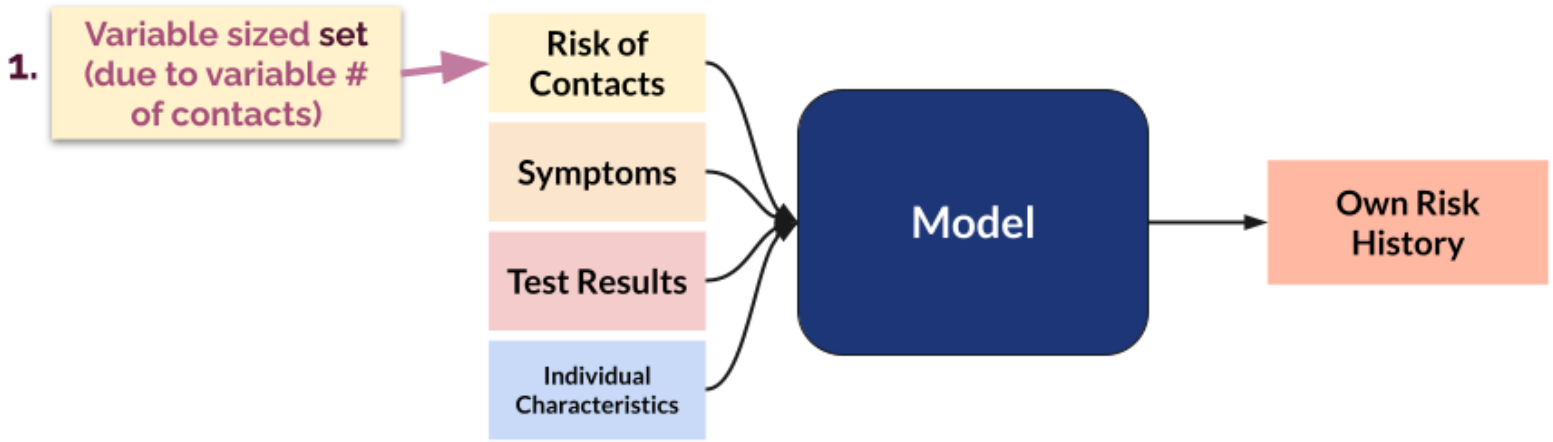
PCT Model: Constraints



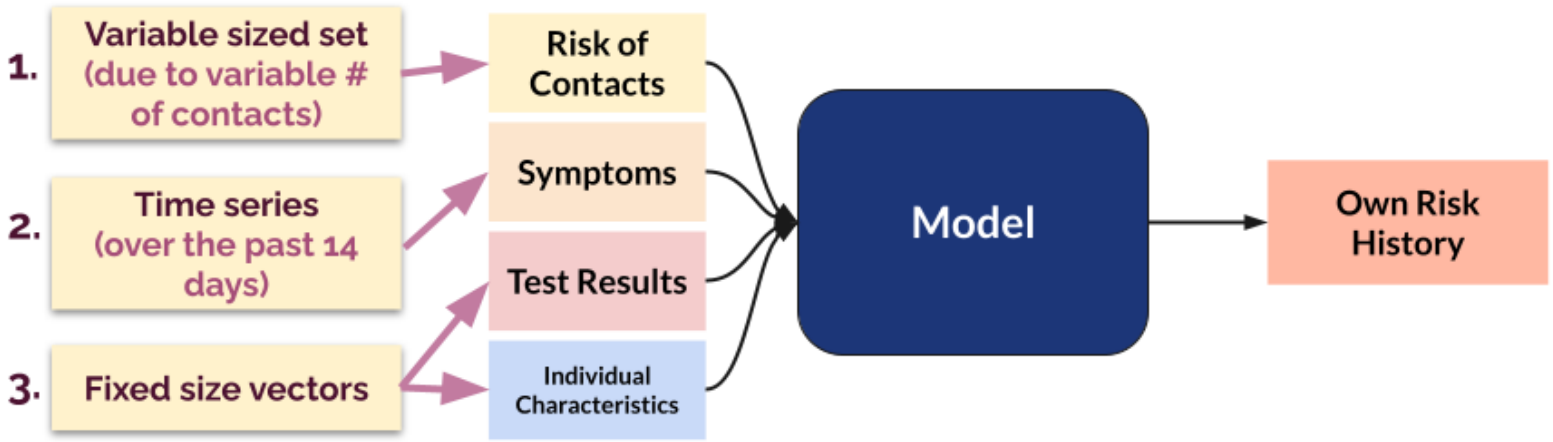
PCT Model: Constraints



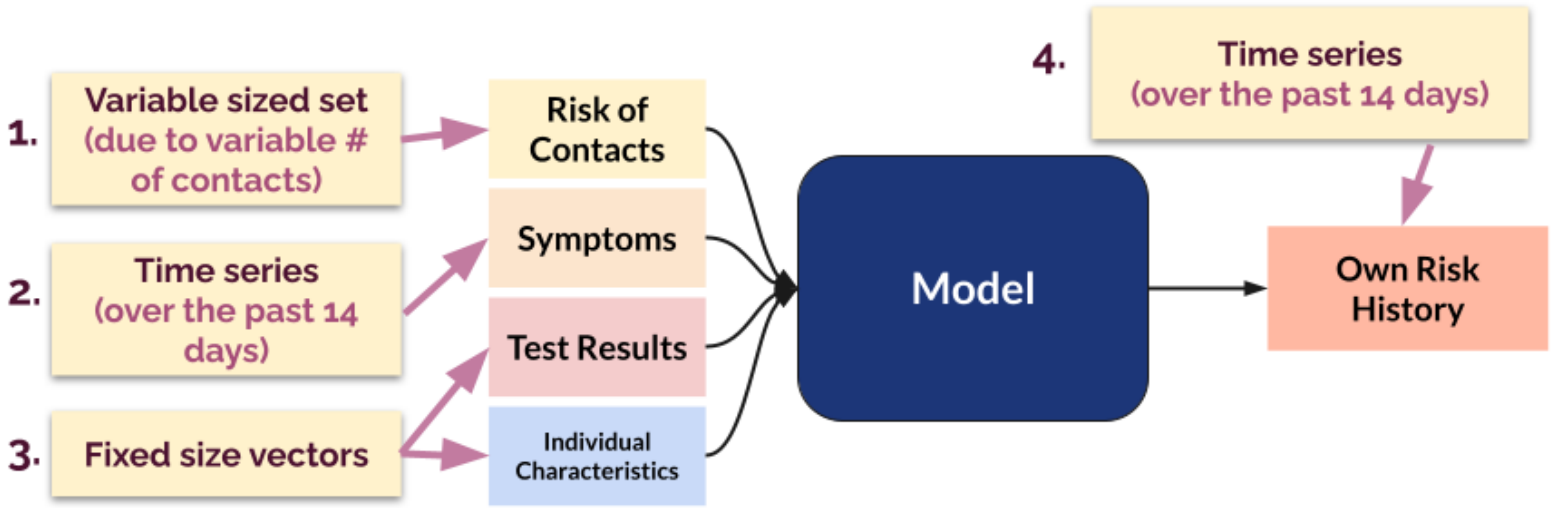
PCT Model: Constraints



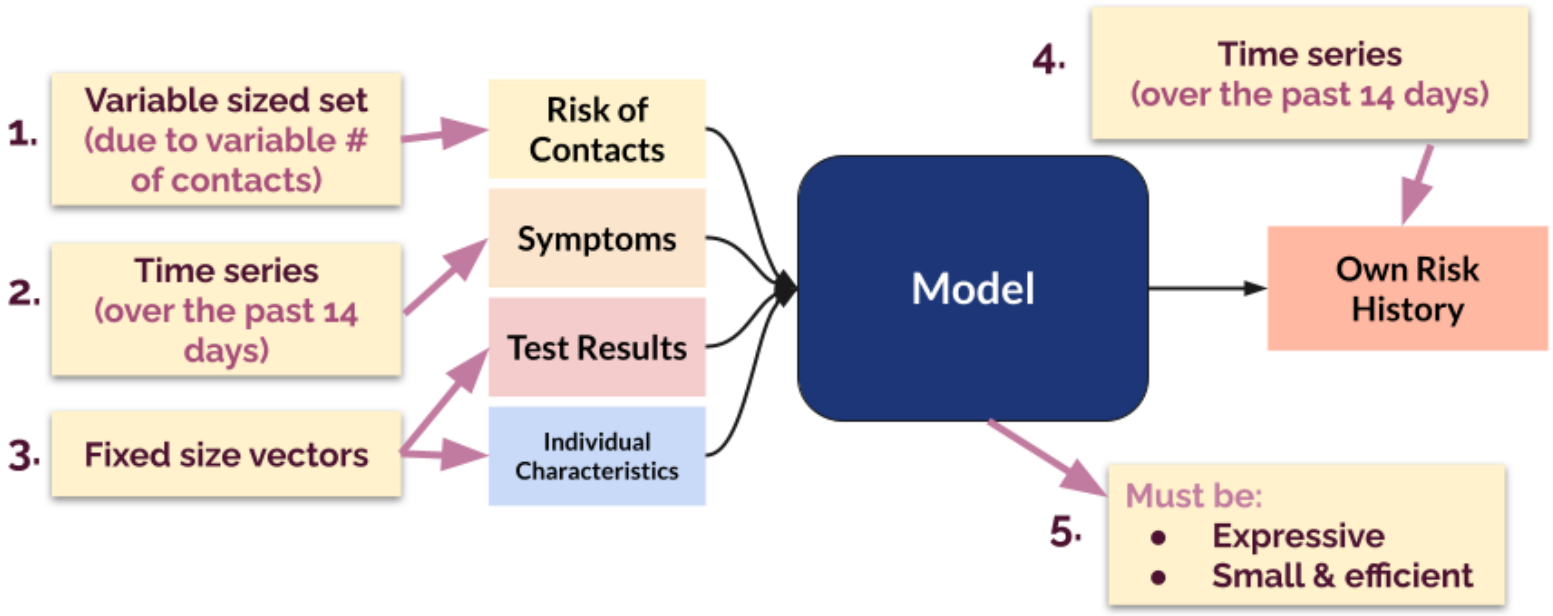
PCT Model: Constraints



PCT Model: Constraints

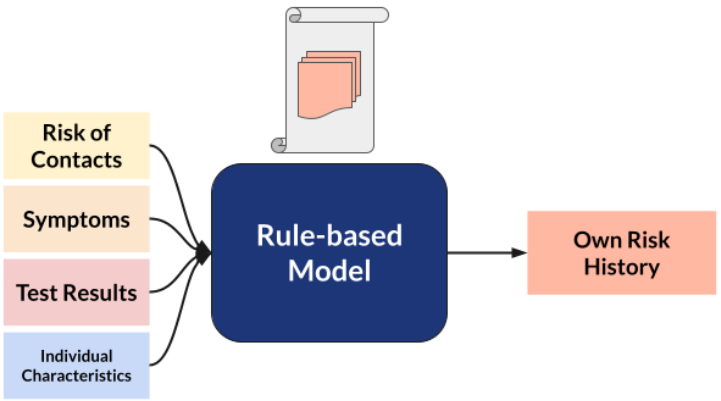


PCT Model: Constraints



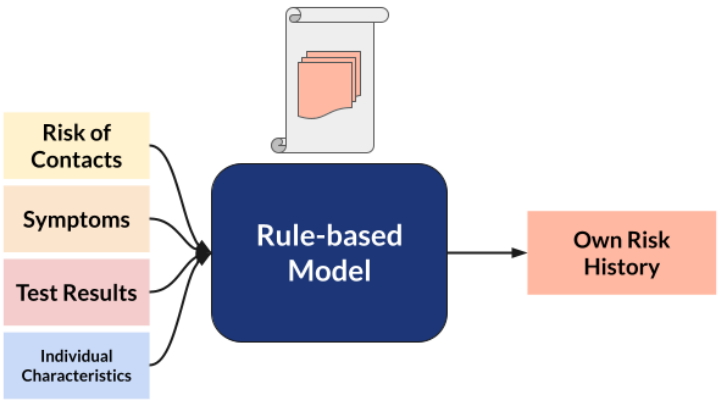
PCT Rule-based Model: Heuristic

- Rules designed by public health officials



PCT Rule-based Model: Heuristic

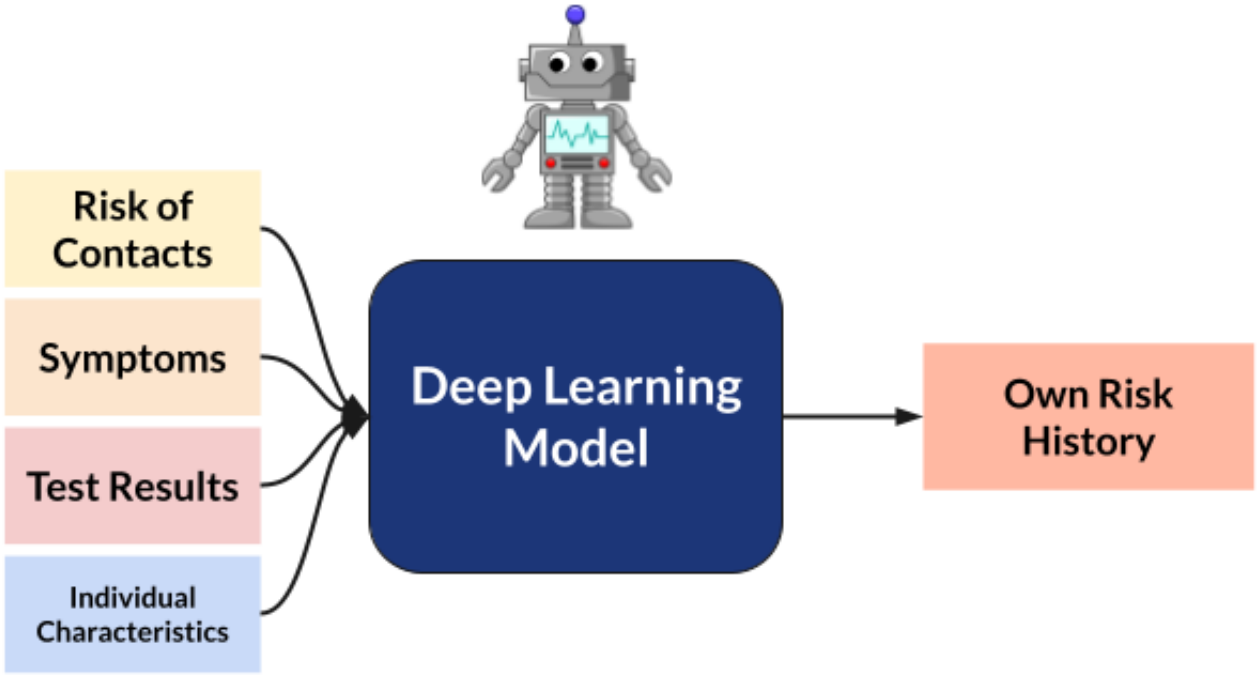
- Rules designed by public health officials
- Gupta et al., 2020 runs experiments on one such heuristic using **COVI-AgentSim**, an agent-based model



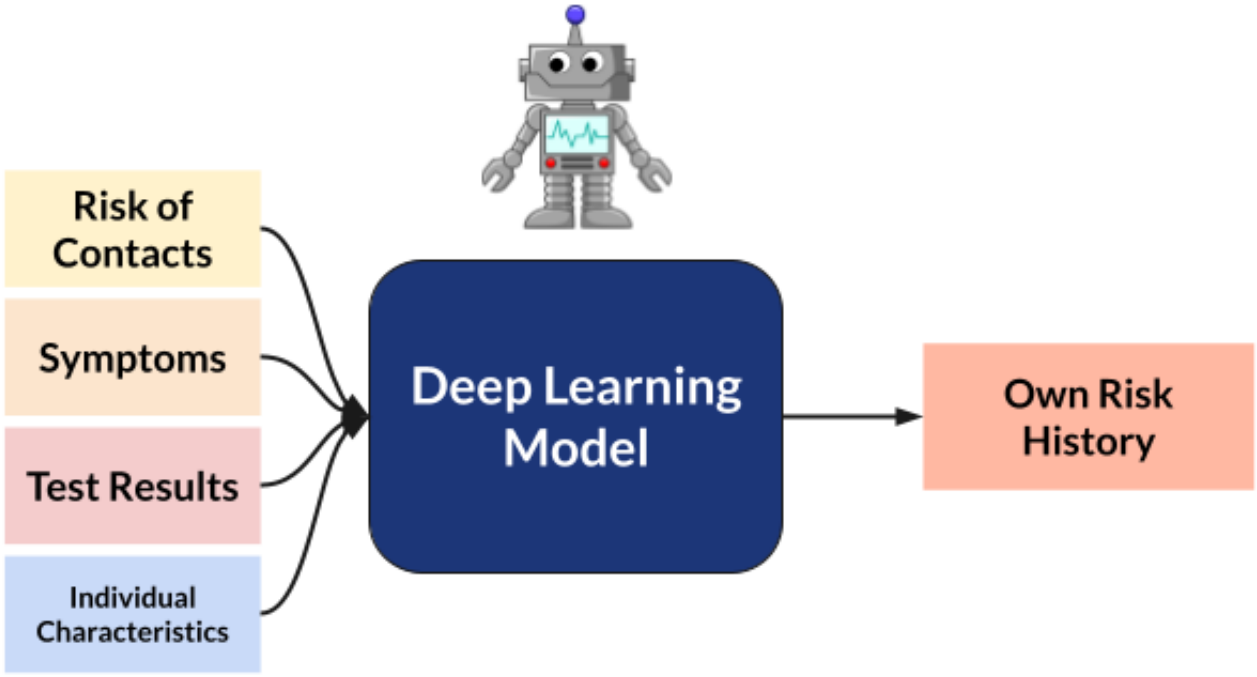
Algorithm 2 *Heuristic-FCT*

function HandleRecovery($\mathbf{S}^i_d$, $\mathbf{T}^i_d$, $M^i_{i,:}(:)$, $\mathbf{r}^i_d$)
  $\mathrm{Rx} \leftarrow 1$
  if $\sum \mathbf{S}^i_{d,\{:,d:d-d_{max}/2\}} \geq 1$ or $\sum_{d' \in D} \mathbb{1}_{\{\mathbf{T}^i_{d,d'}=+1\}} \geq 1$ **then**
    $\mathrm{Rx} \leftarrow 0$
  if $\sum_{j \in \mathcal{N}(i),\, d' \in D,\, d'' \in \{d,d-1,\ldots d-7\}} \mathbb{1}_{\{M^{d'}_{i,j}(d'')=r_{\mathrm{HIGH}}\}} \geq 1$ **then**
    $\mathrm{Rx} \leftarrow 0$
  else if $\sum_{j \in \mathcal{N}(i),\, d' \in D,\, d'' \in \{d,d-1,\ldots d-4\}} \mathbb{1}_{\{M^{d'}_{i,j}(d'')=r_{\mathrm{MODERATE}}\}} \geq 1$ **then**
    $\mathrm{Rx} \leftarrow 0$
  else if $\sum_{j \in \mathcal{N}(i),\, d' \in D,\, d'' \in \{d,d-1\}} \mathbb{1}_{\{M^{d'}_{i,j}(d'')=r_{\mathrm{MILD}}\}} \geq 1$ **then**
    $\mathrm{Rx} \leftarrow 0$
  if $\mathrm{Rx} = 1$ **then**
    $\mathbf{r}^i_{d,d:d-d_{max}/2} \leftarrow 0$
  return $\mathbf{r}^i_d$, Rx
function ApplyNegativeTest($\zeta^i_d, \mathbf{r}^i_d, \mathbf{T}^i_d, W$)
  $d_n \leftarrow$ day of the latest negative test
  $\mathbf{r}^i_{d,\, d_n-W/2\,:\,d_n+W/2} \leftarrow 0$
  if $\mathbf{r}^i_{d,d} = 0$ **then**
    $\zeta^i_d = 0$
  return $\mathbf{r}^i_d$, ζ^i_d
function ComputeRisk($\mathbf{T}^i_d, \mathbf{S}^i_d, M^i_{i,:}(:), \mathbf{X}_i, \mathbf{r}^i_{d-1}$)
  $W \leftarrow 8$
  $\mathbf{r}^i_t, \zeta^i_t \leftarrow$ TestResultsComputeRisk($\mathbf{T}^i_d$)
  $\mathbf{r}^i_s, \zeta^i_s \leftarrow$ SymptomsComputeRisk($\mathbf{S}^i_d$)
  $\mathbf{r}^i_m, \zeta^i_m \leftarrow$ RiskMessagesComputeRisk($M^i_{i,:}(:)$)
  $\mathbf{r}_r, \mathrm{Rx} \leftarrow$ HandleRecovery($\mathbf{S}^i_d$, $\mathbf{T}^i_d$, $M^i_{i,:}(:)$, $\mathbf{r}^i_{d-1}$)
  if $\mathrm{Rx} = 1$ **then**
    return $\mathbf{r}_r$, 0
  $\mathbf{r}_d \leftarrow \max(\mathbf{r}_t, \mathbf{r}_s, \mathbf{r}_m, \mathbf{r}_{d-1})$ ▷ element-wise maximum
  $\zeta^i_d \leftarrow \max(\zeta_t, \zeta_s, \zeta_m)$
  if $\sum_{d' \in D} \mathbb{1}_{\{\mathbf{T}_{d,d'}=-1\}} \geq 1$ **then**
    $\mathbf{r}^i_d, \zeta^i_d \leftarrow$ ApplyNegativeTest($\zeta^i_d, \mathbf{r}^i_d, \mathbf{T}^i_d, W$)
  return $\mathbf{r}^i_d$, ζ^i_d

PCT Deep Learning Models



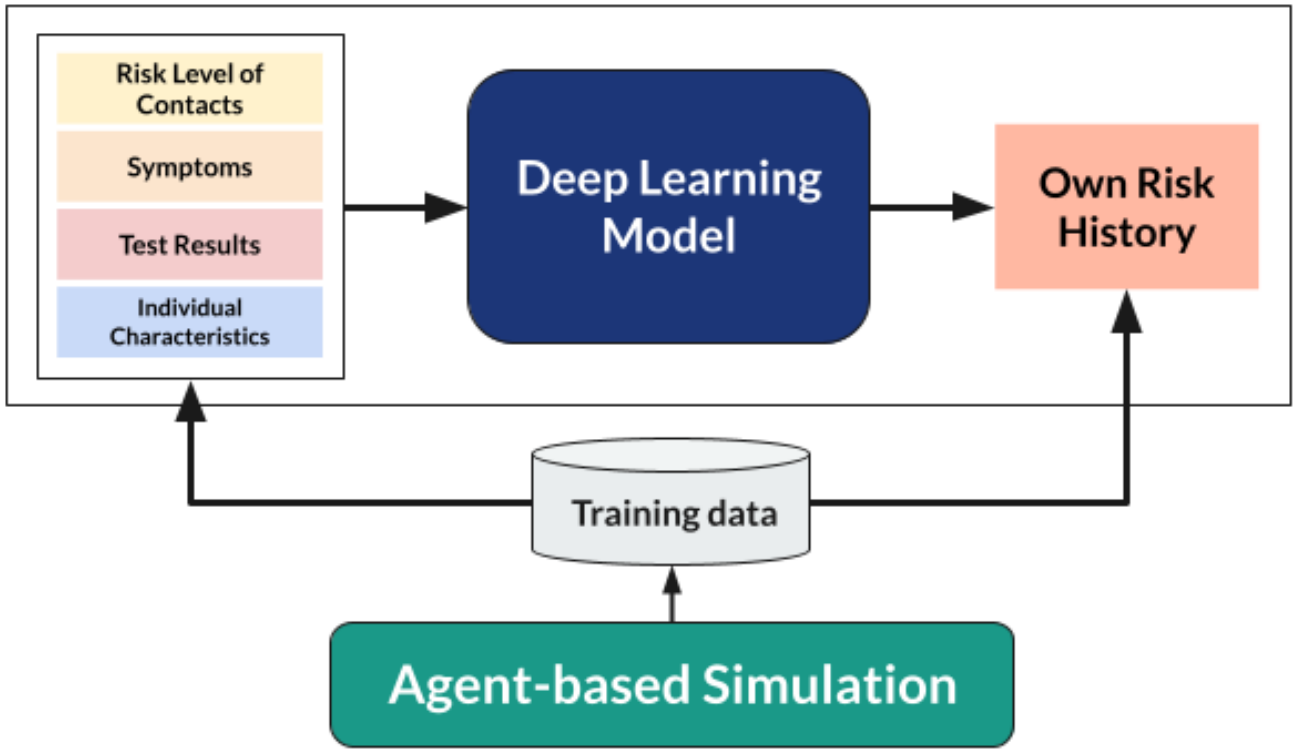
PCT Deep Learning Models



Bengio et al., 2020 (ICLR - Top 20) proposes neural network architecture and training protocol for deep learning based PCT predictor

Where does training data come from?

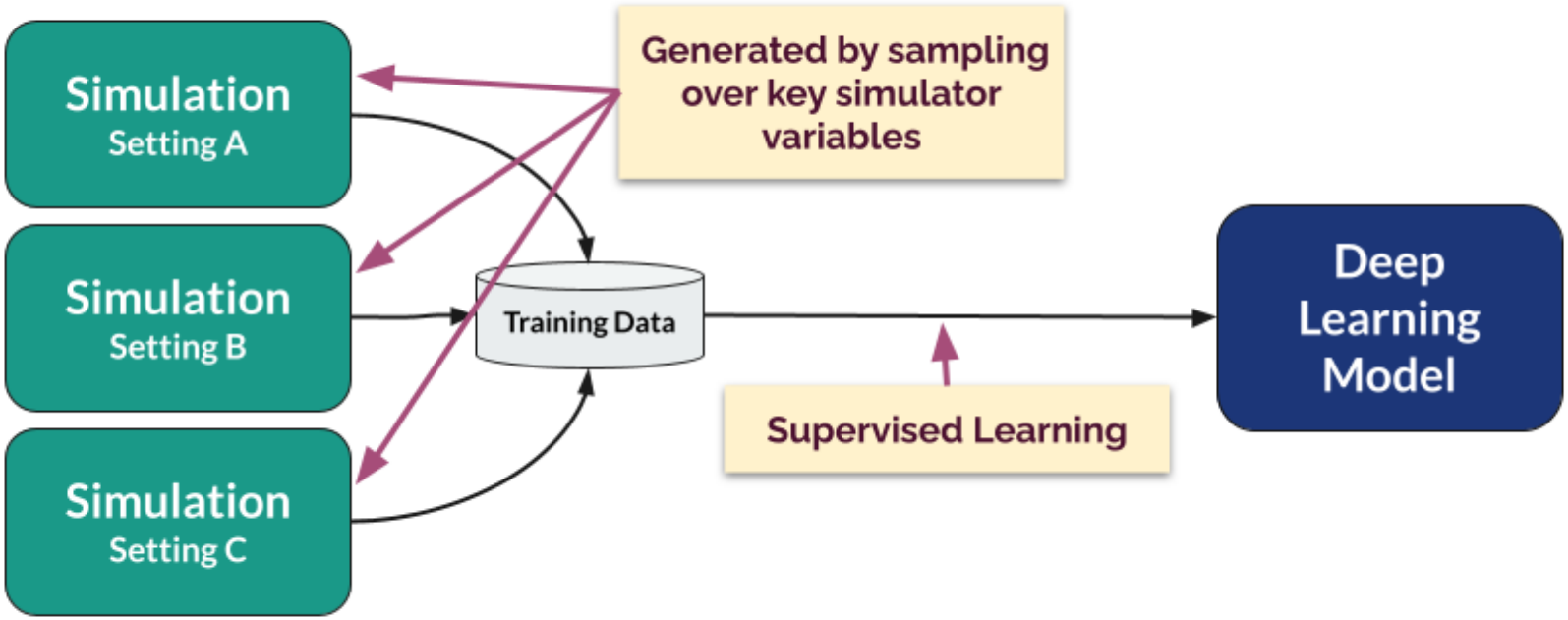
Learn from simulations



COVI-AgentSim (Gupta et al., 2020) is used as a simulator

But simulations aren't reliable ...

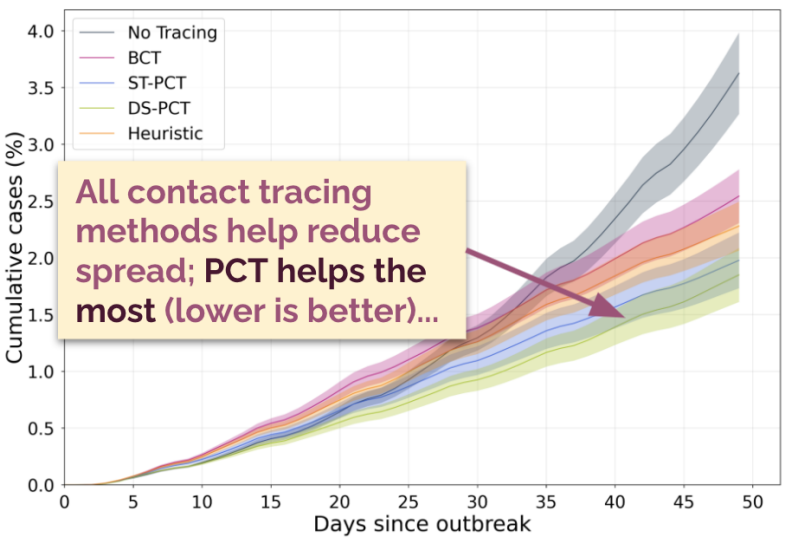
Domain Randomization

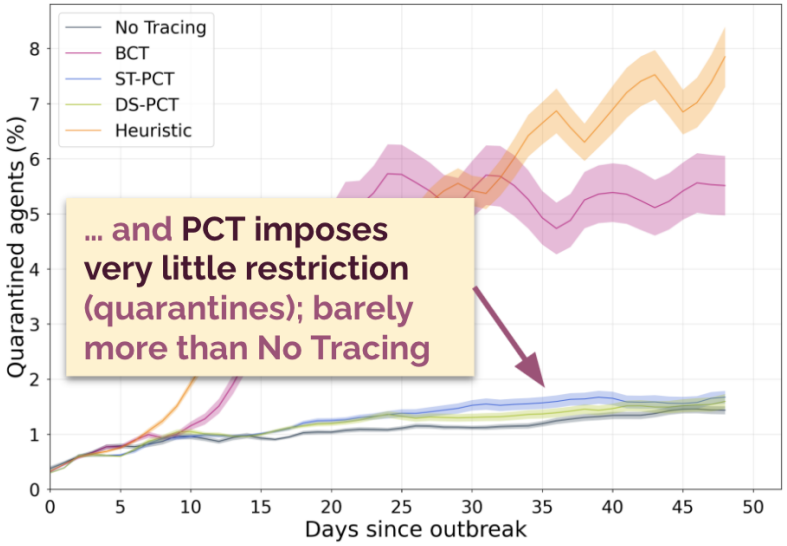


But ...

And many more challenges were identified and rectified in our ICLR submission Bengio et al., 2020

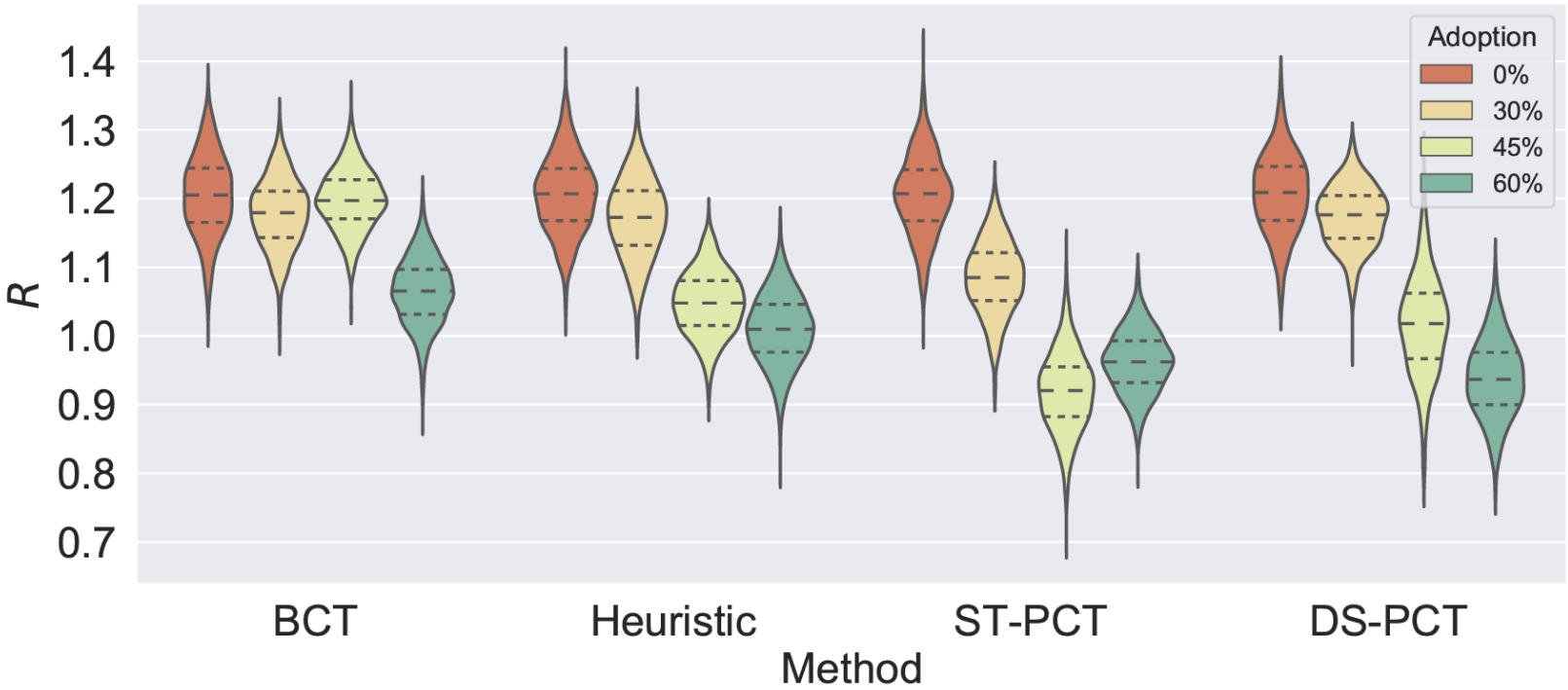
Results: Case Curves





Simulated results on 3000 agents constrained to the same number of mean daily contacts

Results: Adoption Rate



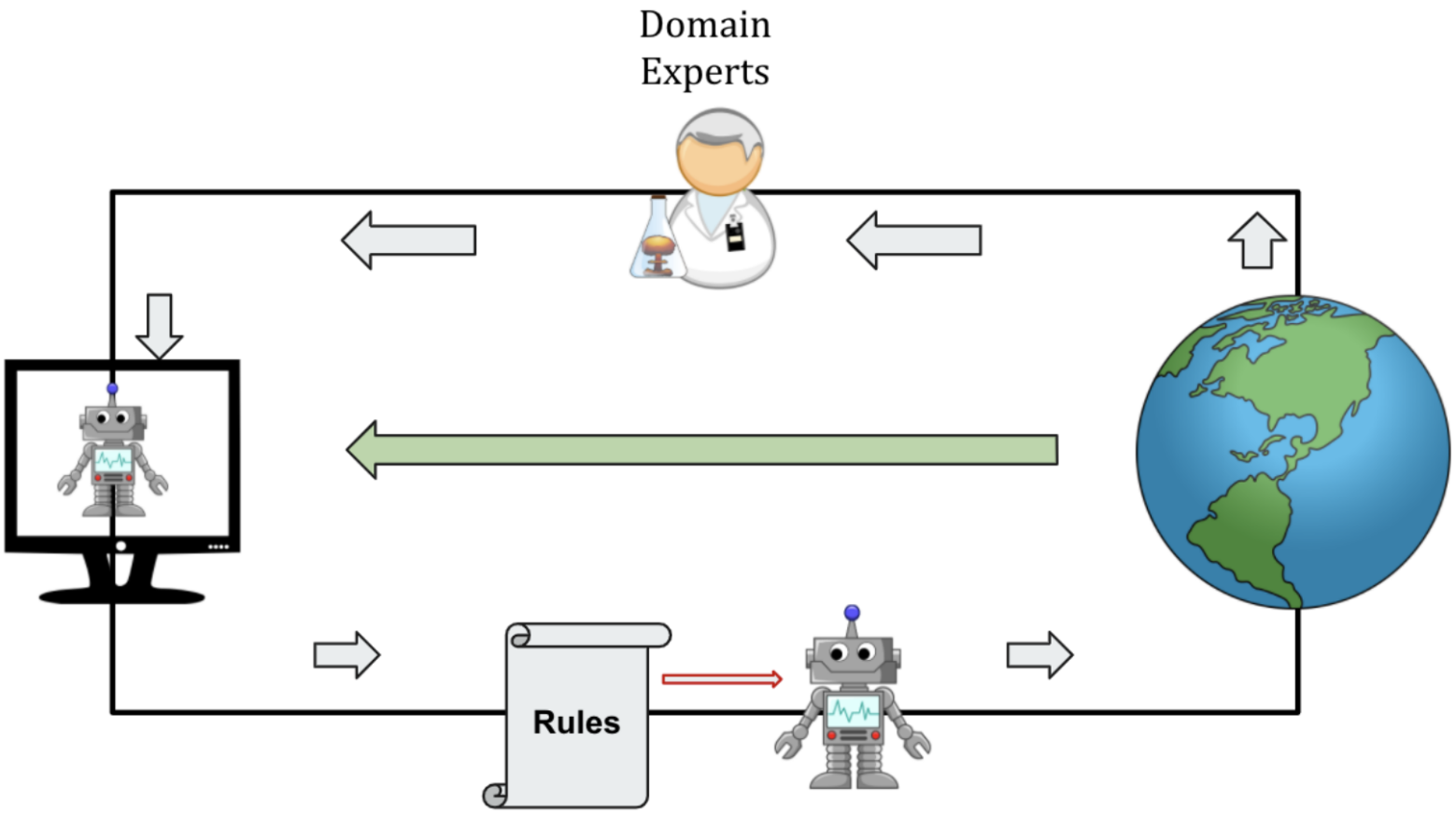
Simulated results on 3000 agents constrained to the same number of mean daily contacts

COVI App

White Paper: `https://arxiv.org/abs/2005.08502`

Open Questions

Blog: `https://www.pgupta.info/blog/2021/ct-5/`



Machine learning model learned using Offline-RL on data collected using the rule based models

Conclusion

Conclusion

- We **proposed PCT framework** that serves as a common platform for epidemiologists, behavior researchers, privacy experts, and computer scientists to collaborate

Conclusion

- We **proposed PCT framework** that serves as a common platform for epidemiologists, behavior researchers, privacy experts, and computer scientists to collaborate
- We **proposed a rule-based implementation** of PCT

Conclusion

- We **proposed PCT framework** that serves as a common platform for epidemiologists, behavior researchers, privacy experts, and computer scientists to collaborate
- We **proposed a rule-based implementation** of PCT
- We **proposed a deep learning based implementation** of PCT

Conclusion

- We **proposed PCT framework** that serves as a common platform for epidemiologists, behavior researchers, privacy experts, and computer scientists to collaborate
- We **proposed a rule-based implementation** of PCT
- We **proposed a deep learning based implementation** of PCT
- We identified key areas of research to help improve the AI techniques to be applicable for PCT

Thank you & Resources

Slides:
www.pgupta.info/talks

Blog:
www.pgupta.info/blog

COVI White Paper:
https://arxiv.org/abs/2005.08502

Smartphone App:
https://mila.quebec/en/project/covi/

COVI-AgentSim Paper:
https://arxiv.org/pdf/2010.16004.pdf

COVI-AgentSim Code:
https://github.com/mila-iqia/COVI-AgentSim

COVI-ML Paper:
https://arxiv.org/pdf/2010.12536.pdf

COVI-ML Code:
https://github.com/mila-iqia/COVI-ML

QR Codes generated via https://www.qr-code-generator.com/

Proactive Contact Tracing

Thank you!

Prateek Gupta

The Alan Turing Institute

UNIVERSITY OF OXFORD

Mila