OPTIMIZING THE ORDER OF ACTIONS IN A MODEL OF CONTACT TRACING

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INTRODUCTION

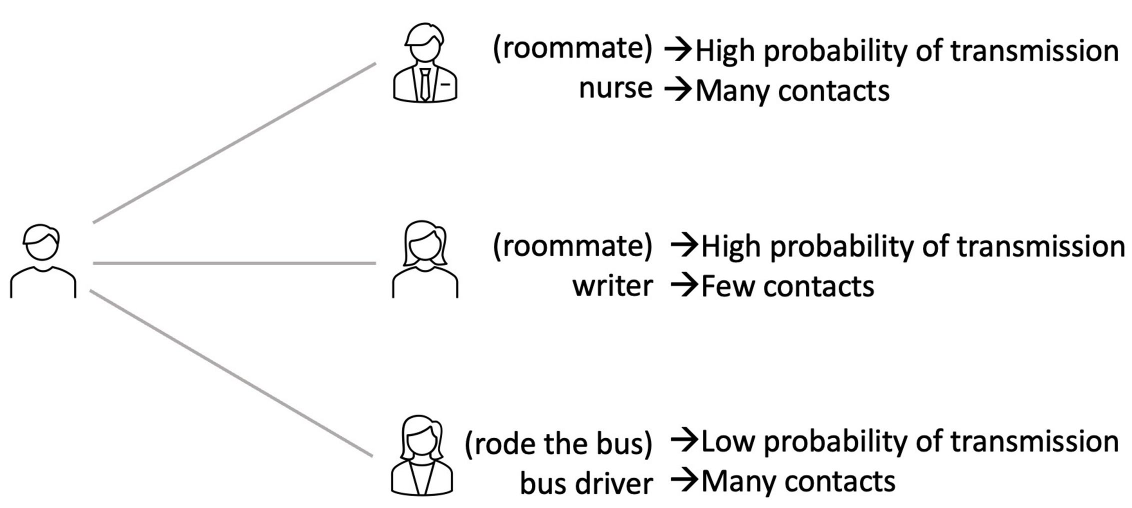
- Contact tracing is the process of *iteratively* identifying, testing, and treating the close contacts of an infected individual.
- Primary public health intervention for HIV, TB, and COVID-19.
- Requires significant human time and effort, which is often in limited supply.

A Motivating Example:

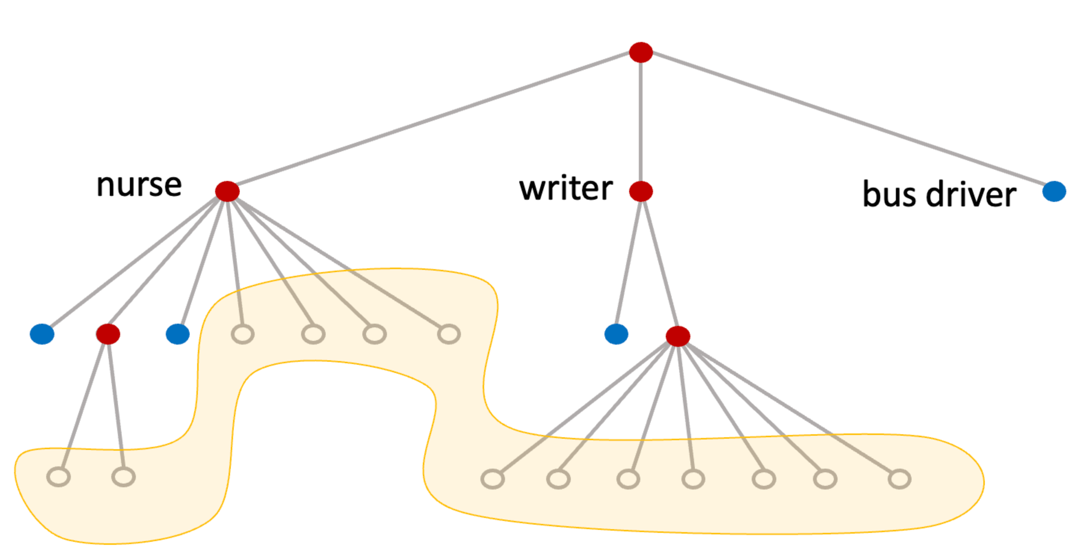
A student becomes infected with a respiratory illness. They name three contacts:

- a roommate who is a nurse at a hospital
- a roommate who is a writer and works from home
- the bus driver who drove them to campus

Suppose we can only trace one contact at a time. Which contact should we trace first?



We can model this process as a tree:



- Querying an individual ≈ expanding a node
- Each step, we query a child of an infected node queried in the past
- Hints about a node's probability of infection, or its degree
- Goal: Find infected nodes as efficiently as possible

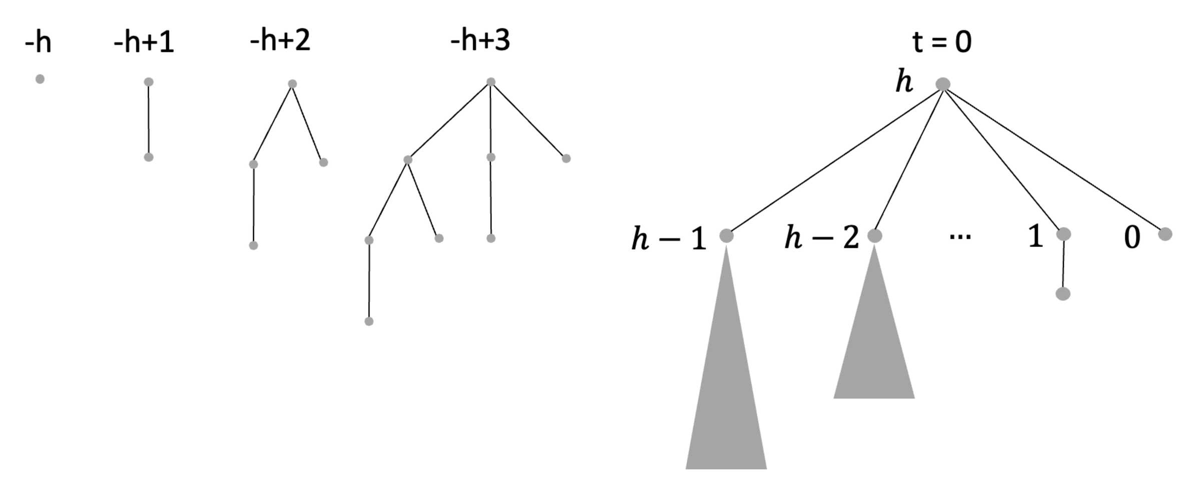
METHODS

- We develop a mathematical model with two phases.
- Through analyzing our model, we give provably optimal prioritization policies via a clean connection to a tool from operations research called a "branching bandit" (Weiss '88).
- We prove that there is an optimal algorithm that categorizes nodes into types, and assigns a priority to each type. Then at each step, it selects a node from the frontier according to this prioritization.
- We analyze an extension of our model via computational simulations.

THEORETICAL ANALYSIS

Phase 1: Infection Model

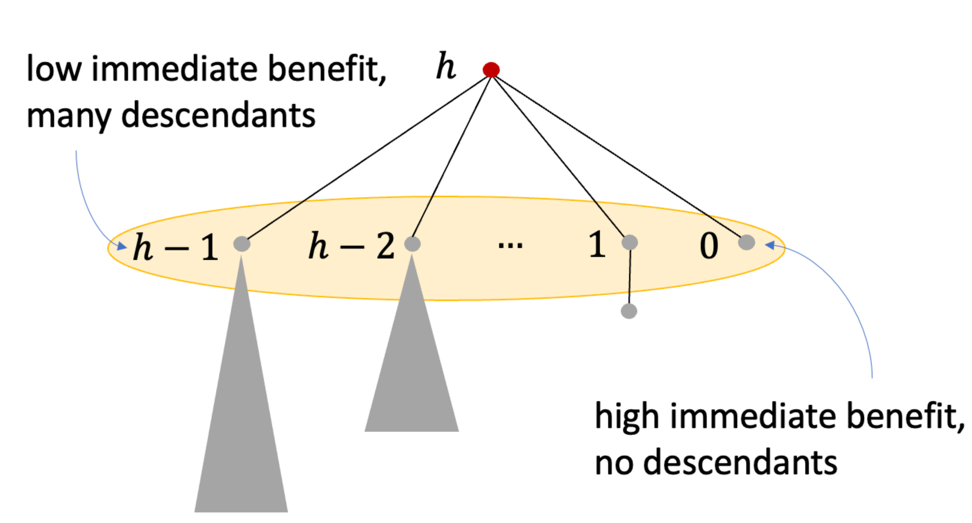
- At t = -T a single node exists.
- At each step t, each node meets a new contact with probability q.
- Infected nodes probabilistically infect each new contact they meet.
- After t = 0, no new infections occur.
- A node that arrives at time t=-h has recency h.



A node of recency h has h children, of recencies 0, 1, …, h-1.

Phase 2: Query Process

- At t = 0, a is identified as an index case with recency h_a.
- At each step t >= 0, the tracer queries one node.
- Querying a node reveals its infection status and children.
- The tracer may only query a node if it is an index case or the child of an infected node queried in the past.
- We call this candidate set the *frontier.*
- The benefit of querying a node infected for τ steps is $e^{-\beta\tau}$.
- The benefit of querying an uninfected node is 0.
- Goal: Find a policy for querying nodes which maximizes the total expected benefit.



How should we trade-off immediate benefit vs access to descendents?

RESULTS

Theorem 1: The general model, which includes the basic, univariate, and bivariate models, reduces to the branching bandit problem.

Theorem 2: In the basic model, for any $\beta > 0$ and any transmission probability $p \in (0,1]$, the optimal policy queries nodes in order of recency.

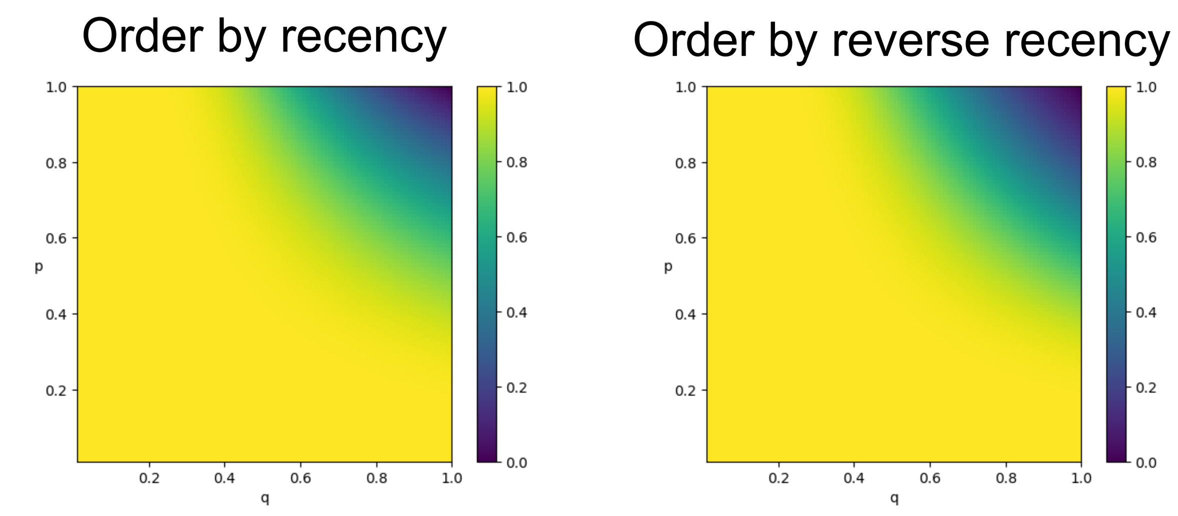
EXTENSION TO A DYNAMIC MODEL

Simulation Model

- Infection continues to spread after tracing begins
- Querying a node = quarantining a node
- Until a node is queried, it generates new contacts at each step
- Goal: contain the infection = query all infected nodes
- Infection probability p, contact probability q

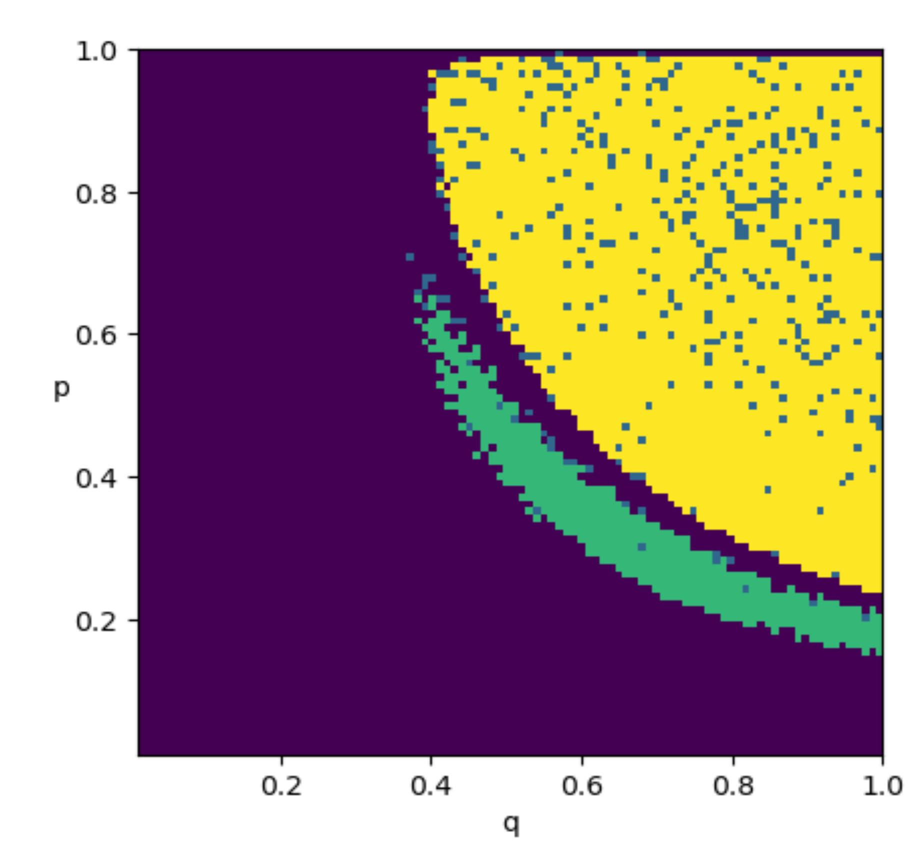
Heatmaps showing the probability of containment for two policies:

- Order by recency: earliest infection is queried first
- Order by reverse recency: most recent infection is queried first



Regions of dominance

- Yellow: order by recency is significantly better
- Green: order by reverse recency is significantly better



CONCLUSION

- Develop optimal policies that align the tracer's present decision with their longterm objective of maximizing total benefit.
- Discovered a clean connection between contact tracing and the branching bandits problem

REFERENCES

- Michela Meister and Jon Kleinberg.*Optimizing the order of actions in contact tracing,* 2021.
- Michela Meister and Jon Kleinberg. *Containing the spread of a contagion on a tree,* 2022.
- Gideon Weiss. *Branching bandit processes.* Probability in the Engineering and Informational Sciences, 2(3):269–278, 1988.

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