Engineers without borders: An engineering approach towards controlling infectious diseases

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Infectious Disease

- Stochastic process evolving over time and space
- Stochastic process
  - State of infection of each human
    - Susceptible, Infected, Stages of infection, immunized, recovered, dead
- Evolution over time
- Evolution over space
  - Network of humans
  - Disease spreading through proximity between susceptibles and infectious

Control of Infectious Diseases

- Control Mechanisms:
  - Testing and isolation
  - Mass quarantining
  - Vaccinations
- Cost of each control strategy
  - Resource consumption and constraints
- Benefits of each control strategy
  - Public health metrics
    - Number of cases, hospitalizations, deaths
- Goal
  - Optimizing benefits subject to cost constraints
- Terminologies familiar in network science
  - Recurring phenomena
  - Similarities and differences

Testing for Infectious Diseases

What testing tells us

- Disease spreads through contact
- Spatio temporal correlation of disease states of nodes
  - State of a node (human) at time t reveals information about
    - State of the node at time $t + 1$
    - State of neighbors at $t, t + 1, \ldots$
- Dual role of testing
  - Detect and Isolate infected nodes
  - Predict evolution of disease in neighborhoods of tested nodes

Exploitation vs Exploration

- Spread of disease
  - Symptomatic
  - Asymptomatic
- Tests typically only **exploit available knowledge**
  - Contact tracing
    - Test neighbors of infected nodes
    - Doesn't venture to untested regions
      - Silent spread in untested regions
        - sudden appearance of large clusters
- Need to **explore the unknown**
  - Test nodes even if they are far off from infected nodes
- Test Budgets
  - **Tradeoff between exploitation of knowledge and exploration of the unknown**

Multi Armed Bandit: Analogy and Differences

- Bandit with k arms
- States of the arms evolve as per Markov processes
  - Possible correlation across arms
- Trying an arm gives a reward and reveals its state
- Exploit results of tests or Explore the unknown?
- Differences with testing problem
  - Number of arms vary with time in testing context
    - Number of infected nodes change with time
    - Nodes are isolated after testing positive
      - ➢ Tests can't be repeated for the nodes that test positive
  - Exploitation vs Exploration Tradeoff arises in testing context because of
    - Lack of knowledge of evolving set of infected nodes
    - Even when network and process model and parameters are fully known

Our contributions

- Design of a principled greedy testing policy towards attaining desired exploitation exploration tradeoffs
- Design of a message passing algorithm to
  - continually update probabilities of infection of every node based on results of each test
  - Posterior probability of infection given history of test observations

Xingran Chen, Hesam Nikpey, Jungyeol Kim, Shirin Saeedi Bidokhti, Saswati Sarkar: "Containing a Spread through Sequential Learning: to exploit or to explore?" Transaction on Machine Learning Research, March 2023

Challenges in deployment

- Computational complexity
- Proximity to currently deployed solutions
  - Contact tracing
- Contact Tracing only exploits available knowledge
- Can contact tracing be generalized to explore as well?
- **Multihop communication of communication networks inspires multihop contact tracing**

Multihop contact tracing

- Test k hop neighbors of nodes who test positive
- Increasing k
  - Reduces overall infection count over time
    - ➢Diminishing return with increase of k?
  - Increases testing load, or does it ?
- Testing load with increase of k
  - Overall testing load can also decrease because infection is contained faster through aggressive testing early on
  - Maximum testing load does increase

Cost Benefit tradeoff of Multi-hop testing

- Benefit
  - Case count differential with 1-hop testing
- Cost
  - Number of overall tests
- Cost benefit tradeoff shows phase transition with respect to growth rate of disease
  - Low growth rate: Marginal benefit
  - Intermediate growth rate: Significantly higher benefit, yet lower cost
  - High growth rate: Substantial benefits but higher costs
- Diminishing return:
  - Benefit saturates with increase in k
  - Saturation point increases with increase in growth rate
  - Saturation point is mostly 2 or 3 hops
- Growth rate captures network topology
- Attributes that arise in practice:
  - Cooperativity
  - Errors in tests
  - Start time of contact tracing (initial infection level)

Papers

- Results based on Monte Carlo Simulations over large number of topologies
  - Synthetic
  - Obtained from actual contact data

Kim J, Chen X, Nikpey H, Rubin H, Saeedi Bidokhti S, Sarkar S. Tracing and testing multiple generations of contacts to COVID-19 cases: cost–benefit trade-offs. Royal Society Open Science. 2022 Oct 12;9(10):211927.

Kim J, Bidokhti SS, Sarkar S. Capturing COVID-19 spread and interplay with multi-hop contact tracing intervention. Plos one. 2023 Jul 13;18(7):e0288394.

Group Testing

- Test a group of nodes together.
  - Negative only if everyone is negative
  - Positive otherwise
- Useful to rule out multiple nodes in 1 test after mass events
  - Large congregations eg concerts, sports events
  - Public transport venues, stations, seaports, airports
- Goal: Identify state of each node after a mass event through minimum number of tests and asymptotically vanishing probability of error
- State of the art:
  - Assume node states are independent
  - Lower bounds on the requisite tests in terms of entropy of the state vector
  - Upper bounds through constructive algorithms
  - Limited results known for correlated node states

Our results on Group Tests

- Specific stochastic model for node correlation
  - Lower bounds
  - Upper bounds through constructive algorithms

Nikpey H, Kim J, Chen X, Sarkar S, Bidokhti SS. Group Testing with Correlation via Edge-Faulty Graphs. In 2022 IEEE International Symposium on Information Theory (ISIT) 2022 Jun 26 (pp. 880-885). IEEE.

- Arbitrary stochastic model for node correlation
  - Lower bounds
  - Upper bounds through constructive algorithms
  - *Nikpey H, Kim J, Chen X, Sarkar S, Bidokhti SS: Submission to IEEE International Symposium on Information Theory (ISIT) 2024*

Impact of human behavior on testing

- Individuals may refuse to test
- Opinion regarding testing evolves with time, space, infection level
- Joint models for evolution of infectious diseases and opinions regarding cooperating with counters

Ali RN, Sarkar S. Impact of opinion dynamics on the public health damage inflicted by COVID-19 in the presence of societal heterogeneities. Frontiers in Digital Health. 2023 Jun 8;5:1146178.

Ali RN, Rubin H, Sarkar S. Countering the potential re-emergence of a deadly infectious disease—Information warfare, identifying strategic threats, launching countermeasures. Plos one. 2021 Aug 20;16(8):e0256014.