Network Based Digital Contact Tracing and Testing Strategies for the COVID-19 Pandemic

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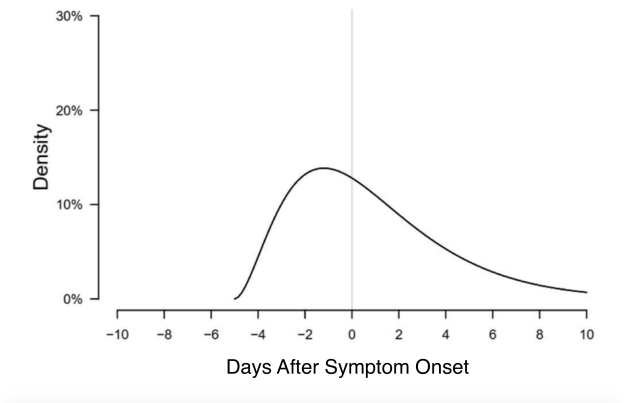
Problem 1: COVID-19 Infectivity and Incubation Distributions Over Time

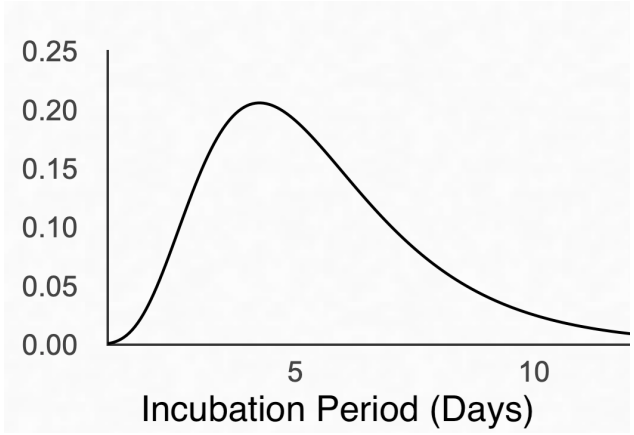
Problem 1:

Over 44% of infections are in the presymptomatic stage



Infectivity Distribution

Source: He, X., Lau, E.H.Y., Wu, P. et al. 2020



Incubation Distribution

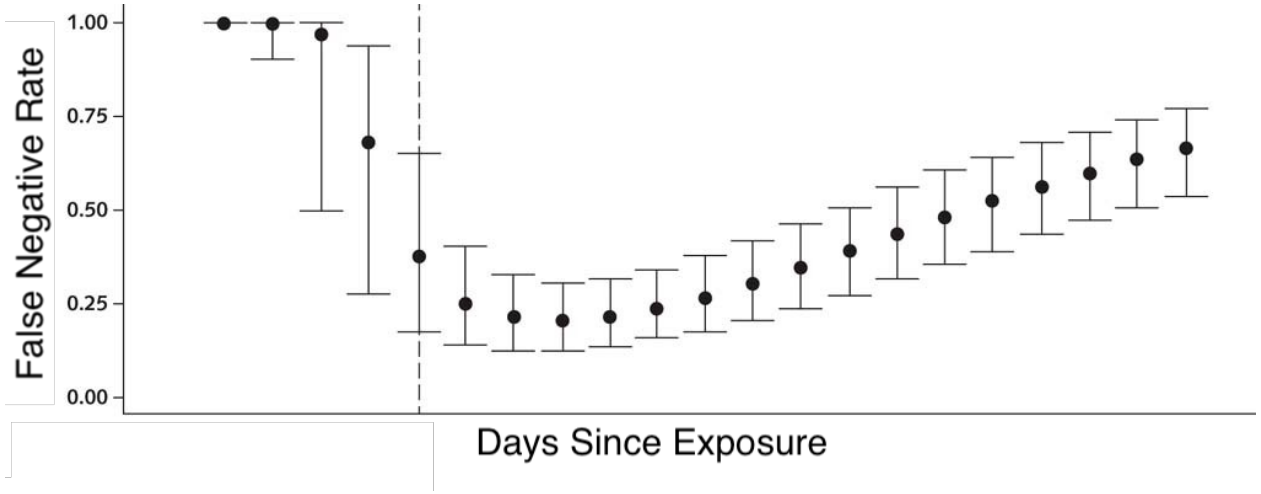
Source: Stephen A. Lauer, Kyra H. Grantz, Qifang Bi. et al. 2020

Bulk of infectivity is before symptom onset

Problem 2: Test Sensitivities Over Time

Problem 2:

COVID-19 tests are not very accurate in early days of exposure



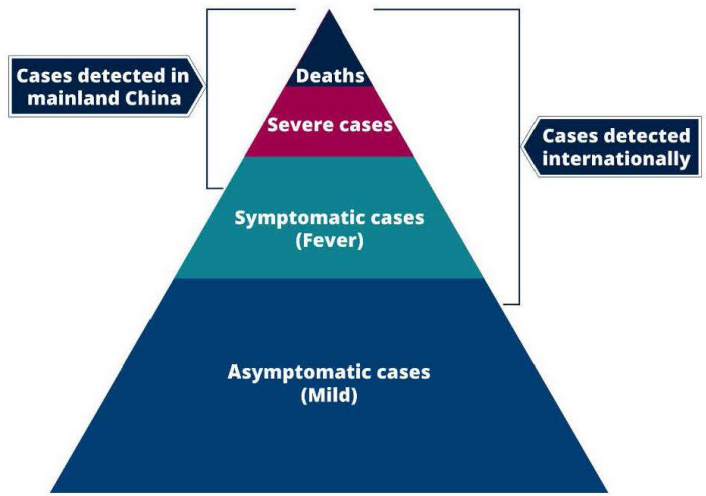
Test Sensitivity

Source: Kucirka LM, Lauer SA, Laeyendecker O, Boon D, Lessler J. 2020

Problem 3: Asymptomatic Cases Account for 40% of Total

Problem 3:

CDC estimates 40% of cases remain asymptomatic(Could be up to 80% for kids)



Asymptomatic Proportion

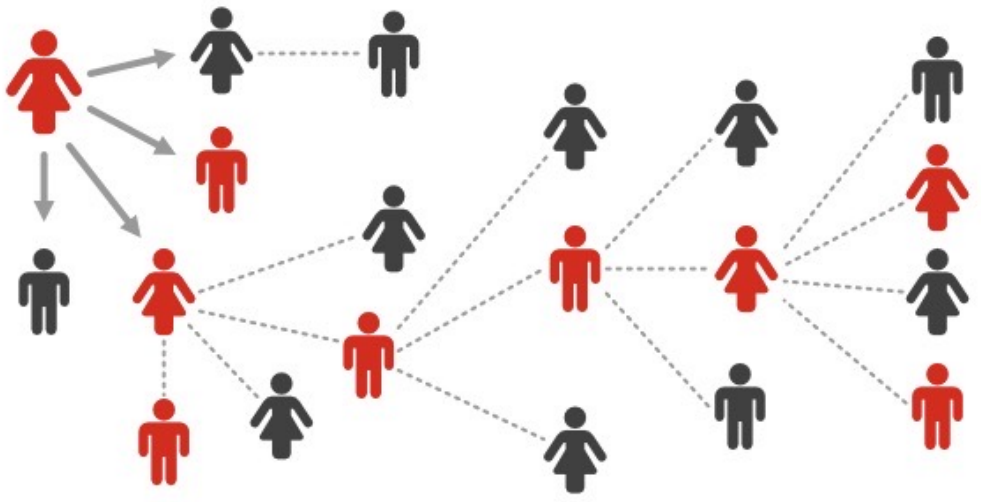
Source: https://www.cato.org/blog/misleading-arithmetic-covid-19-death-rates

Asymptomatic individuals are almost as infectious as symptomatic individuals

How Digital Contact Tracing works?

Purpose:

Prevent asymptomatic and presymptomatic infections



Contact Network

Source: https://www.bbc.com/news/technology-52246319

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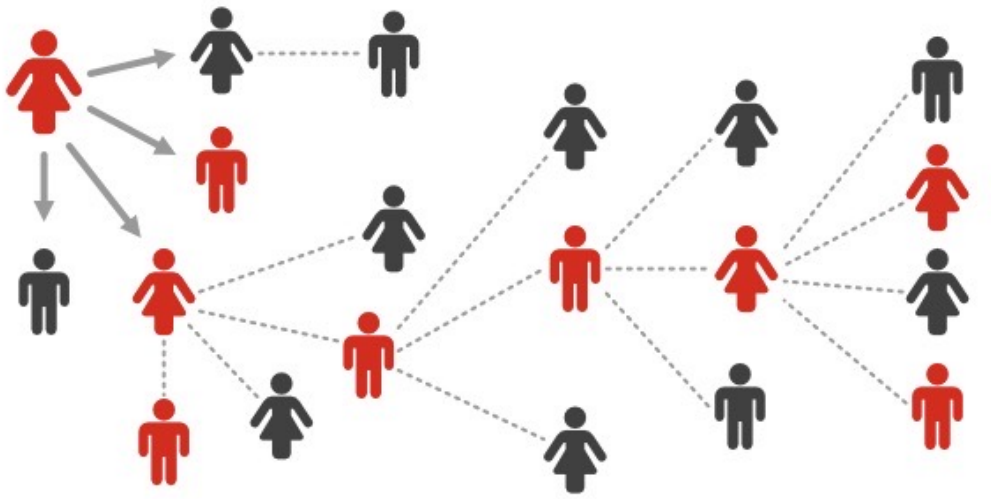

Contact Network

Source: https://www.bbc.com/news/technology-52246319

- Phone senses contacts pseudonymously
- Users report positive tests
- Exposed contacts are notified

SEIR Model

- Prediction (infections or deaths)
- Simulate hypothetical intervention

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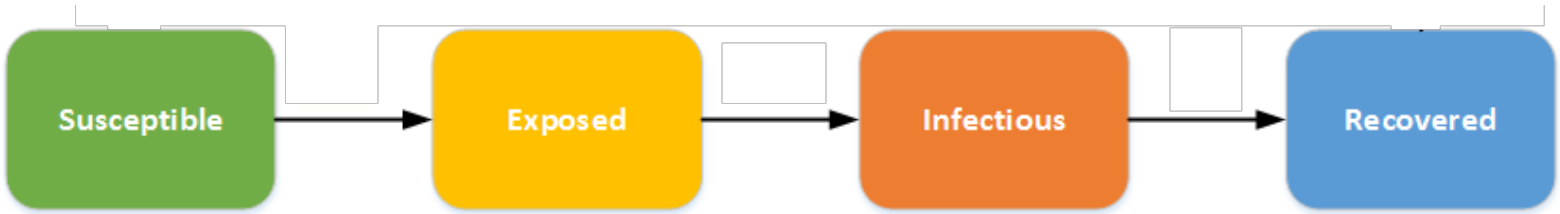
- Simulate hypothetical intervention

1. Susceptible
2. Exposed
3. Infectious
4. Recovered



SEIR Flow

Source: https://www.idmod.org/docs/emod/hiv/model-seir.html

Our Modelling Approach

Our enhanced network SEIR model:

- Incorporate difficulties of COVID-19
  - Test sensitivity over time
  - Change in infectivity over time
  - Incubation period
  - Asymptomatic proportion
- Realistic contact network - using real high school student contact data
- Incorporate higher degree contact chains into contact tracing app model

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Our Model Part 1: Enhanced Network SEIR

- Graph G where G_{ij} is contact duration between i and j (units of $20s$)
- Infection probability:

$$1 - (1 - p)^{G_{ij}}$$

- $p = c \cdot ID(t)$
- t is the number of days since symptom onset (can be negative)
- ID is the relative infectivity distribution function
- c is a constant that we will vary in our simulation.

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Our Model Part 2: Contact Chains

Contact: (p_1, p_2, t, d)

- p_1, p_2 are the people involved in the contact
- t is the day of contact
- d is the duration of the contact measured in units of 20 seconds

Degree k contact: a chain of contacts $c_1, \ldots, c_k$ where

1. $c_i = (p_i, p_{i+1}, t_i, d_i)$
2. p_1 reported a positive test during days t_1 to $t_1 + 7$
3. p_i, p_{i+1} are not in the Recovered stage during t_i
4. $t_i + 2 \leq t_{i+1} \leq t_i + 7$

Contact chain weight:

$$\prod_{i=1}^{k} (1 - (1 - p)^{d_i})$$

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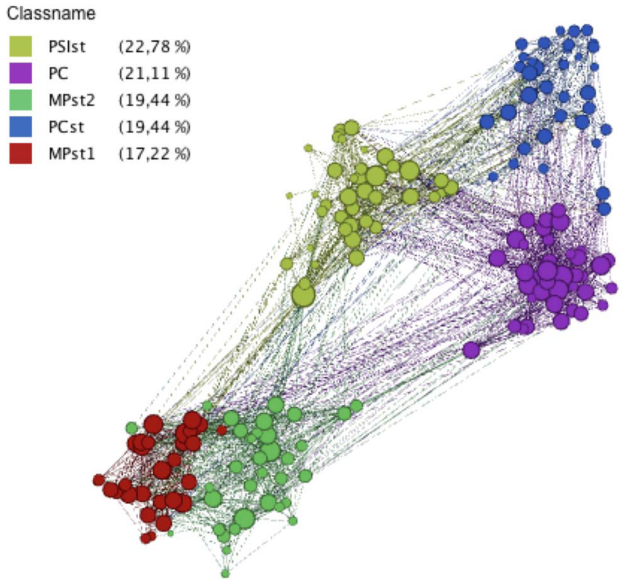
Data Source: Contact Network Generation

RFID sensors on students over 7 days



Contact Network

Source: Fournet J, Barrat A. 2014

Generate more days(MUNGE-like heuristic):

- Pick 2 random days
- G_{ij} determined by "coin flip"

Performance Metrics: Measuring How Well a Configuration Works

Outbreak Size:

Total number of infections

Tests:

Total amount of tests used

Quarantine:

Total number of days spent in quarantine across all individuals

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Simulation Parameters

- Everyday symptomatic individuals have a 33% chance to get tested
- Quarantine direct contacts
- Followup testing up to degree 3 contacts
- One person starts as infected
- Simulation runs for 80 days
- Each person is seed infection 10 times for a total of 1800 simulations

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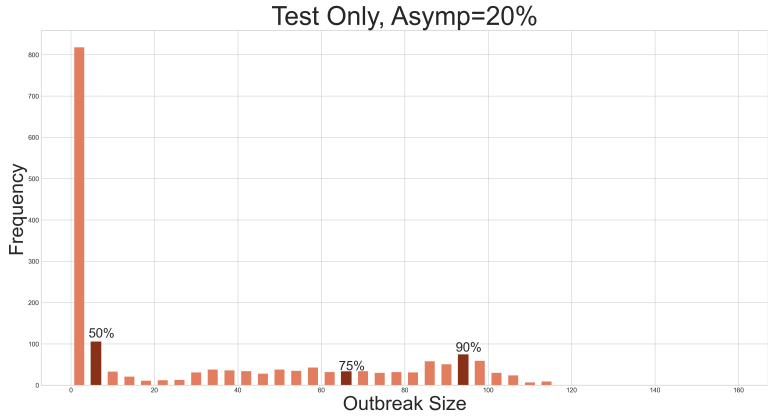
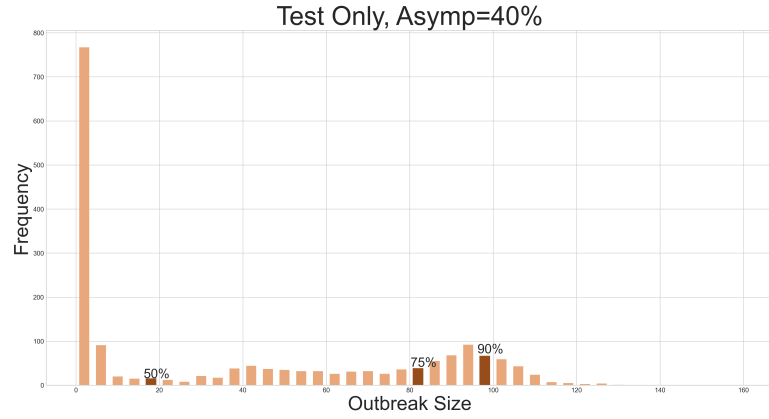
Simulation Results 1: Test Only vs With Tracing

Quarantine Direct Contacts, No Followup Testing

Scenario		Outbreak Size	Quarantine	Test
App Proportion	Asymptotic			
0%	20%	32.6178	0	27.1983
70%	20%	20.8094	74.8006	17.2706
95%	20%	14.5506	94.3311	12.1217
0%	40%	38.3811	0	23.7956
70%	40%	27.4078	83.8822	17.1056
95%	40%	20.7094	111.053	12.7422
0%	60%	45.465	0	18.5733
70%	60%	35.3583	78.4317	14.5117
95%	60%	29.5439	118.217	12.0506

40% Asymptotic: App reduces infections up to 46%


Test Only, Asymp=20%
Frequency
Outbreak Size
50%
75%
90%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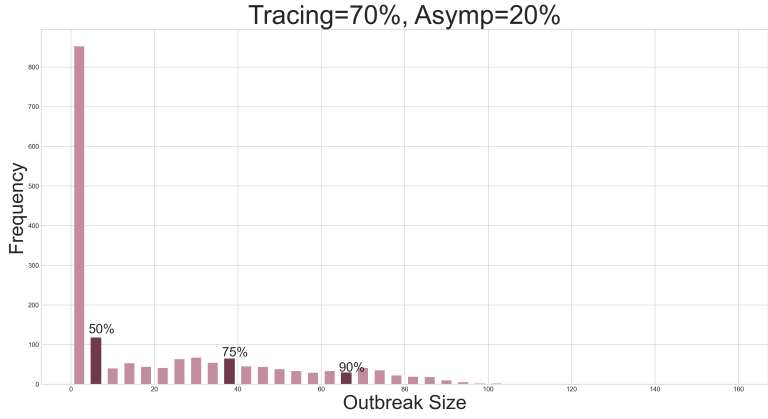
Tracing=70%, Asymp=20%
Frequency
Outbreak Size
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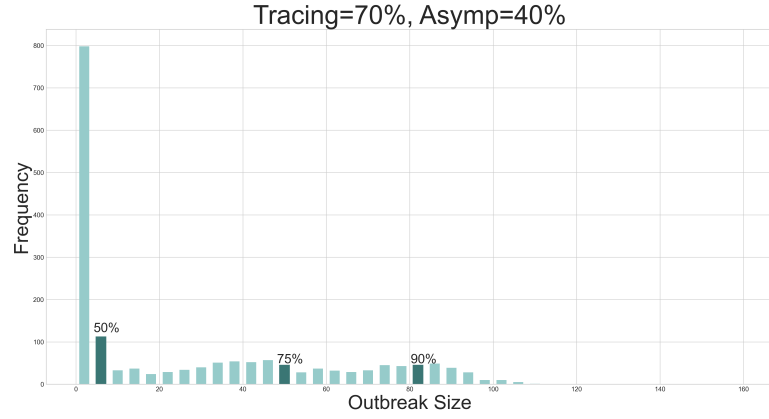
75%
90%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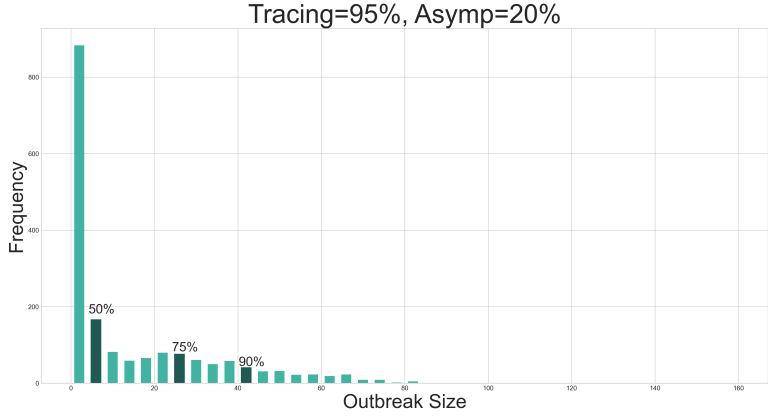
Tracing=95%, Asymp=20%
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50%
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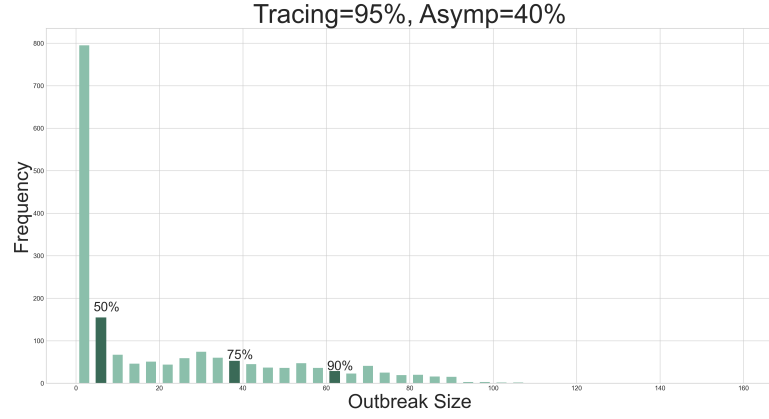
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Simulation Results 2: Testing Strategy

Quarantine Direct Contacts, Testing 2nd,3rd degree contacts every 3 days

Scenario		Outbreak Size	Quarantine	Test
App Proportion	Asymptotic			
0%	20%	34.0678	0	28.4478
70%	20%	20.5928	58.1444	71.8978
95%	20%	13.1806	63.3756	100.497
0%	40%	38.0956	0	23.5056
70%	40%	25.5811	57.8872	72.089
95%	40%	17.608	70.0633	107.149
0%	60%	44.7022	0	18.3
70%	60%	32.4928	54.1961	66.5139
95%	60%	25.005	72.1194	107.991

40% Asymptotic: App reduces infections by 53%

Explanation of Why Previous Conclusion is True: Tracing with Hypothetical 70%, Followup Test degree 2,3 contacts

Scenario		Outbreak Size	Quarantine	Test
App Proportion	Asymptotic			
0%	20%	33.9039	0	28.1376
70%	20%	15.9594	34.4244	45.5867
95%	20%	9.5561	34.2633	62.505
0%	40%	39.205	0	24.3522
70%	40%	22.1178	39.5294	49.2111
95%	40%	12.3272	36.7378	63.9978
0%	60%	45.428	0	18.6872
70%	60%	28.565	38.1172	45.0906
95%	60%	18.6328	42.7967	67.372

40% Asymptotic: App reduces infections by 68%

Conclusion

- Digital Contact Tracing can reduce infections by 46%
- Testing degree 2 and 3 contacts cannot be relied on as a method for identifying individuals to test

Future work

- Delayed testing of degree 2 and 3 contacts
- Simulations on larger networks
- Testing individuals every few days

Key References

- He, X., Lau, E.H.Y., Wu, P. et al. Temporal dynamics in viral shedding and transmissibility of COVID-19. Nat Med 26, 672–675 (2020). https://doi.org/10.1038/s41591-020-0869-5
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- PRIMES-USA for giving me this research opportunity
- Parents who give so much support