Mathematical Modeling of Early Detection of Infectious Disease Outbreaks

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Problem

- **Current surveillance systems cannot detect new outbreaks in real time with low false positives**
  - **Art of surveillance remains disconnected from the science of infectious disease dynamics**
- **Goals of the technology**
  - **Detect outbreaks in hours to days**
  - **Focus limited resources in critical areas**
  - **Mitigate deadly consequences of biothreats and naturally occurring outbreaks**

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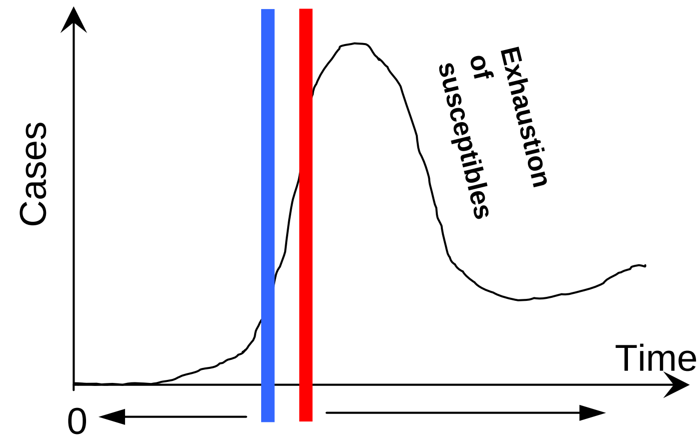
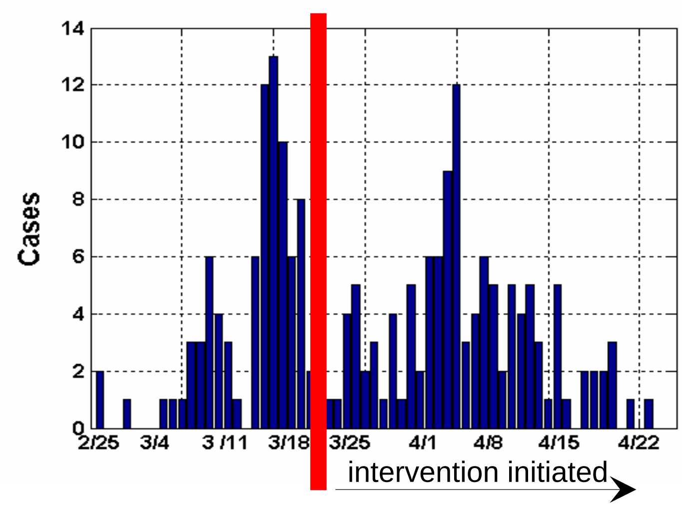
Background

- CDC defines surveillance as "the ongoing, systematic collection, analysis, interpretation, and dissemination of health related data to reduce morbidity, mortality and to improve health."
  - Real-time data
    - Time lag of minutes
    - Real-time hospital admission data acquisition is in place in major cities
  - Real-time interpretation
    - Time lag of hours to days – communicable diseases
    - State of the art in detection is primitive – high false positives

Early Detection of Outbreaks



Number of SARS Cases in Singapore 2/25/03-4/22/03[1]



[1]Source: Science, May 2003

Objectives

- Develop mathematical and computational models for early detection of infectious disease outbreaks
- Coordinate with the Harvard Medical School (HMS) and its affiliated hospitals to manage, integrate, and test models against real datasets
- Transition models to AEGIS, a real-time surveillance system being developed at the Children's Hospital Boston (CHB)
- Transition new technology to DHS, HHS, DoD, IC

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Activities

- **Transients in Time (FY 05)**
  - Develop temporal models of early detection, apply models to time series data, validate, and transition models to AEGIS
- **Transients in Time and Space**
  - Develop spatio-temporal models of early detection, apply to spatio-temporal data, validate, and transition models to AEGIS
- **Transients in Time, Space, and Social Networks**
  - Develop socio-spatio-temporal models of early detection, apply to social network data, and transition models to AEGIS

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Highlight

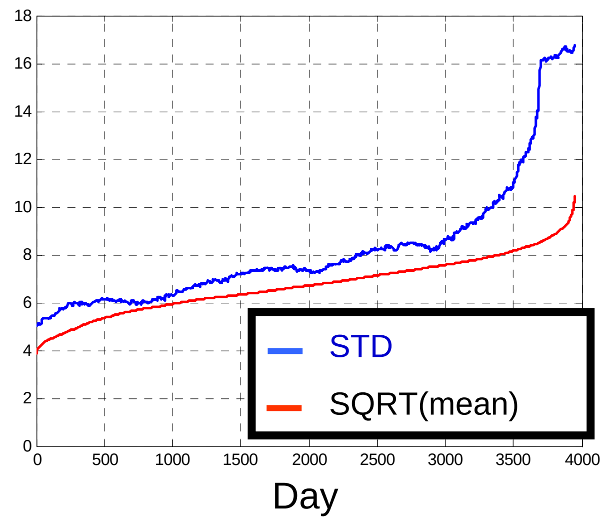
Nonstationary Binomial Model of Detection

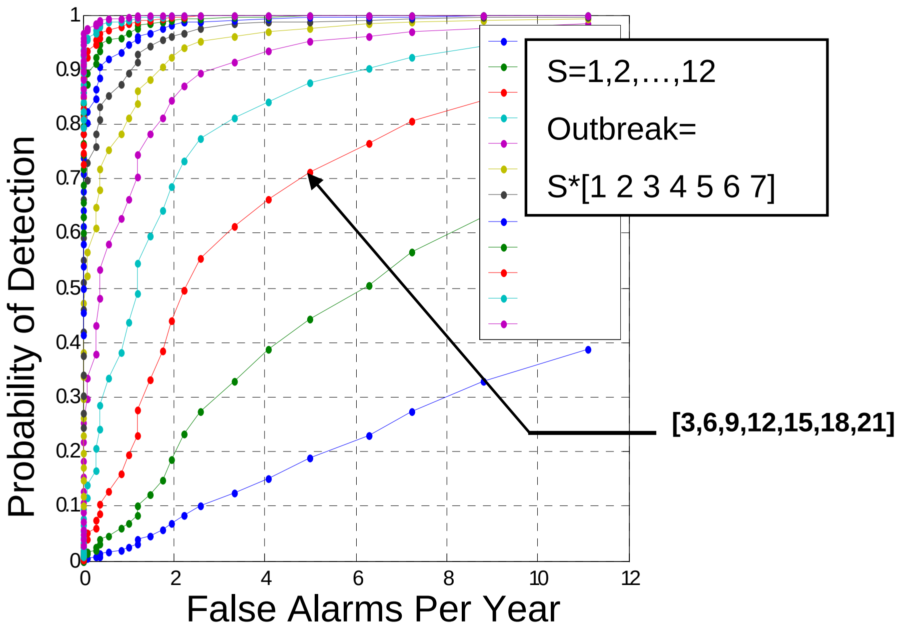
Binomial sampling theory

$$\mu(t) : mean$$

$$\sigma^2(t) = \mu(t)\left(1 - \frac{\mu(t)}{N}\right)$$

- **Apply Likelihood Ratio Test to develop Constant False Alarm Rate detector. Resulting test is Uniformly Most Powerful for linear outbreak shapes.**





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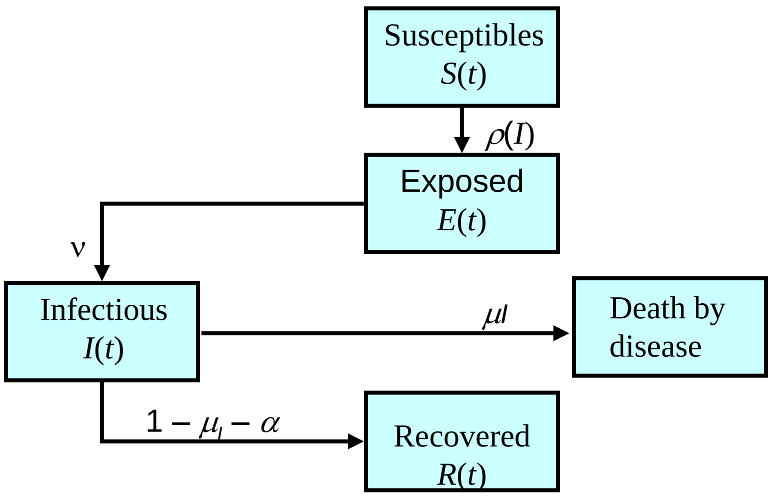
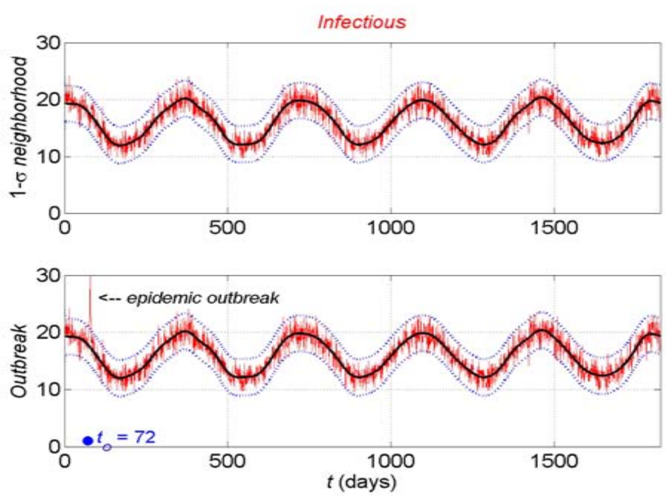
Highlight

Stochastic SEIR Model of Detection





$$\frac{dS}{dt} = -\rho(I)S(t) \equiv -\beta I(t)S(t)$$

$$\frac{dE}{dt} = \rho(I)S(t) - \nu E(t) \equiv \beta I(t)S(t) - \nu E(t)$$

$$\frac{dI}{dt} = \nu E(t) - \mu_I I(t) - (1-\mu_I-\alpha)I(t)$$

$$\equiv \nu E(t) - (1-\alpha)I(t)$$

$$\frac{dR}{dt} = (1-\mu_I-\alpha)I(t)$$

System Model: $\frac{d\mathbf{X}(t)}{dt} = A\mathbf{X}(t) + \mathbf{w}(t)$

***System Noise Covariance*:** $Cov[\mathbf{w}(t)] \equiv Q(t)$

***Measurement*:** $m(t) = \hat{I}(t) \equiv H\mathbf{X}(t)$

***Measurement model*:** $m(t) = H\mathbf{X}(t) + \mathbf{v}(t)$

***Measurement Jacobian*:** $H = [0,1]$

Measurement Noise Covariance: $Cov[\mathbf{v}(t)] \equiv V(t)$

***System error* :** $\mathbf{w}(t) \sim N(0, Q(t))$

***Measurement error* :** $v(t) \sim N(0, V(t))$)

Impact

Biodefense

- Strengthens biosecurity
- Saves lives (military and civilian)
- Reduces cost of post-epidemic management
- Reduces economic loss in productivity
- Improves public health surveillance both in the short term and long term (HHS, CDC, WHO)

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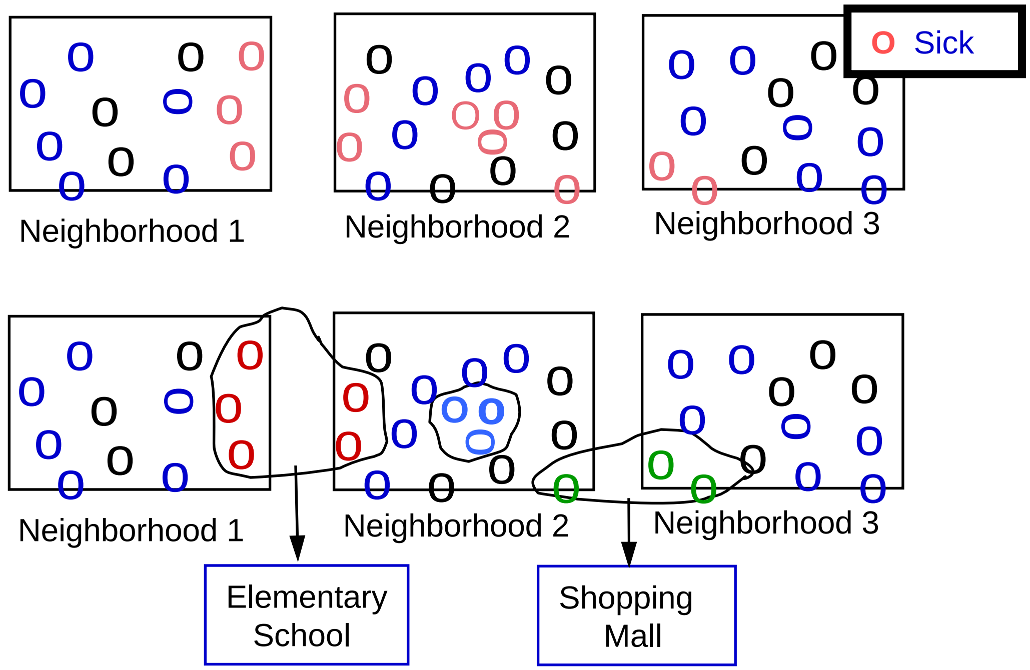
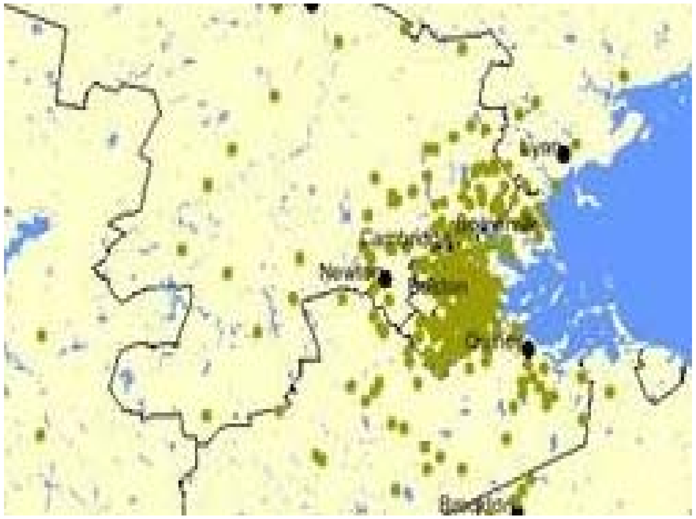
- Opportunity to model real data and validate models against real data
- Collaborations with leading academic and medical institutions
- Enhances MITRE expertise and leadership in disease modeling and surveillance

Future Plans

Signatures of social contacts are embedded in spatial data!





Currently there are no surveillance techniques for interpreting patient geographic data.

Source: Children's Hospital Boston

Transients in Time, Space, and Social Networks

Develop social network models of spread of disease for early detection, apply to social network data, validate, and transition models to AEGIS.

Transients in Time and Space

Develop spatio-temporal models of early detection, apply to spatio-temporal data, validate, and transition models to AEGIS.

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