Mathematical Modeling of Early Detection of Infectious Disease Outbreaks

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MSR

MITRE Technology Program

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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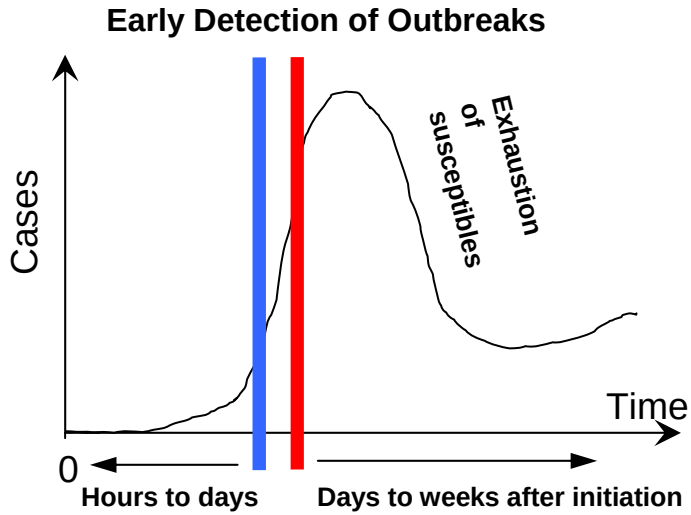
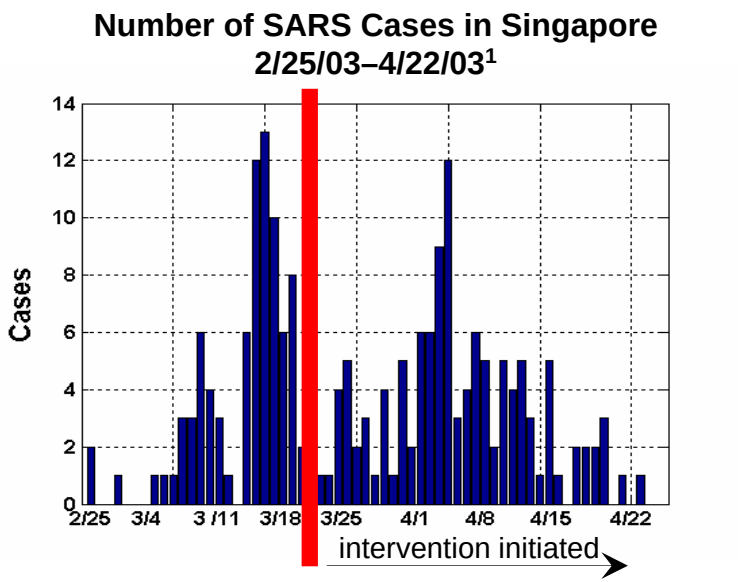
Background

- 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





[1]Source: Science, May 2003

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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 HIPAA-compliant real datasets
- Transition models to real-time surveillance systems
- Transition new technology to MITRE's sponsors

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Activities

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

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Highlight

Multi-Syndromic Analysis of Transients

$\mathbf{X}_{n \times m}$: n **observations** (samples), m **variables,** $n > m$

$\mathbf{X} = \mathbf{t_1 p'_1} + \mathbf{t_2 p'_2} + \ldots + \mathbf{t_k p'_k}, \quad \mathbf{k} \leq \min\{m, n\}$

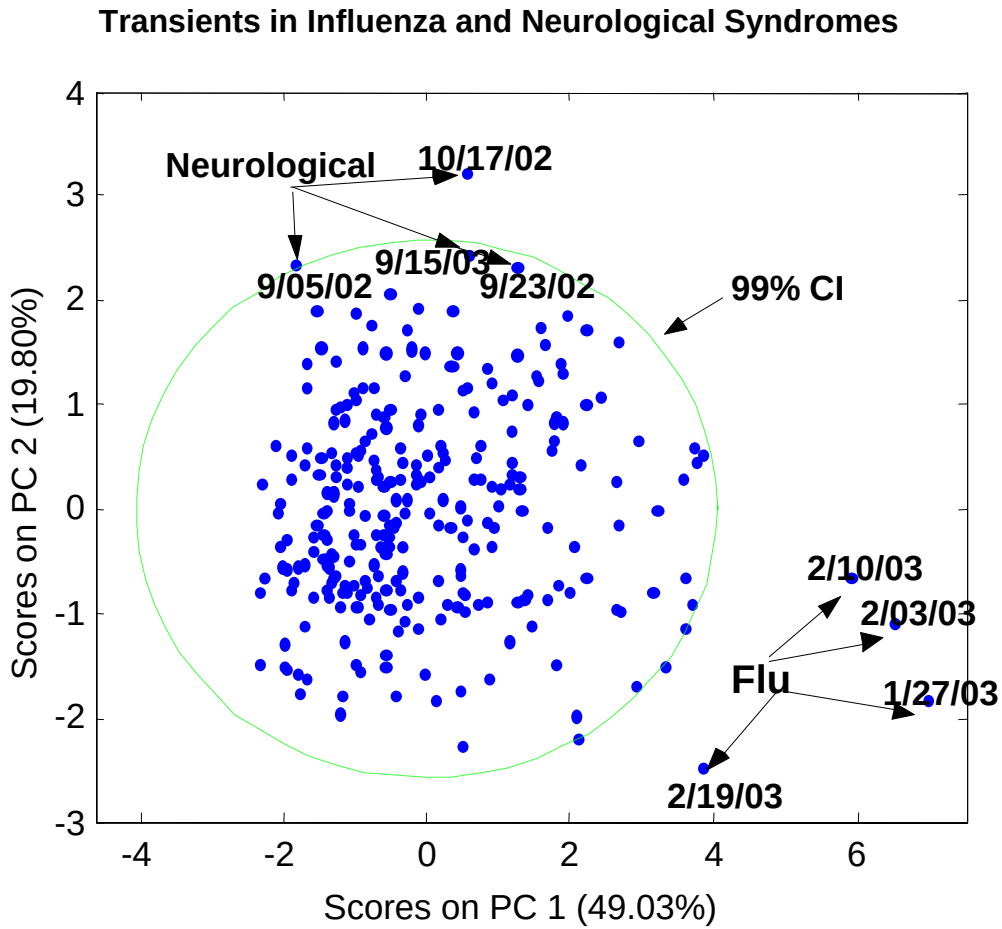
$\mathbf{p_i}$: eigenvectors of the covariance matrix

$\mathbf{t_i}$: vector of scores on principal component **i**

$\mathbf{X p_i} = \mathbf{t_i}$ (projection of **X** onto the $\mathbf{p_i}$)

$\mathbf{t'_i t_j} = 0, \quad i \neq j$ (orthogonal)

$\mathbf{p'_i p_j} = 0, \quad i \neq j$ (orthonormal)



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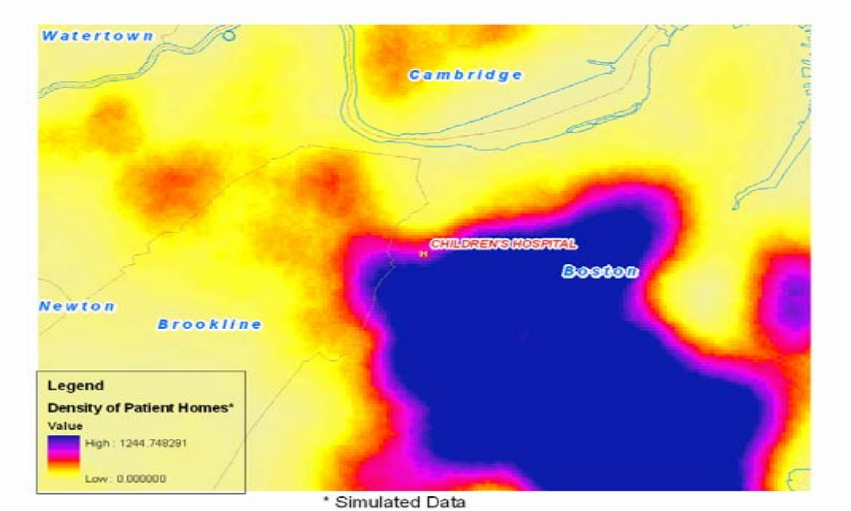
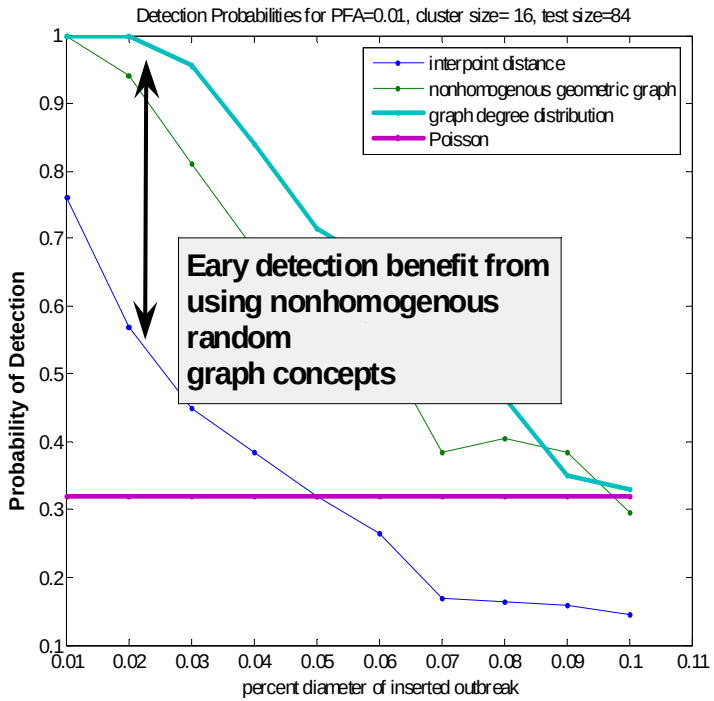
Highlight

Spatial Detection Based on Random Geometric Graphs

- **Approach:**
  - Choose a time window
  - Choose a set of interpoint distance thresholds $d_1<d_2<\ldots<d_n$
  - For each interpatient distance d_k, F_k=fraction of interpoint distances <= d_k
  - This cumulative distribution vector is the test statistics
  - Historical data is used to calculate thresholds



Population catchment area of Children's Hospital, Boston



$$S = \left(\vec{D} - E(\vec{D})\right)' COV(\vec{D})^{-1} \left(\vec{D} - E(\vec{D})\right)$$

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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

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

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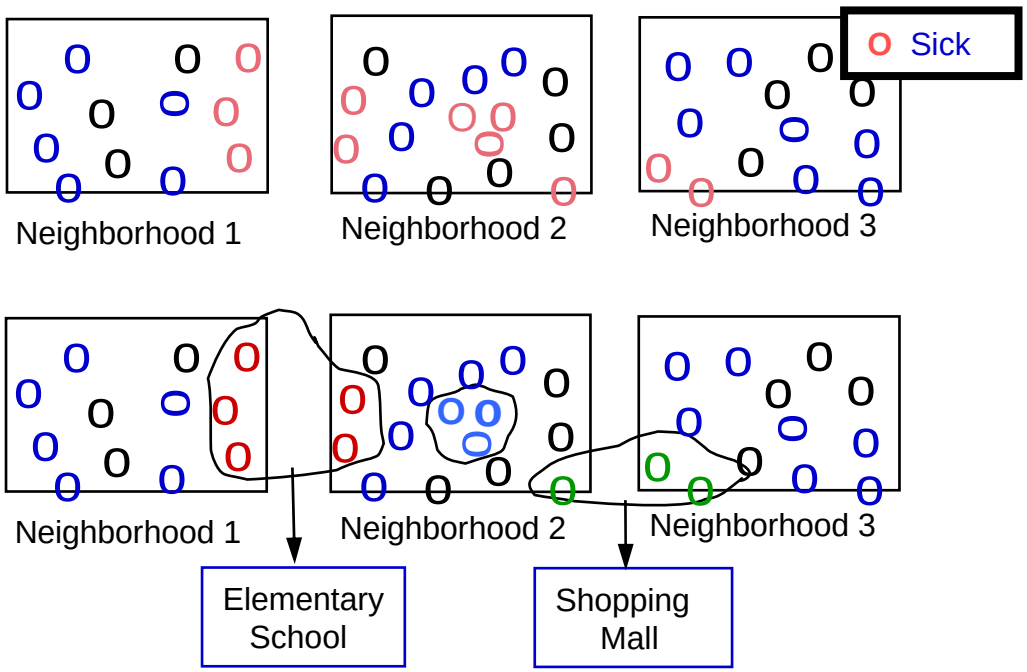
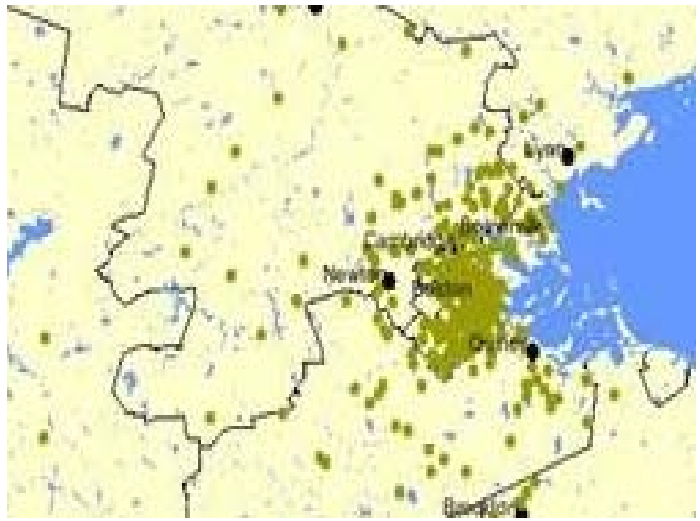
Future Plans

Signatures of social contacts are embedded in spatial data!





Source: Children's Hospital, Boston

Transients in Time, Space, and Social Networks

Develop social network models of spread of disease, apply to HIPAA-compliant social contact data from public health communities, and transition to real-time surveillance systems

Transients in Time and Space

Develop spatio-temporal models of early detection, apply to HIPAA-compliant data, validate, and transition to real-time surveillance systems

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