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A Complex Adaptive Systems Modeling Framework for Public Health Action

Exemplified by the Veterans Affairs Modeling Object Oriented Simulation Environment

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Modeling for Public Health Action: From Epidemiology to Operations
Centers for Disease Control and Prevention
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Many Examples of CASoS

- Tropical Rain forest
- Agro-Eco system
- Cities and Megacities (and their network on the planet)
- Interdependent infrastructure (local to regional to national to global)
- Government and political systems, educational systems, health care systems, financial systems, economic systems and their supply networks (local to regional to national to global)… Global Energy System and Green House Gasses

Why Public Health is a CASoS

Public health systems are

- ***Complex*** due to the large number of interdependencies and non-linear interactions among autonomous agents, such as individuals, health care organizations, and governmental agencies
- ***Adaptive*** in that the behaviors of individuals, organizations, and diseases are highly responsive to the behaviors of other such agents, as well as to hazards and natural disasters
- ***System-of-systems*** structure is evident in their ability to be recursively decomposed into collections of interacting components, generally to an arbitrarily low level of detail

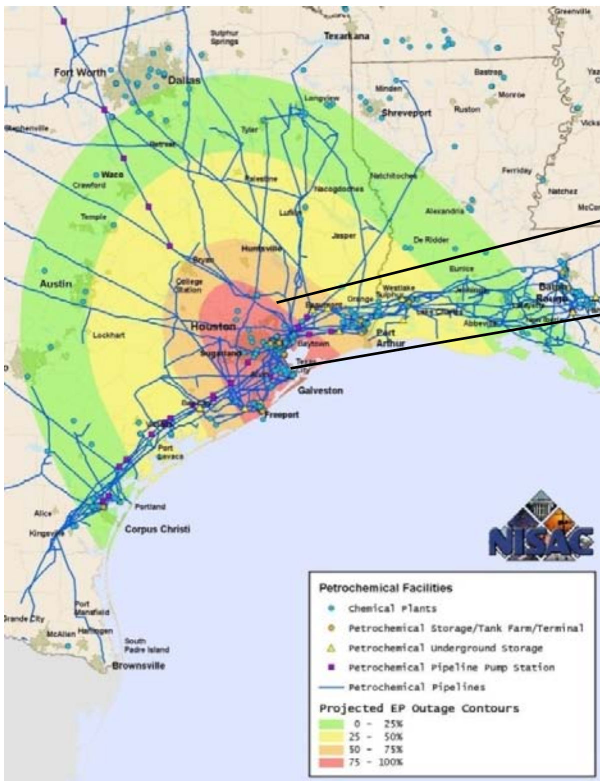
Ultimately, designed solutions (public health care actions) must be shown to be robust to the uncertainties inherent within the CASoS.

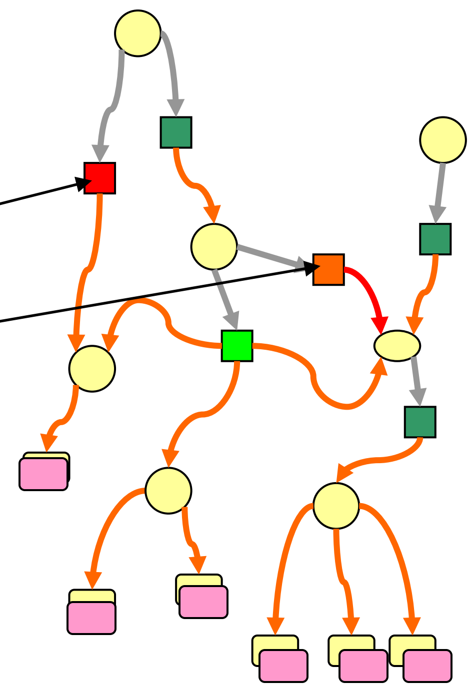
In a CASoS such as the VHA…

Everything is connected
skilled workers-utilities-transportation-structures-supplies-emergency services

In a threat like a hurricane, if components are disrupted…

Reduced health care capacity





Increased morbidity
Decreased preventive services
Diminished health status

Aspirations

- To develop a CASoS modeling framework for public health action built on an object-oriented, agent-based conceptualization of a health care system.
- Support analysis of a wide variety of scenarios, policy options, scales of system realization, and various or mixed levels of fidelity.
- Evaluate the effectiveness of public health actions to a wide variety of imposed threats (such as natural disasters, epidemics, acts of war, or a changing patient population mix).
- Embed sophisticated sensitivity and uncertainty quantification techniques to enable selection of the policy options most robust to a diversity of threats and model assumptions, and to determine the requirements for the chosen policy actions to be most effective.

A Conceptual Lens for CASoS Modeling

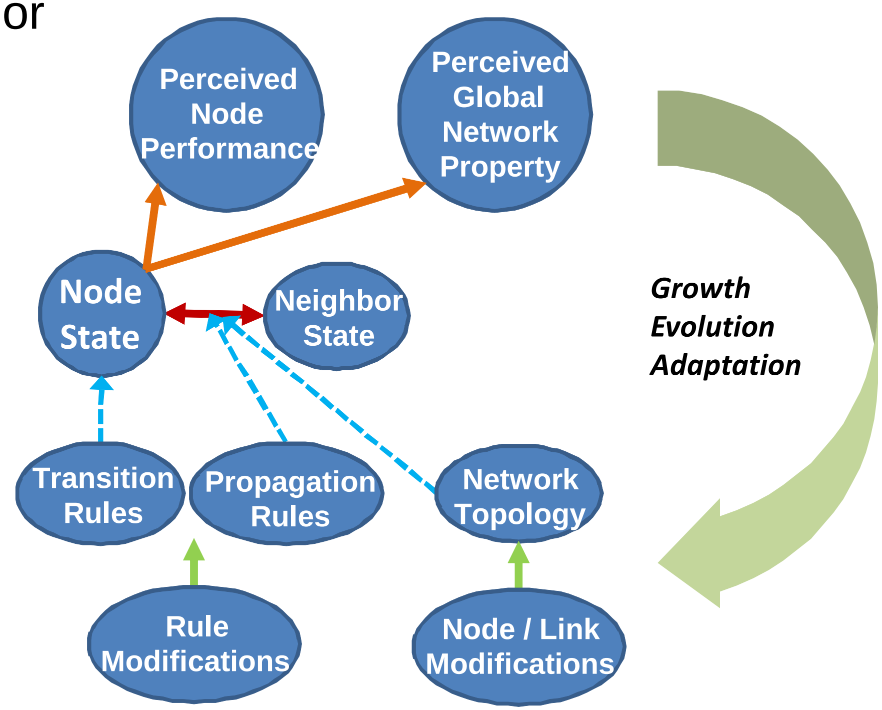
Take any system and abstract as:

- Nodes (with a variety of "types")
- Links or "connections" to other nodes (with a variety of "modes")
- Local rules for Nodal and Link behavior
- Local Adaptation of Behavioral Rules
- "Global" forcing, Local dissipation

Connect nodes appropriately to form a system (network)

Connect systems appropriately to form a System of Systems

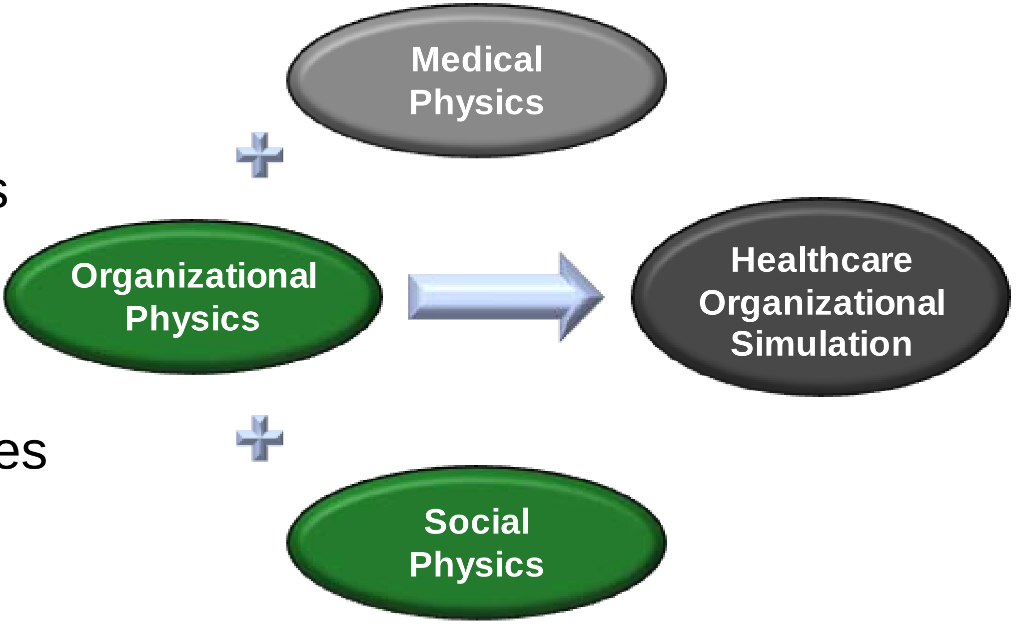
Lumped to discrete
System dynamics to agent-based
Infinite to Finite State machines
Hybrid



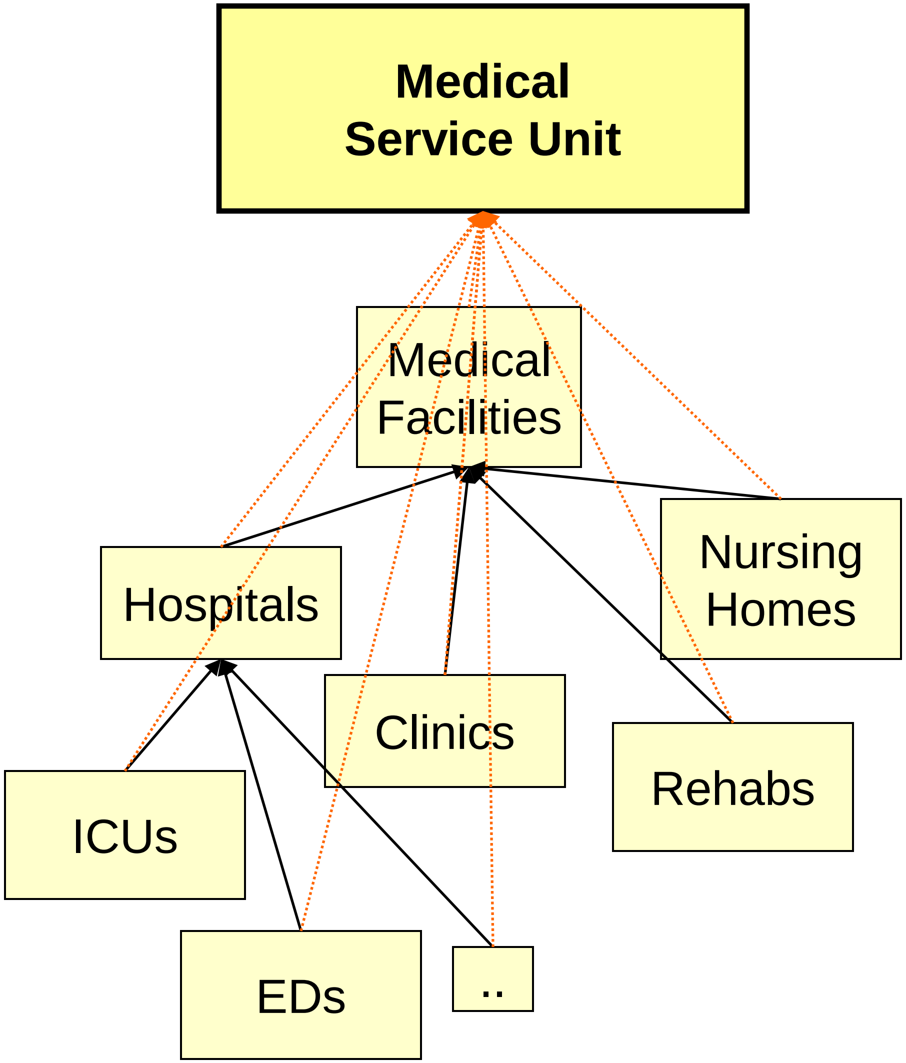
CASoS Engineering

Fundamental Categories of Process

- Medical Physics
  - Diseases and treatments
  - Labor, resources
- Organizational Physics
  - Distinction between MSUs
    - Capacity
    - Capabilities
    - Resources
  - Resource allocation policies
    - Initial
    - Dynamic
- Social Physics
  - Mood contagion in social networks
  - Social components of lifestyle associated diseases
  - Dissemination of practice



Fundamental building block for Health Care Facilities



We've defined a **Medical Service Unit** (MSU) as a generic model for any location where some kind of medical service is provided.

It can be applied at a large scale (to represent an entire hospital for example) or at a small scale (to represent an individual ICU station), and ***may be nested***

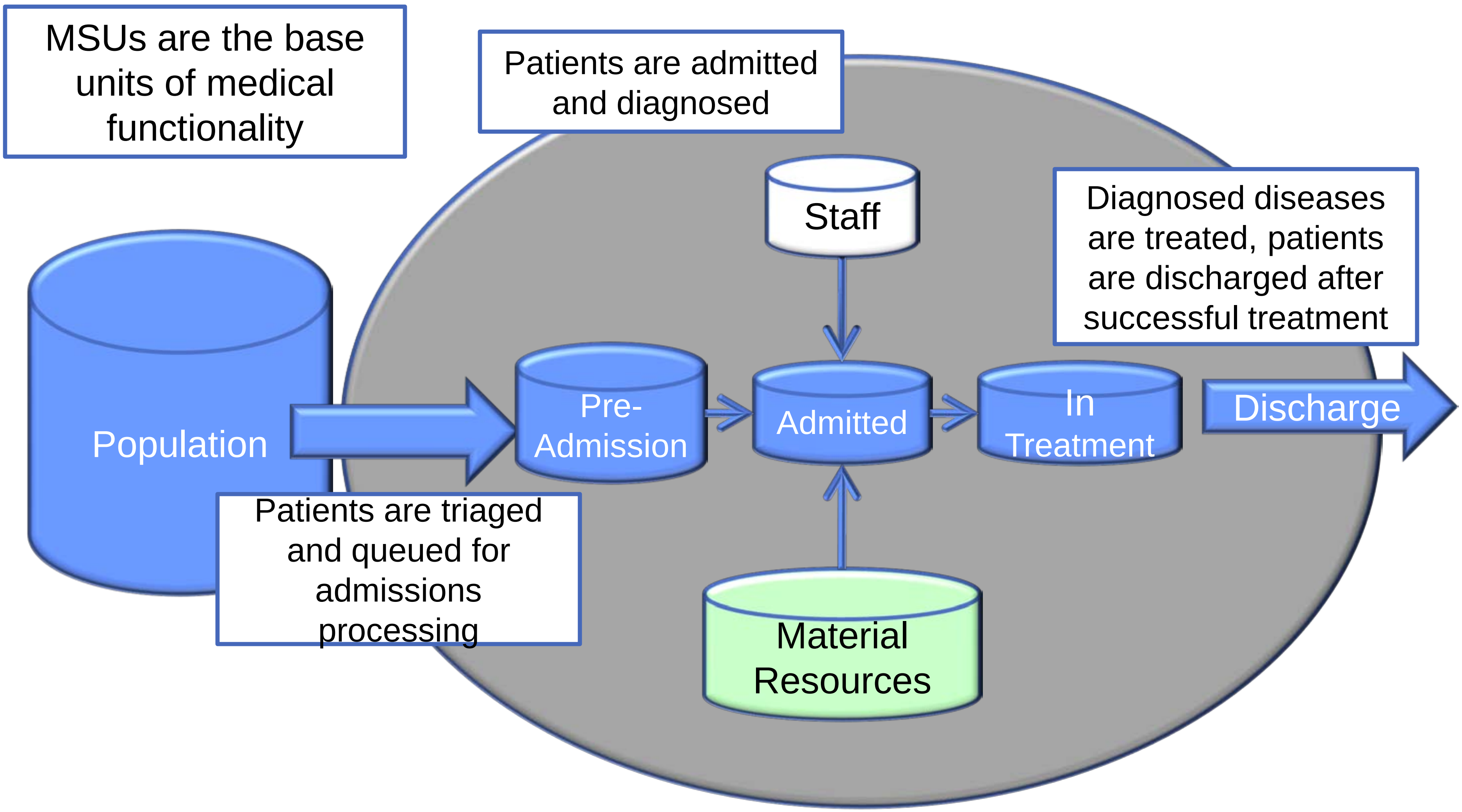
Demonstration Problems

A network of healthcare facilities is subjected to two types of surges in demand:

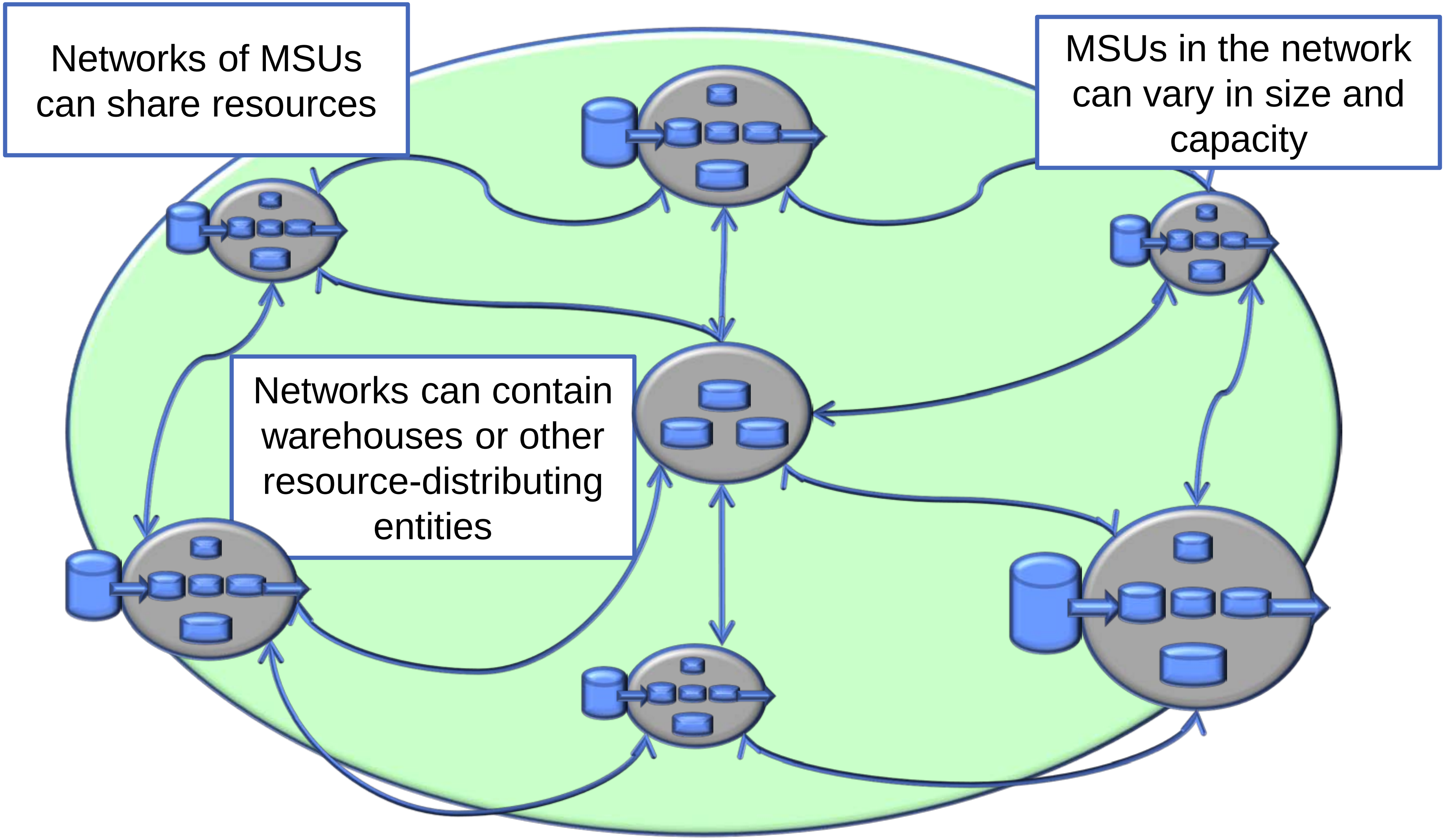
1. a spike, representing a natural disaster which introduces patients with acute trauma requiring immediate treatment
2. a steady increase in demand imposed by the increasing prevalence of hepatitis C, which can result in a population with a significantly increased burden of end-stage liver disease and hepatocellular carcinoma.

We consider policy actions that are medical center-level focused and network-level focused

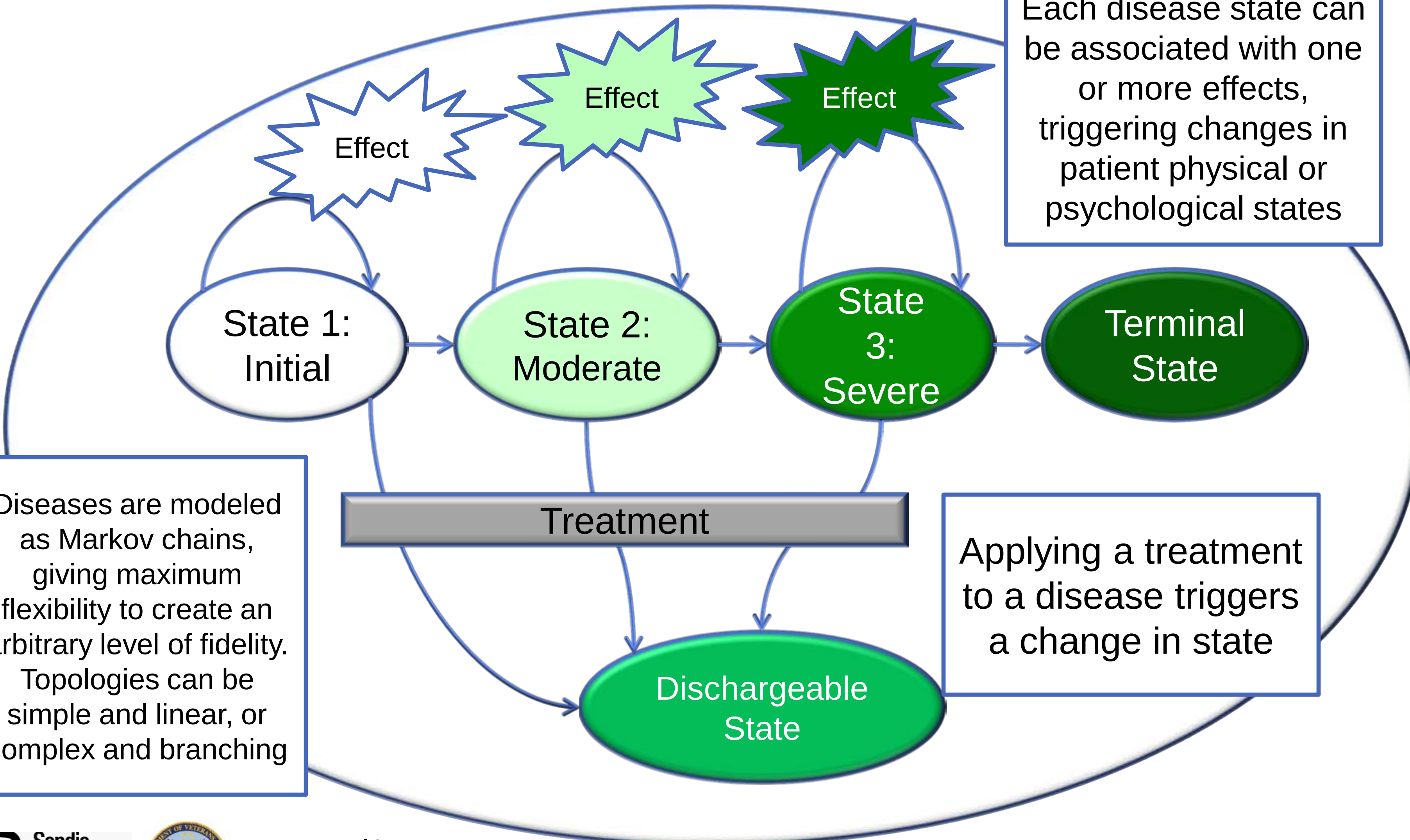
Individual MSU Configuration



MSU Networks



Disease Representation

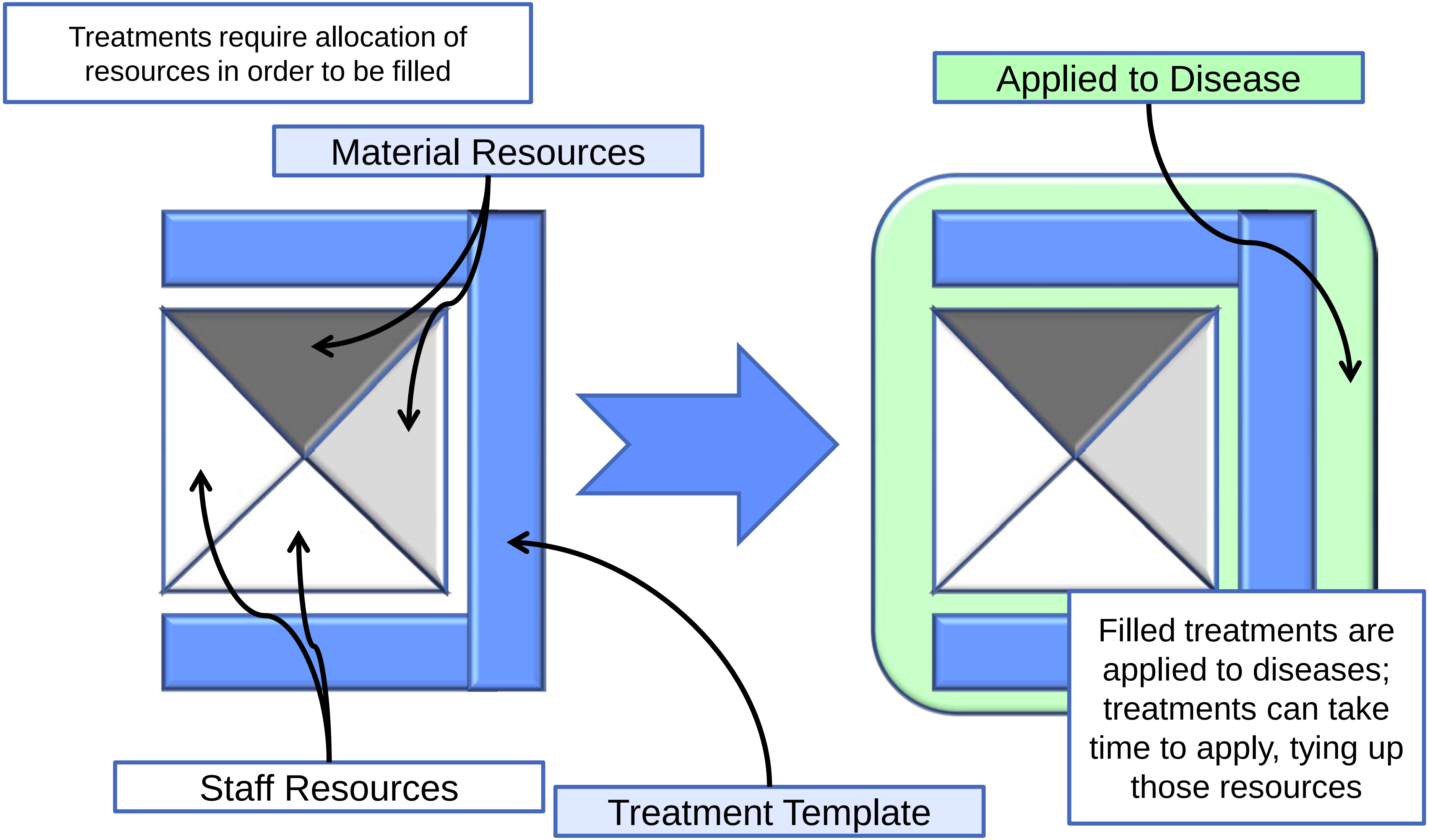


Each disease state can be associated with one or more effects, triggering changes in patient physical or psychological states

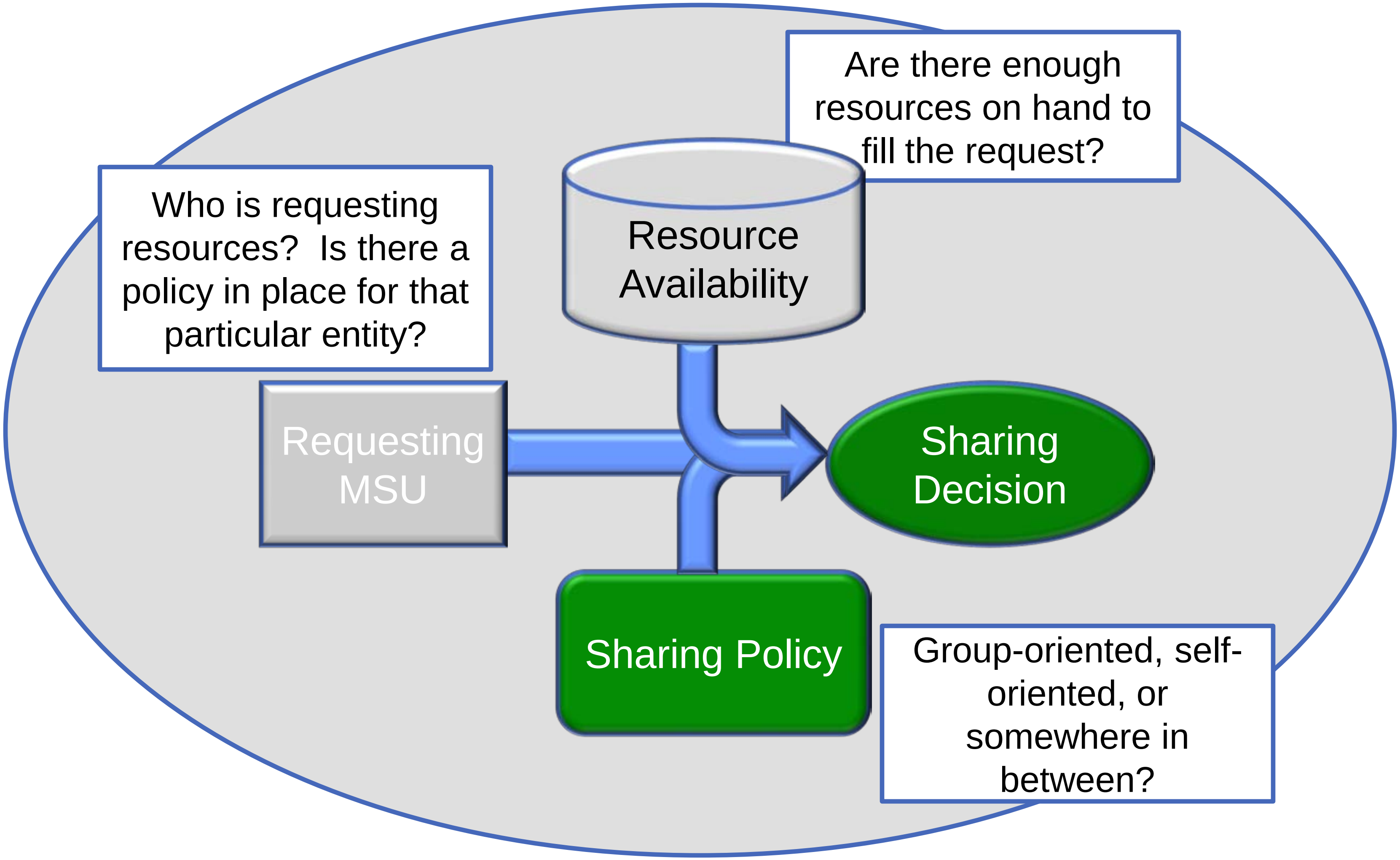
Diseases are modeled as Markov chains, giving maximum flexibility to create an arbitrary level of fidelity. Topologies can be simple and linear, or complex and branching

Applying a treatment to a disease triggers a change in state

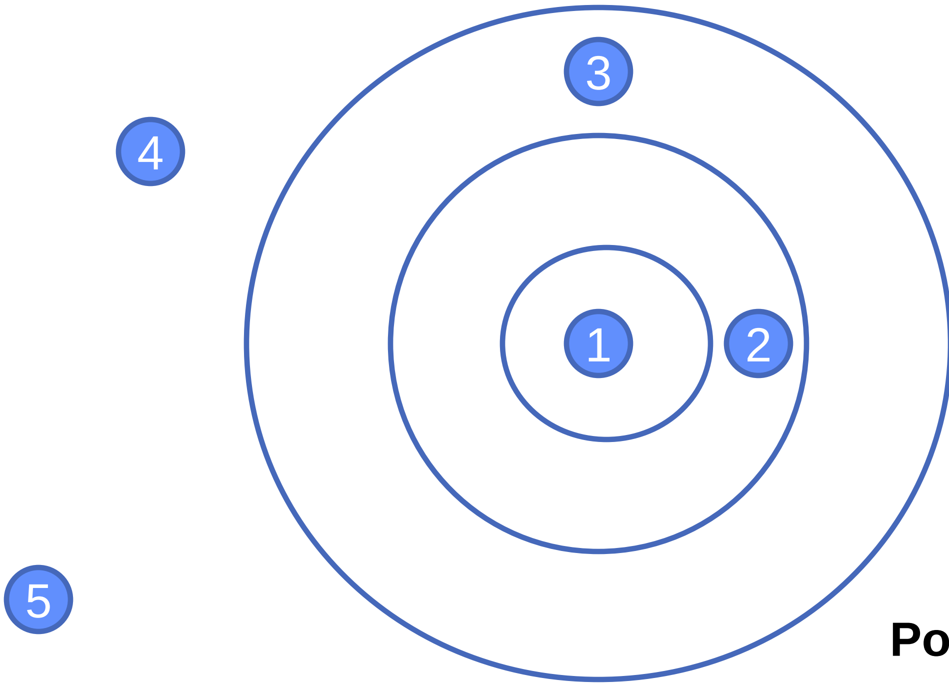
Treatment Representation



Policies for Resource Dynamics



Spike Problem Configuration



Scenario:
- Network of MSUs
- Spike (earthquake) centered at one MSU
- Multiple aftershocks
- Damaged MSU is shut down
- Some MSUs unaffected

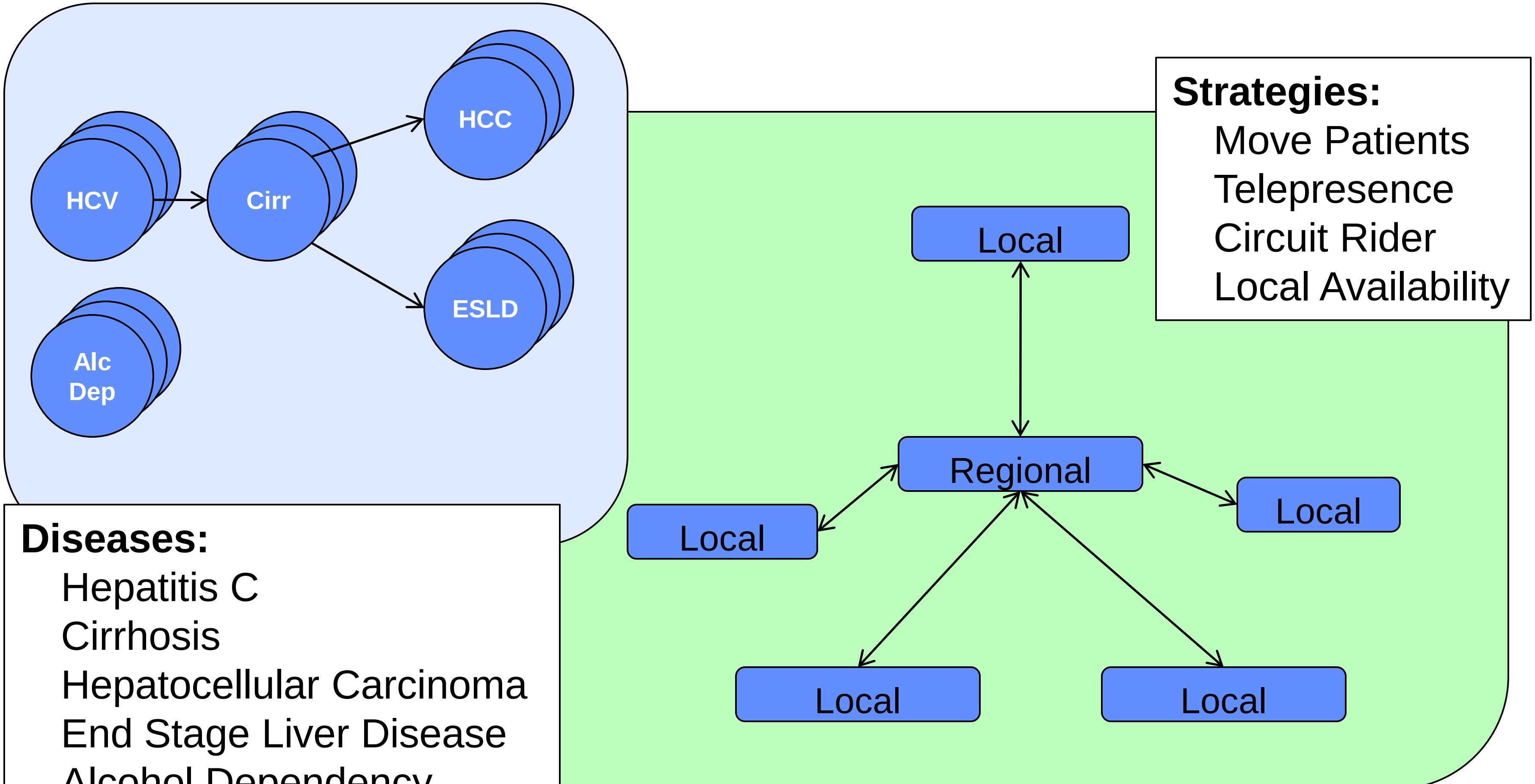
Policies:
- Trigger for expansion of capacity
- How many times to expand capacity, and how much to expand
- Trigger for transfer of waiting patients
- Selection of patient transfer location
  - -Nearest neighbor
  - -Furthest neighbor (outside spike effect zone)

Strategies:
- Expand capacity
- Transfer waiting patients
- Levels of resource sharing

Spike Results

- Key variables
  - Whether or not to expand capacity
  - Capacity expansion amount
  - Number of times to expand capacity
  - Patient transfer location selection policy
  - Response coordination and resource sharing policies
- Findings
  - “Double Spike” effect exhibited
  - Transferring patients outside of the secondary effect zone can yield better treatment results than trying to minimize transfer delay
  - Coordination and resource sharing :
    - increases robustness to perturbation
    - strongly decreases mortality resulting from severe perturbations

Hepatitis C Problem Configuration



Strategies:
- Move Patients
- Telepresence
- Circuit Rider
- Local Availability

Diseases:
- Hepatitis C
- Cirrhosis
- Hepatocellular Carcinoma
- End Stage Liver Disease
- Alcohol Dependency

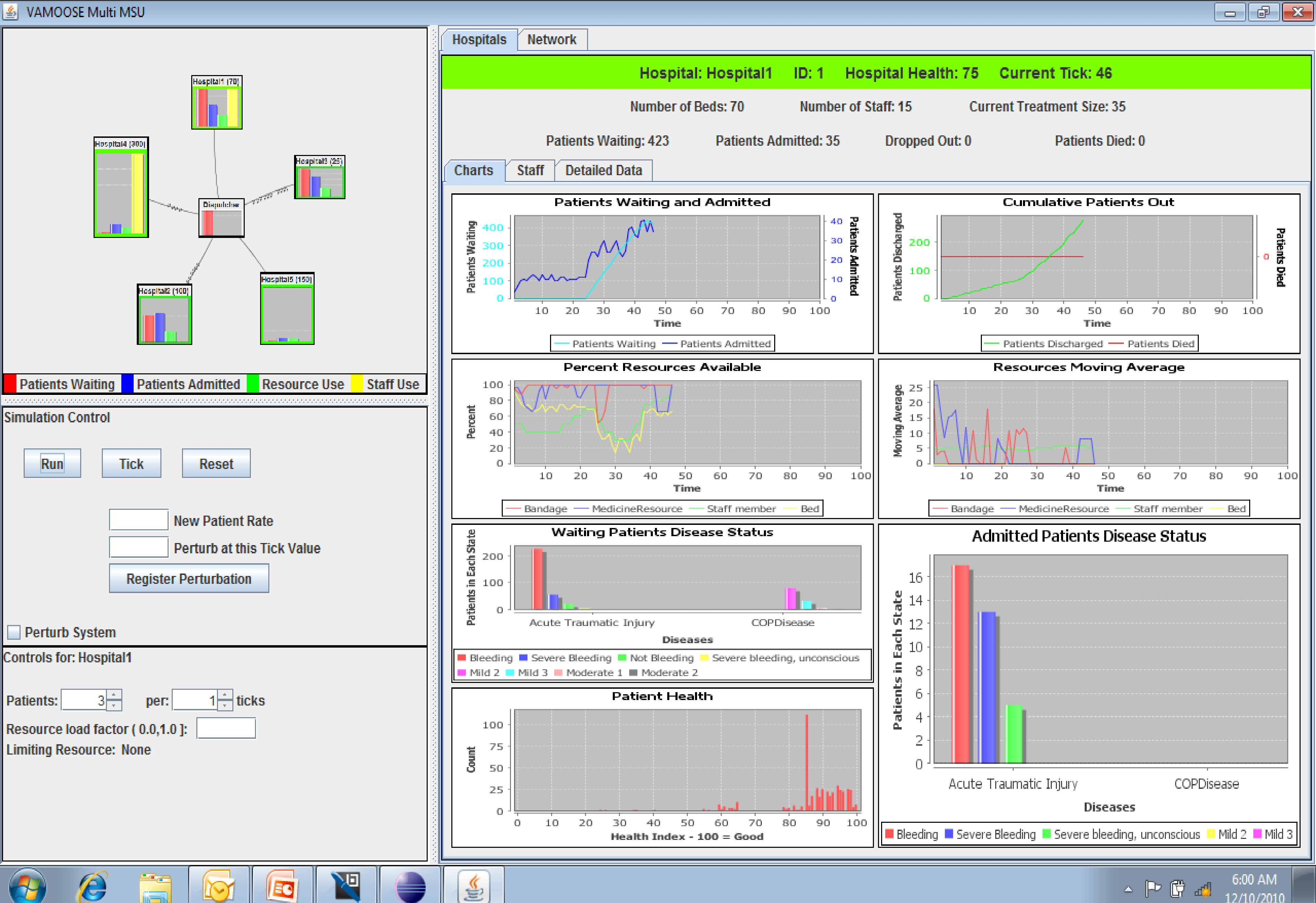
Hepatitis C Results

- Key variables
  - Population size
  - Population age (epidemiological profile)
  - Co-morbidities, disease progression rates (disease profiles)
- Findings
  - Moving patients is a reasonable strategy with limited population size
  - Telepresence extends capabilities and can multiply effectiveness of key personnel, constrained by disease severity
  - Circuit riders play a key role, constrained by local resource availability, patient load (population size)
  - Local presence becomes required for high load, advanced disease population
  - Dynamic population profiles require dynamic policies

Conclusion

- The inherent complexity and adaptivity of the public health care and the associated systems implies that there is an opportunity for general tools that consider large scale questions relating to preparedness, understanding, and system optimization
- Some sets of problems, while distinct on the surface, contain underlying common elements that can be incorporated into such tools to bring diverse sets of answers into more commensurable spaces
- These problems benefit from a strongly interdisciplinary approach, as each discipline brings new perspectives, tools, and models

Backup Slides



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Modeling for Public Health Action
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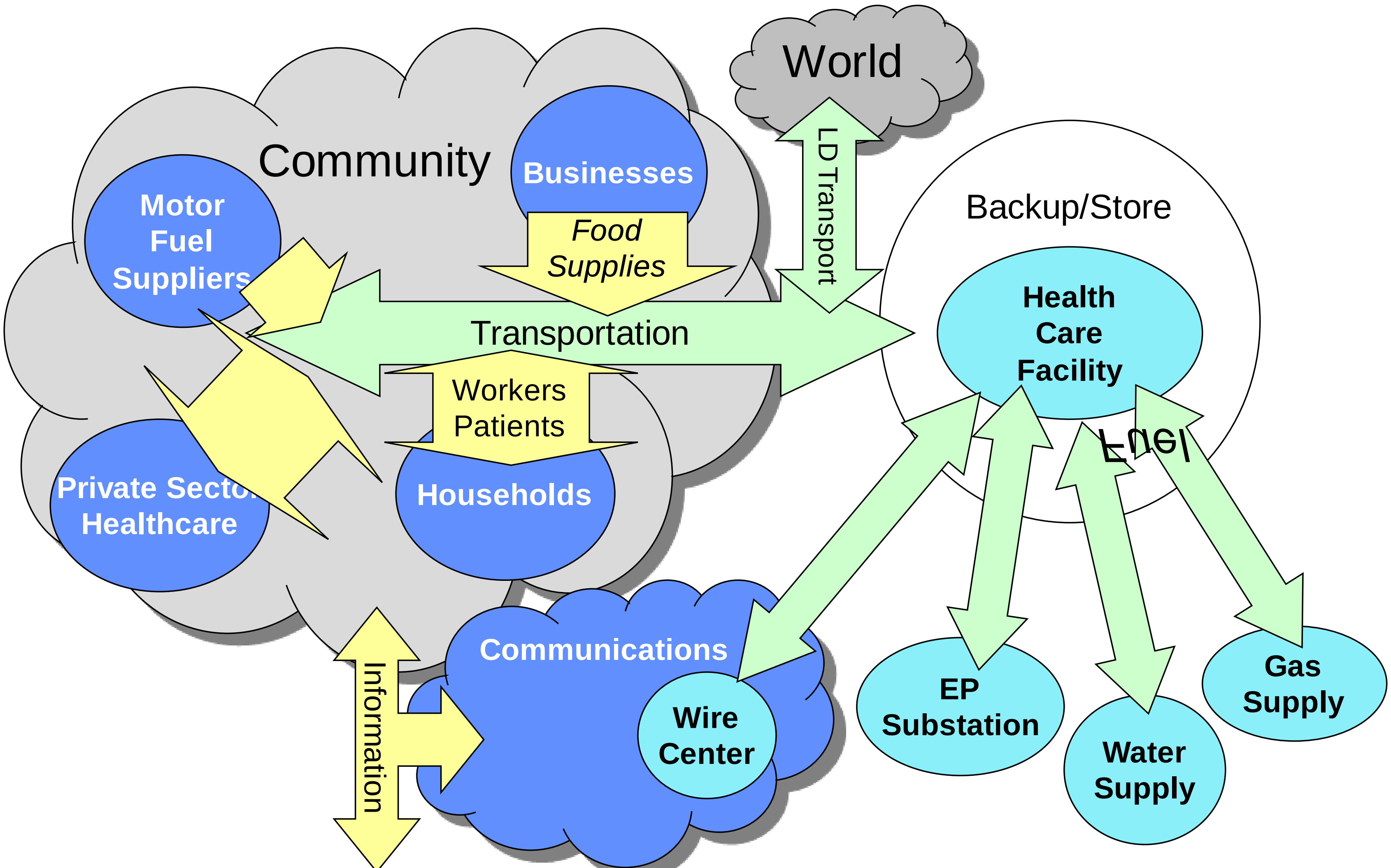
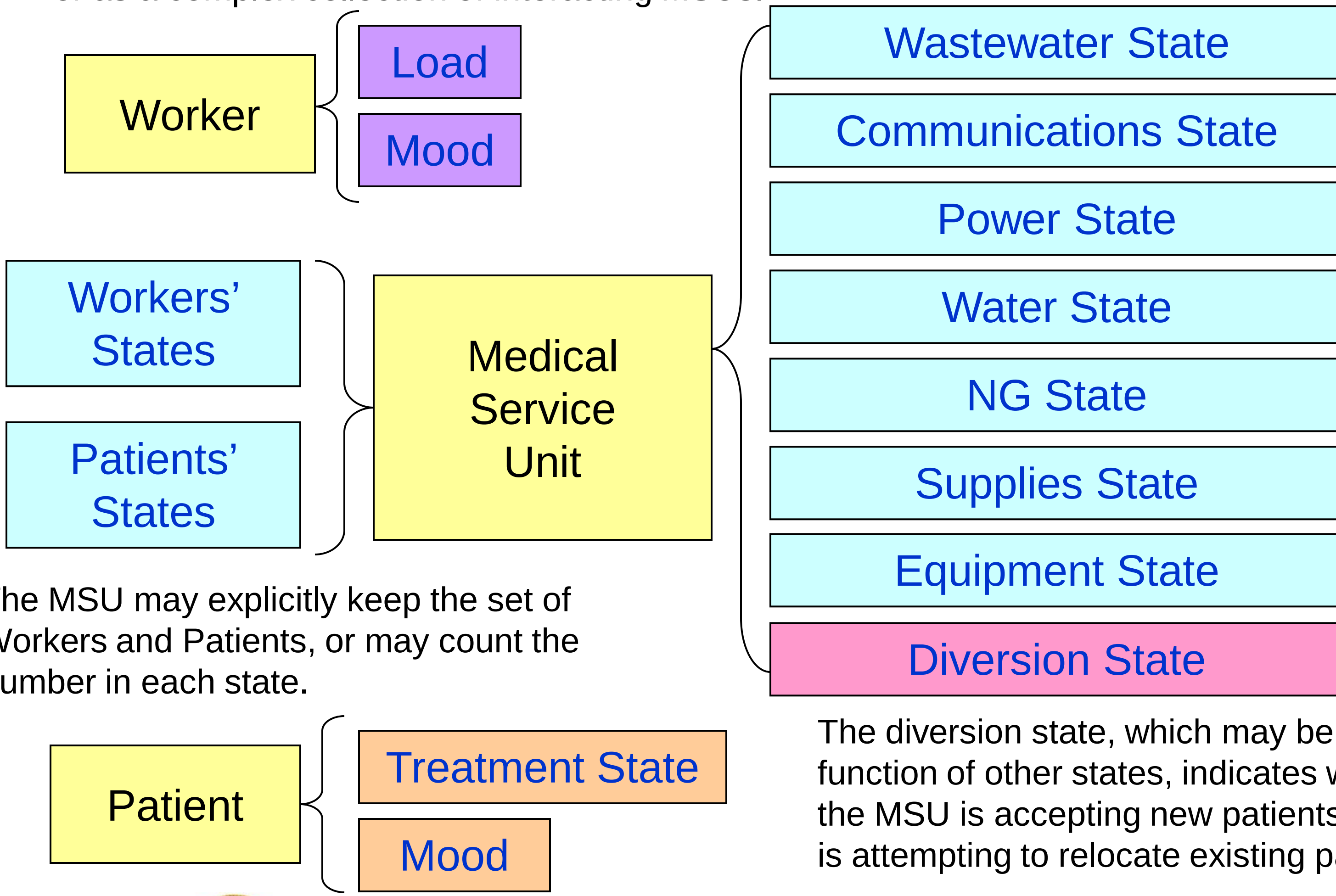
Major Entity Types, Aggregations, and Relations



CASoS Engineering

Basic Medical Service Unit - States

A Medical Service Unit (MSU) is a location at which workers (of one or more types) service patients (having one or more kinds of conditions). MSU's capture the basic processes common to many facilities at many scales. Complex facilities (hospitals) can be represented as an MSU or as a complex collection of interacting MSUs.



An MSU's infrastructure states may be defined by an embedding MSU (for example a ward's power state is determined by the hospital's power state)

The MSU may explicitly keep the set of Workers and Patients, or may count the number in each state.

The diversion state, which may be a simple function of other states, indicates whether the MSU is accepting new patients and/or is attempting to relocate existing patients

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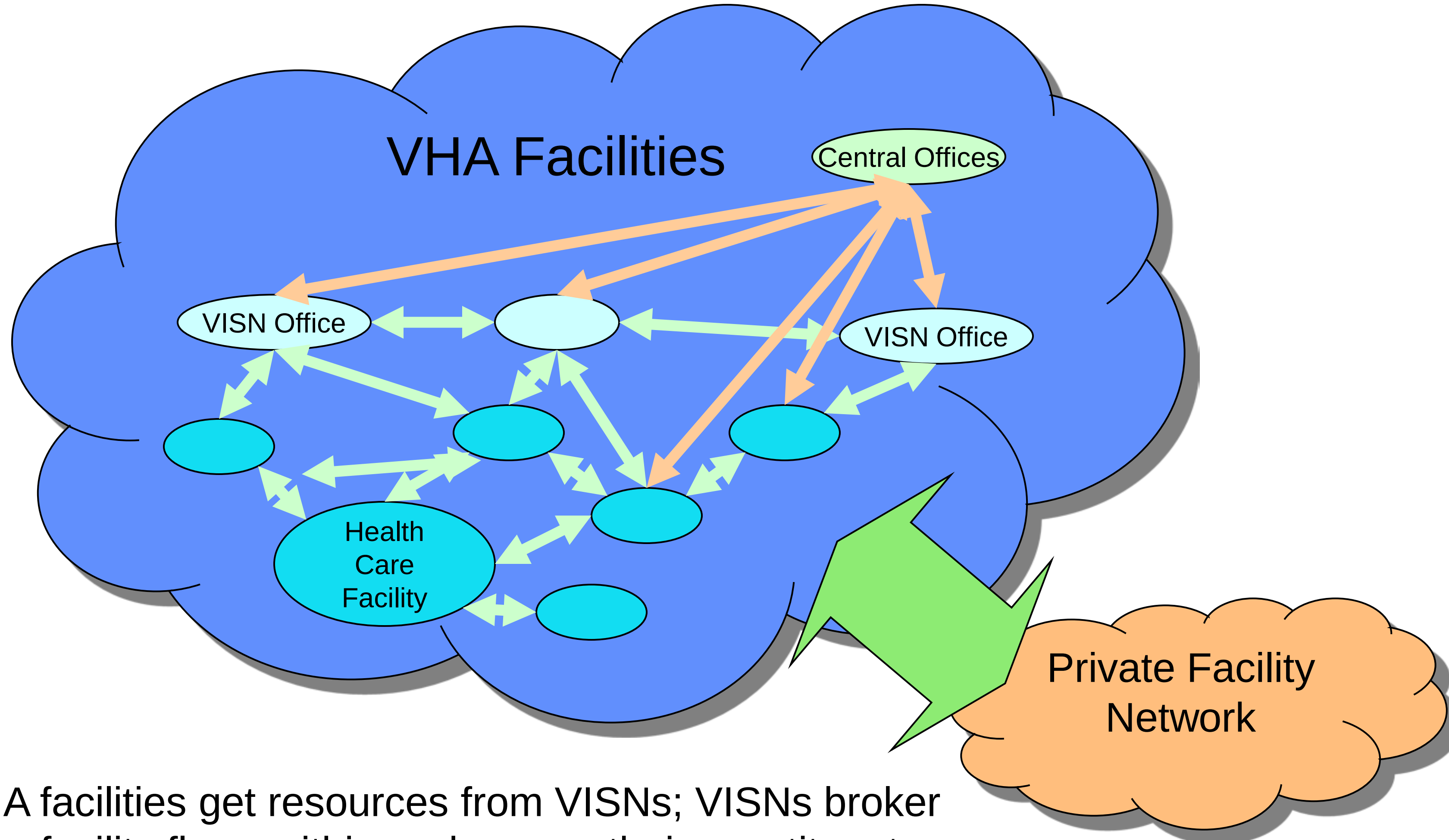
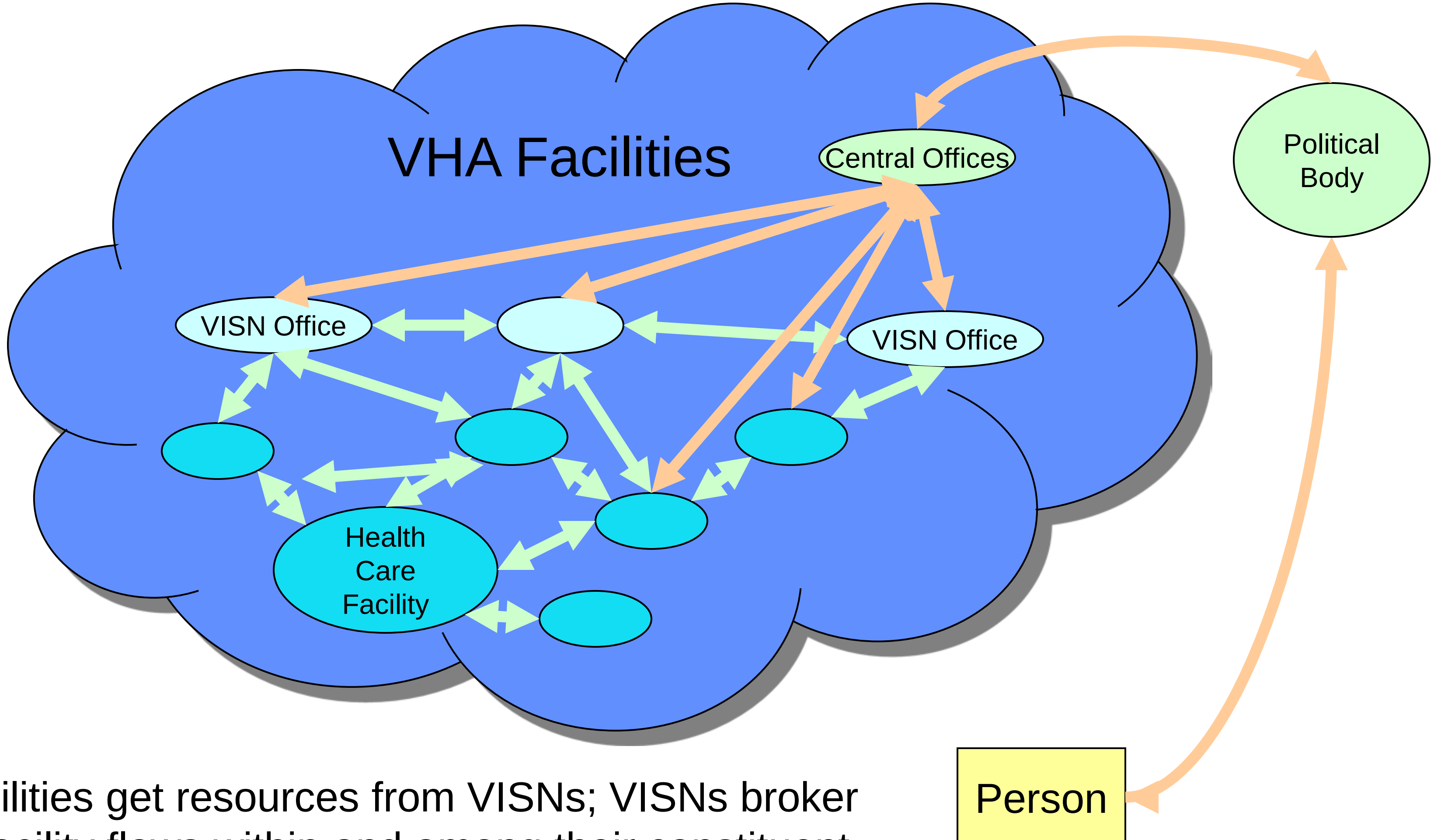
Towards a view of the complete System



VHA facilities get resources from VISNs; VISNs broker inter-facility flows within and among their constituent facilities; VHA provides funding, resources, information, and obtains status information

Political/Funding pathways



VA facilities get resources from VISNs; VISNs broker inter-facility flows within and among their constituent facilities; VHA provides funding, resources, information, and obtains status information

Problem Overview

- Local versus systemic optimization
- Resource allocation, distribution, and sharing policies
- Staffing Issues
  - Team formation
  - Workplace stress and satisfaction
- Patient-centric care

Local vs. Systemic Optimization

- In a resource constrained environment, entities exist in competition with each other
- When entities exist within functioning groups, competition between entities can detract from group-level performance metrics[4]
- Real and perceived resource constraints encourage individual hospitals to run at or above capacity, which can make individual hospitals less likely to share resources
- Local surges in demand are more difficult to address if resources cannot be efficiently reallocated, compromising network performance

Resource Policies

- Resource sharing among affiliated healthcare institutions can yield better resource utilization, greater accessibility to care, and reduced overall costs
- Lack of capacity and incompatible incentive structures combine with technical and policy-based problems restrict sharing of resources between and among institutions

Staffing Issues

- People are the VHA's most important resource
- Perceived quality of work environment affects acquisition and retention of staff
- Workload, job related stress, professional and personal work related relationships, and career opportunities can affect retention

Patient-Centric Care

- Informed, engaged and empowered patients
- Care focused on needs and desires of patients rather than needs of providers and institutions
- Patient-driven, team-based approach
- Opportunities for integration of social network technologies and techniques
- Psychosocial support networks foster patient compliance, substance abuse treatment, psychological treatment, social integration

Health Care as CASoS

- Traditional organizational theory and optimization practices (e.g., CQI) apply poorly to CASoS environments[1]
- Complex characteristics can affect patient care and staff efficiency[2]

Architectural Philosophy

- Human Centric – Patients and Staff[3]
- Resource Constrained
- Illustrate and explore interpersonal and interinstitutional dynamics
- Explore policy impacts on operating efficiency and medical outcomes
- Medical Service Unit as core of medical functionality

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Sandia National Labs and the Department of Veterans Affairs

- Sandia
- Veterans Health Administration
- Pandemic Influenza 2005
  - DHS responding to perceived threat of pandemic H5N1 outbreak
  - How to mitigate pandemic effects without vaccines or antivirals?
  - Need to model complex adaptive system of systems and evaluate policy alternatives, quantifying and reducing uncertainty and risk
- What is a threat?
  - Source and focus: Infrastructural, medical, organizational

CASoS Introduction

- Complex
  - Interactions and interdependencies among large numbers of heterogeneous agents
  - Multi-scale phenomena
- Adaptive
  - People (Behavior)
  - Organizations/systems
  - Diseases
- System of Systems
  - Resource deconstruction into collections of interacting components
  - Staff, patients, administration
  - Community
  - Social networks

CASoS Engineering Aspirations

From an engineering perspective, *Aspirations* fall into a set of clearly identified categories:

- **Predict** the evolution of the system and, in particular, the results of events (*e.g.,* perturbations of a variety of qualities and quantities) with direct and consequential changes in system health
- **Prevent or Cause** an event to occur
- **Prepare** elements of the system for impending events (*e.g.*, minimize/maximize influence)
- **Monitor** important aspects of a system to record the response of the system to events
- **Recover or Change** in response to events
- **Control** system behavior to avoid or steer the system towards specified regimes through the design of appropriate incentives and feedback
- **Design** an artificial CASoS

Complex Systems Require Robust Solutions to Achieve Aspirations

- **Complex**: Interacting and interdependent components contribute to possibilities for unanticipated, unintended consequences
- **Adaptive**: In responding to changes or perturbations, system will evolve along lines constrained by internal dynamics and external selective pressure – what are you selecting for?
- **Systems of systems**: Systems with fuzzy boundaries means cascading consequences
- Hierarchical structure means single actions or selection pressure can act in unexpected ways on other system components

Creating Robust Solutions

- Robust solutions generate desired outcome under a wide range of possible scenarios
- Some solutions only perform well under typical or expected conditions
- Modeling policy outcomes over all conceivable implementation scenarios helps to find most robust options
- Rigorous sensitivity analysis and uncertainty quantification key to finding robust solutions

Steps in Uncertainty Analysis

- Apply design of experiment to ensure full parameter space is sampled
- Perform Sensitivity Analysis (SA) to determine which inputs have the most effect on outputs
- Run uncertainty quantification (UQ) to identify sources of model uncertainty and how to control
- Run statistical significance tests to gauge reliability and quality of study results
- Repeat until satisfactory levels of confidence reached

Why use Uncertainty Analysis?

- Determines which parameters are most effective in changing model results
- Shows where improved data are needed
  - Better estimates of insensitive parameters not important
  - Important but poorly known parameters can use better data.
- Shows what you can safely ignore in model
- Gives hard estimates on quality of model results under different scenarios
- Helps determine when we’re done

Why Model?

- Models of complex systems are not meant to be predictive in a deterministic sense
- Reveal tradeoffs, uncertainties, sensitivities; discipline the dialogue about options (Epstein 2008)
- Compare and contrast policy cocktails, looking at effects of uncertainty
- Enhance understanding, develop new insights through application and analysis of alternative metaphors

Three Domains

- Medical Physics
  - Diseases and treatments
  - Labor, resources
- Organizational Physics
  - Distinction between MSUs
    - Capacity
    - Capabilities
    - Resources
  - Resource allocation policies
    - Initial
    - Dynamic
- Social Physics
  - Mood contagion in social networks
  - Social components of lifestyle associated diseases

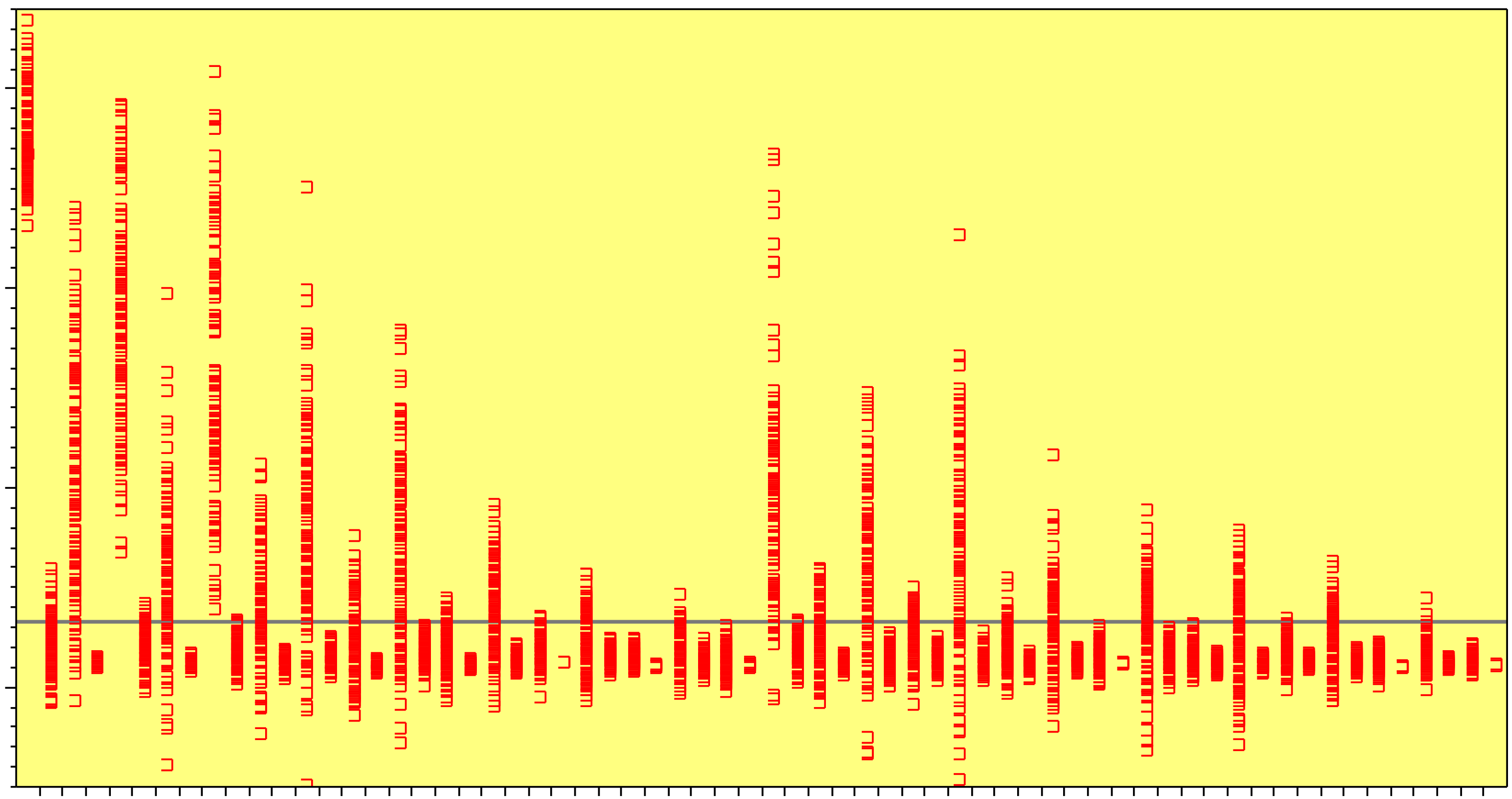
Perturbations and Scripting Scenarios

- Configure scenario – MSUs, networks, patients, staff, diseases, resources
- Schedule events – Decrease in resources, increase in patient flow rates, appearance of new medical conditions
- Coupling between systems will allow events to cascade

Policy Cocktails

- By analogy with drug cocktails
- Different policies to mitigate different aspects of complex problems
- Analyze for synergistic or antagonistic interactions

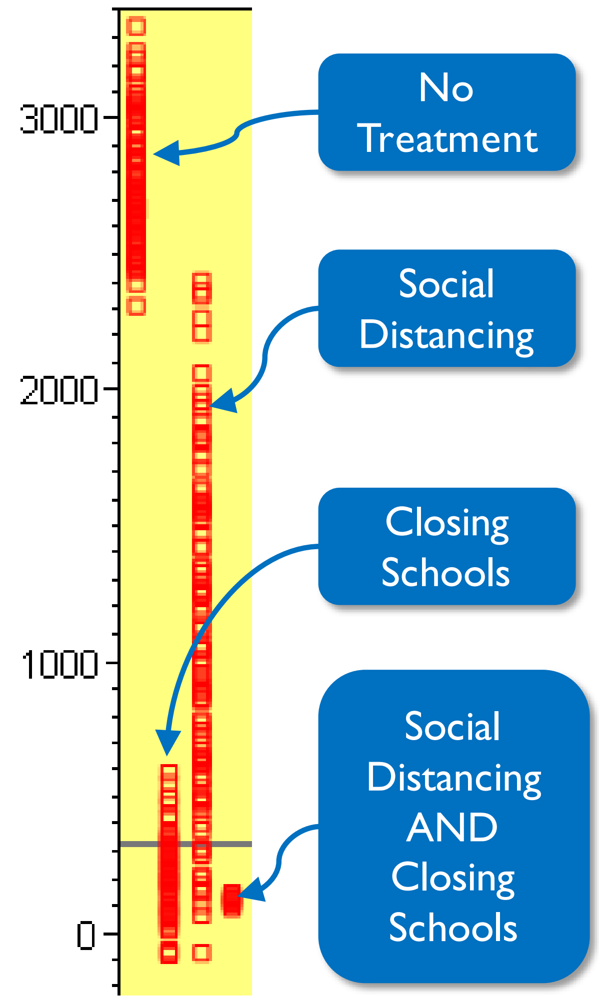
Modeling creates policy option combinations with different outcomes and variability



Pandemic influenza study (baseline scenario): 64 treatments, 6,400 model runs, synthetic data set

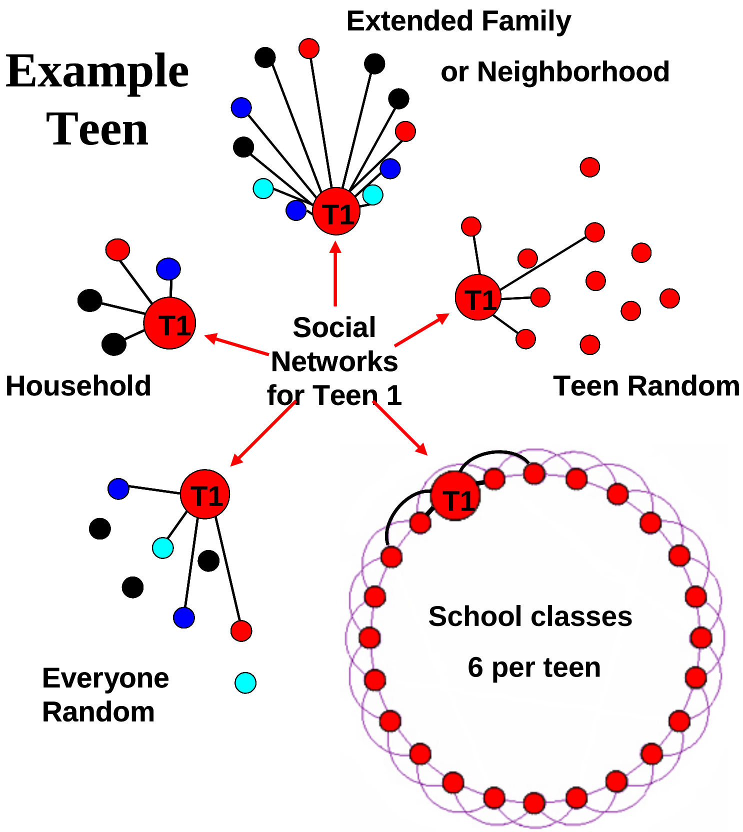
Desirable Outcomes and Low Variability Characterize Robust Policies

- Each policy tried on 100 random social networks
- 2,780 cases expected with no treatment
- Closing schools is best single option
  - Mean = 137 cases
  - Moderate variation
- Social distancing is not as effective
  - Mean = 987 cases
  - Wide variation
- Both policies in conjunction create robust solution
  - Mean = 118 cases
  - Narrow variation
- Robust solution:
  - Good outcome
  - Most stable to randomness



Demonstration

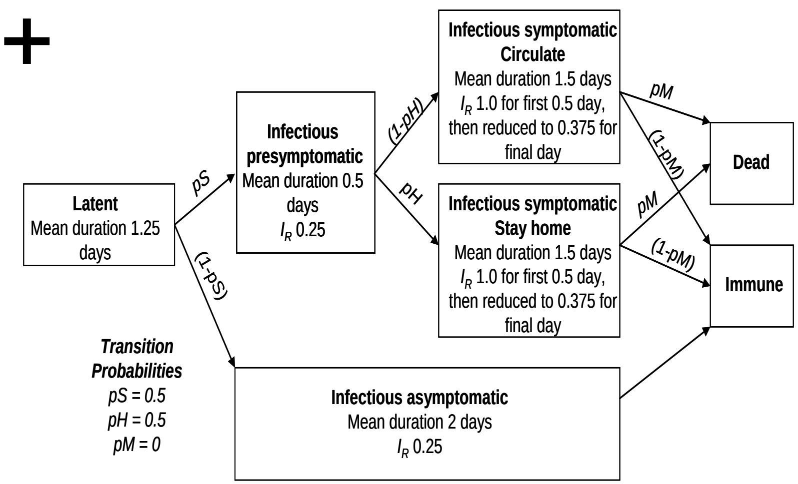
Application of Networked Agent Method to Influenza



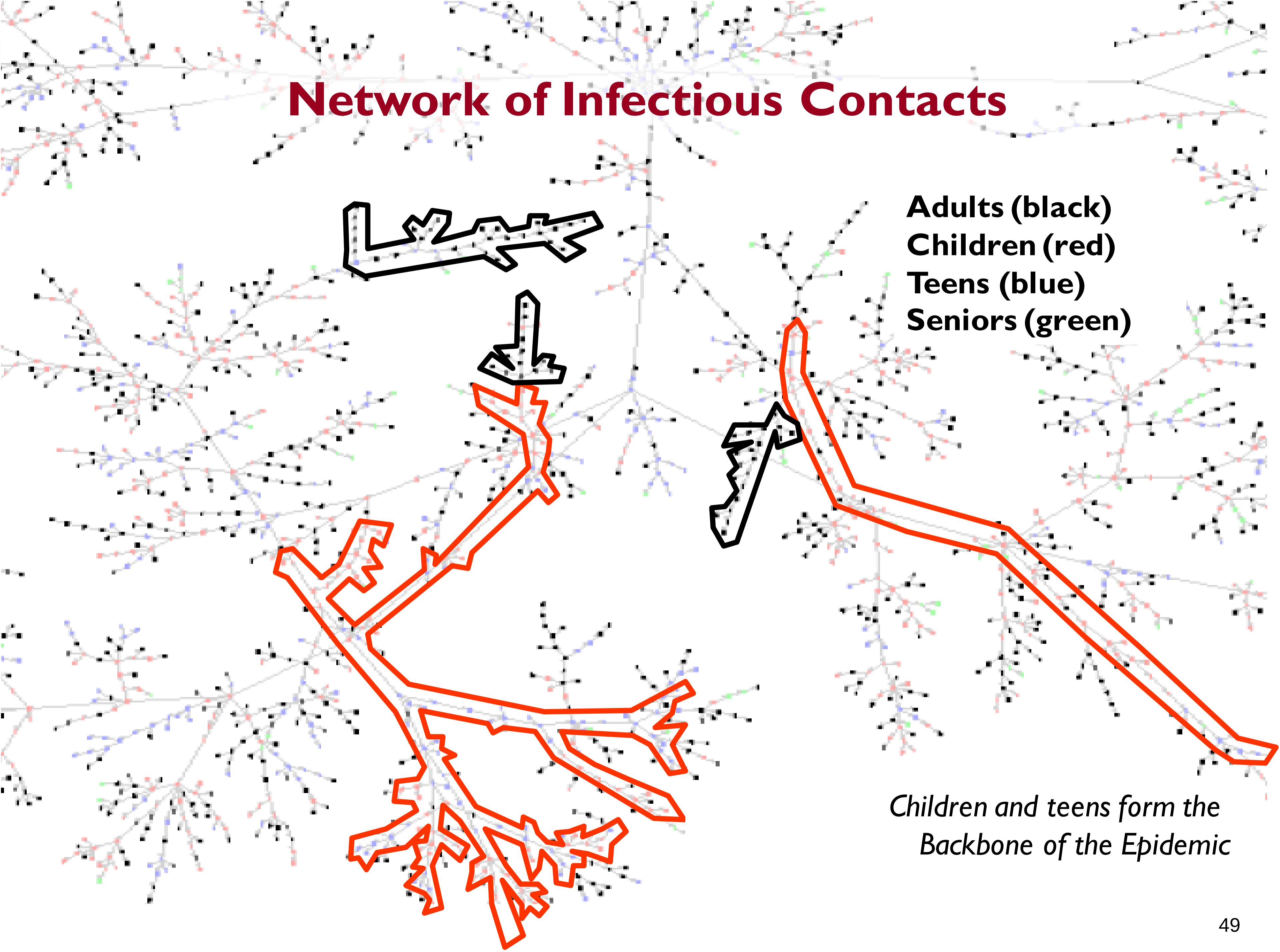
Stylized Social Network
(nodes, links, frequency of interaction)

+

Disease manifestation
(node and link behavior)

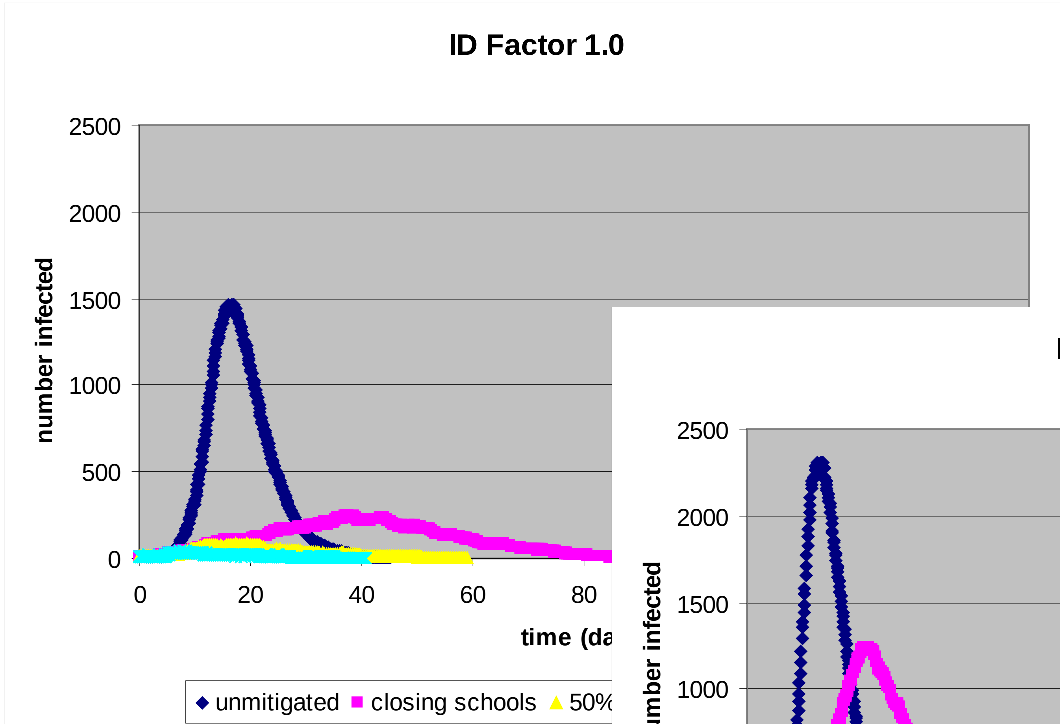


Network of Infectious Contacts

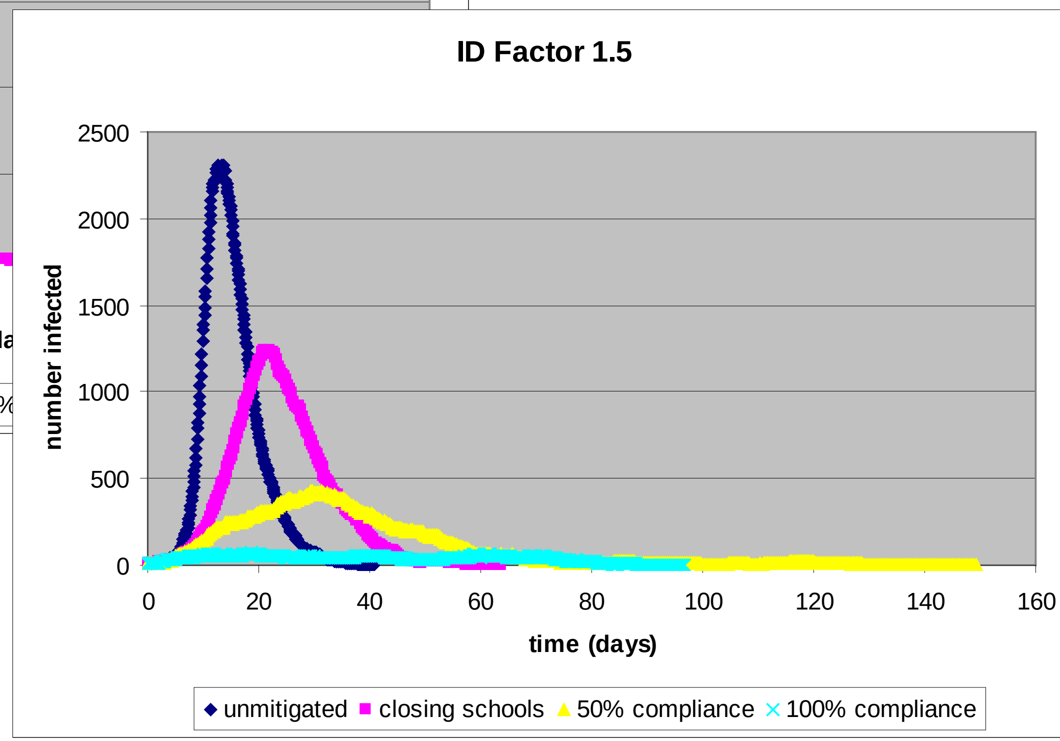


Children and teens form the Backbone of the Epidemic

Closing Schools and Keeping the Kids Home



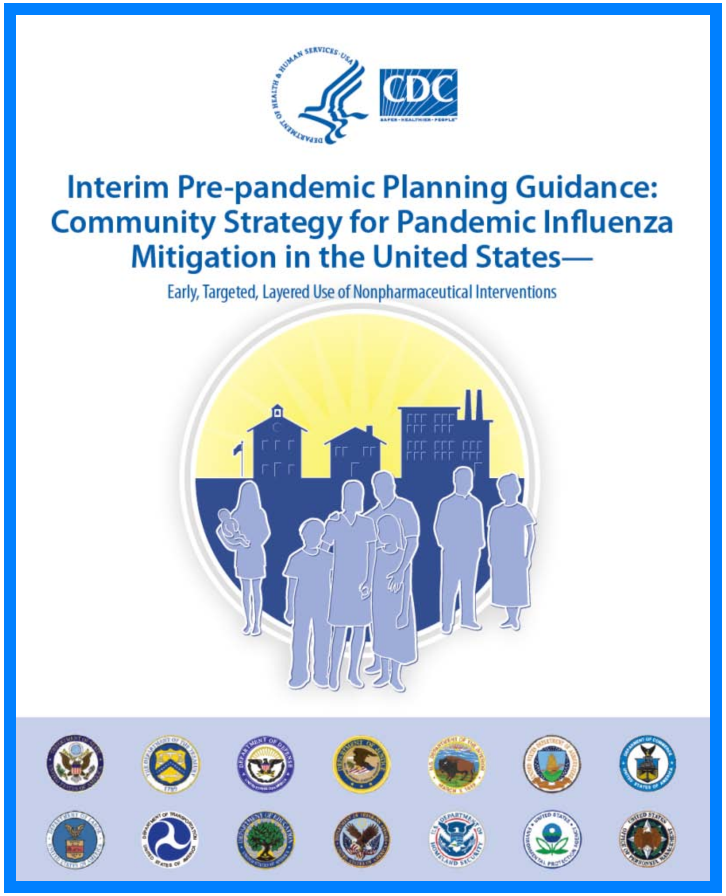
1958-like



1918-like

Worked with the White House to Formulate Public Policy

A year later…



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