

Epidemiologic Considerations in Network Modeling of Theoretical Disease Events

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1.0 INTRODUCTION

Social network modeling is a relatively new addition to the armament of public health and epidemiology. Epidemiologists and communicable disease control researchers have been turning to network analysis to address and understand gaps in traditional outbreak management techniques such as contact tracing. Network analysis has shown utility in the study of a range of communicable disease outbreaks affecting both health and commerce, including SARS, tuberculosis, syphilis and foot-and-mouth-disease, and may have applications in automated disease surveillance systems.

Visualization of these communicable disease networks is an integral component of such analysis. However, visualization of more complex relationships will require consideration of a variety of epidemiologic factors which affect these relationships, and the development of techniques to display them. Any analysis of case level health data has the potential for compromising privacy, and network visualization is no exception. Like other analysis tools such as data mining, or Geographic Information Systems (GIS), network visualization will need to incorporate techniques to ensure confidentiality.

In this paper we shall discuss the role of network analysis in communicable disease outbreak control, epidemiologic considerations in visualizing networks, and the emerging issue of confidentiality.

2.0 NETWORK ANALYSIS AND OUTBREAK CONTROL

Scale-free networks have certain characteristics which are pertinent to the control of communicable diseases.

Firstly, disease outbreaks occurring in scale-free networks have no epidemic threshold [1], making them resistant to random deletions. Even one infected individual can result in an epidemic. Compared to random networks, the initial spread of disease in scale-free networks is much faster and disease is detected at a later stage. Hence traditional contact tracing for disease control requires a much higher effort and accuracy to control an epidemic for a scale-free network than for a corresponding random network [2].

Secondly, while scale-free networks may be resistant to “shotgun” interventions, they are vulnerable targeted attacks which can disrupt and fragment the network [3]. In a retrospective analysis of the 2001 British foot-and-mouth disease epidemic, Shirley & Rushton examined the network of livestock markets and farms involved. The authors concluded that removal of any one of only three key vertices would have

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prevented over 80% of the infected premises and stopped the epidemic [4]. The authors also concluded that it is necessary to “understand the contact pattern of susceptible populations before embarking on any strategy for disease control, which means that populations at risk from disease need to be characterized topologically before an outbreak occurs.” This has implications for public health planning. Prospective characterization of a variety of networks could help inform the design of potential public health interventions before outbreaks occur. Such networks may include commercial air travel routes, hospital and extended care facility separations and transfers, and food supply chains.

Network analysis of disease transmission need not be restricted to known pathogens. The emergence of new organisms, like the SARS-associated corona virus, demonstrates that future outbreaks and epidemics may take the public health community completely unaware. Greater utility may be found in prospectively analyzing potential and theoretical disease events with a range of transmission characteristics and developing intervention options *a priori*.

Also, understanding of communicable disease network topology will be of great use in the implementation of future public health interventions which can mimic the spread of the diseases they are designed to prevent. Examples of this type of intervention include the oral polio vaccine, which like wild-type polio virus is spread by fecal-oral route, and, potentially, commensal bacteria bioengineered to produce HIV-microbicidal peptides or proteins, which are currently under development [5].

3.0 EPIDEMIOLOGIC CONSIDERATIONS IN NETWORK VISUALIZATION OF COMMUNICABLE DISEASE EVENTS

One of the greatest strengths of network models is the ability to visually represent complex and heterogeneous distributions of interactions in an intuitively comprehensible and interactive fashion. However, some epidemiologic characteristics related to the host, the disease agent, and the environment are less easy to represent, but should still be considered in theoretical network models. This is especially important when modelling new or emerging diseases with unknown or changing characteristics. Considerations may be divided into characteristics of the host, the disease agent, and the environment. Listed below are descriptions of such epidemiologic factors and possible ways to address their visualization:

- ♦ The host factor of susceptibility to infectious disease exists on a spectrum which may or may not have definable thresholds. Disease susceptibility may be non-modifiable (e.g. genetic, co-morbidities), modifiable (e.g. by immunization or natural sub-clinical infection, lifestyle, such as smoking), or even intermittent in cases of waning immunity in the absence of wild-type disease challenge. Co-factors for disease, where a single infective or toxic agent or genetic predisposition is necessary, but not sufficient to cause disease may also exist.
Visualization technique: Node colour gradient may be used to show susceptibility. Alternately, numeric probability of susceptibility could also be displayed by each node.
- ♦ The pathogenicity of a disease-causing organism also may not remain constant either, independent of changes in host immunity. Evolutionary pressures favour increasing infectiousness and decreasing pathogenicity of an organism with successive passes through a population. “Successful” organisms tend not to kill their hosts. Conversely, genetic shifts and interspecies jumps, such as can occur with influenza, may lead to dramatically more virulent organisms.
Visualization technique: Edge pattern may be used to denote virulence of transmissible organism. Transmissibility may be reflected by line intensity or pattern density.

- ♦ Environmental factors may profoundly affect the spread of a disease, regardless of whether the spread is person-to-person, food-borne, water-borne, or by fomites (contaminated objects). Diseases such as malaria or lyme disease are spread by arthropod vectors which have their own habitat and dispersion characteristics. Social network modelling of tuberculosis and sexually transmitted illnesses have shown that a geographic location, rather than a specific individual, may be the critical vertex between infected persons.

Visualization technique: Electron orbital models for the representation of chemical interactions may be useful for environmentally-related disease transmission. Environmental spread is not best represented by lines/edges, but by two-dimensional or 3-dimensional shapes such as circles or spheres (“clouds”) around nodes, or ellipses (“orbitals”) or cones where directionality is required. In cases where disease is the result of multiple factors, including both infectious and toxic/environmental elements, visualization may take the form of orbital interactions.

Another way to potentially improve the visualization of communicable disease networks may be to structure the model to reflect the public health response, as well as the disease transmission. For example, response to outbreaks of infectious diseases such as tuberculosis typically occur in an expanding “bullseye” fashion: contact tracing and screening starts with the small group of close and family contacts of the index case, and moves to progressively larger, more distant connections until the limits of the outbreak are defined. Circles have been widely used in the literature to illustrate networks since they allow naïve observers to recognize differences between a specific solution and the idealized pattern from which it deviates [6]. Placement of nodes with similar risk for infection in concentric circles around the index case in a network visualization makes intuitive sense, and may assist in identifying previously unknown or improperly characterized relationships.

Furthermore, network analyses of different aspects of the same issue may yield insight into more appropriate interventions. Thus analyses of both disease spread and utilization of health care or other services may identify optimal intervention points or locations. Another public health area where network visualization may have utility is the analysis of organizational structure for response to communicable disease events. Such analysis has been used to examine command and control for emergency services such as police, fire and hazardous materials [7]. Three-dimensional animation is an effective way to display hierarchical information [8] and may be useful in the analysis and planning of integrated federal, provincial/territorial and local public health responses to communicable disease emergencies. In recent months there has been an unprecedented international effort to prepare for the threats of avian and pandemic influenza (PI). In Canada there has also been an associated proliferation of committees, secretariats and organizational structures to address the issue at all levels of government and public health, although the number of public health officials has not substantially changed and remains small. The Communicable Disease Control Division of the First Nations and Inuit Health Branch of Health Canada has undertaken a preliminary analysis of the PI committee structures and memberships using a custom built visualization application (VITA 6.0b, Exocortex Technologies 2006). This exercise has been instructive in identifying gaps in organizational connections, as well as overlaps and redundancies which could be streamlined.

A final technique which may improve visualization of communicable disease networks is the simultaneous combination of animation with graphing. Existing software has the capability for generating epidemic curves from animated models. Presentation of both the network animation and the epidemic curve on the same screen could be integrated with a “drop-out” animation in which infected nodes fall out into the graph, generating the curve.

4.0 PRIVACY CONSIDERATIONS IN THE VISUALIZATION OF COMMUNICABLE DISEASE EVENTS

One method of increasing the amount of information presented in a network diagram is to superimpose network information on a map. This technique is intuitive and has been used in analyses such as sexual networks in the one Canadian province [9] and networks of livestock movements in Great Britain [10], [11]. GIS and the common use of geocodes, such as address or postal code, for billing or case follow-up in clinical and public health administrative databases make imaging of geographic distributions fairly easy.

Although geographic information may be instructive in understanding communicable disease networks, its use presents privacy issues. Depending on the population density of the area under study, the precision of the geocode, the background detail on the map, and the visualization algorithm, the information conveyed may be sufficient to personally identify an individual. Even identification of individual communities or parts of communities may be considered sensitive. For example, in Canadian First Nations and Inuit (FN/I) communities, sufficient stigma is still attached to communicable diseases such as tuberculosis (TB), that communities with outbreaks may not wish to be identified.

Like geographic location, graphic representation of human relationships may have the potential for inadvertent violations of confidentiality, even when the nature of only a single relationship link in the network is publicly known. Examples of this may include disease spread within an extended family, religious group, or close-knit community. If one individual in the network can be personally identified, then the other members of the network may be deduced.

Spatial epidemiologists have developed a variety of methodologies for masking data to ensure confidentiality, including transformation, random perturbation and aggregation [12]. Aggregation in particular may be applicable to network visualization of disease transmission. Cases or nodes with the same or similar characteristics and relations may be aggregated, simplifying the visualization but destroying much relational information in the process.

5.0 CONCLUSIONS

Combining network analysis with other public health tools such as traditional epidemiologic statistics and geographic information systems may lead to better characterization of disease events. Some possible implications for network analysis research are as follows:

1. Network analyses of the flow of humans, information, and commerce need to be performed before crises occur and the effects of vertex deletion assessed. Network visualization may be useful in the analysis and improvement of public health command and control structures, organization and incident responses and may help model “unforeseen” events such as unintentional/accidental breakdowns in infrastructure, criminal and terrorist acts, and outbreaks of new or emerging communicable diseases.
2. Network analyses of disease events should consider the possibility of situations where vertices have different natures (e.g. person, place, time), may appear, disappear or otherwise change (i.e. changes in immunity or susceptibility, presence of disease co-factors), or have intermediaries (e.g. vectors or fomites). Continued consideration should be given by the research community to interventions and investigations which mimic the behaviour of the disease, especially in cases where network analysis cannot identify appropriate control points. Such interventions are only warranted when the danger of the disease is greater than the risk associated with the intervention, as is the case for oral polio vaccine in endemic countries.

3. As visualization techniques improve and increase the amount of information one is able to present, the potential for breeches in privacy also increase. Attention needs to be paid to developing methodologies which preserve the information critical for both analysis and confidentiality.
4. Innovative ways to visually represent aspects of disease epidemiology in network models need to be explored. Example of this may include use of 3D animations, edge patterns, and “electron orbital-like” models for disease transmission relationships.

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Outline

- Background
- Network analysis in CD outbreak control
- Epidemiologic considerations in visualization
- Privacy concerns
- Conclusions

Background

- Limits to traditional public health methods (eg. contact tracing) and interventions
- STI's - eg. Syphilis
- Uncertainty regarding relationships
- Social network vs. sexual network

Network Analysis in CD Outbreak Control

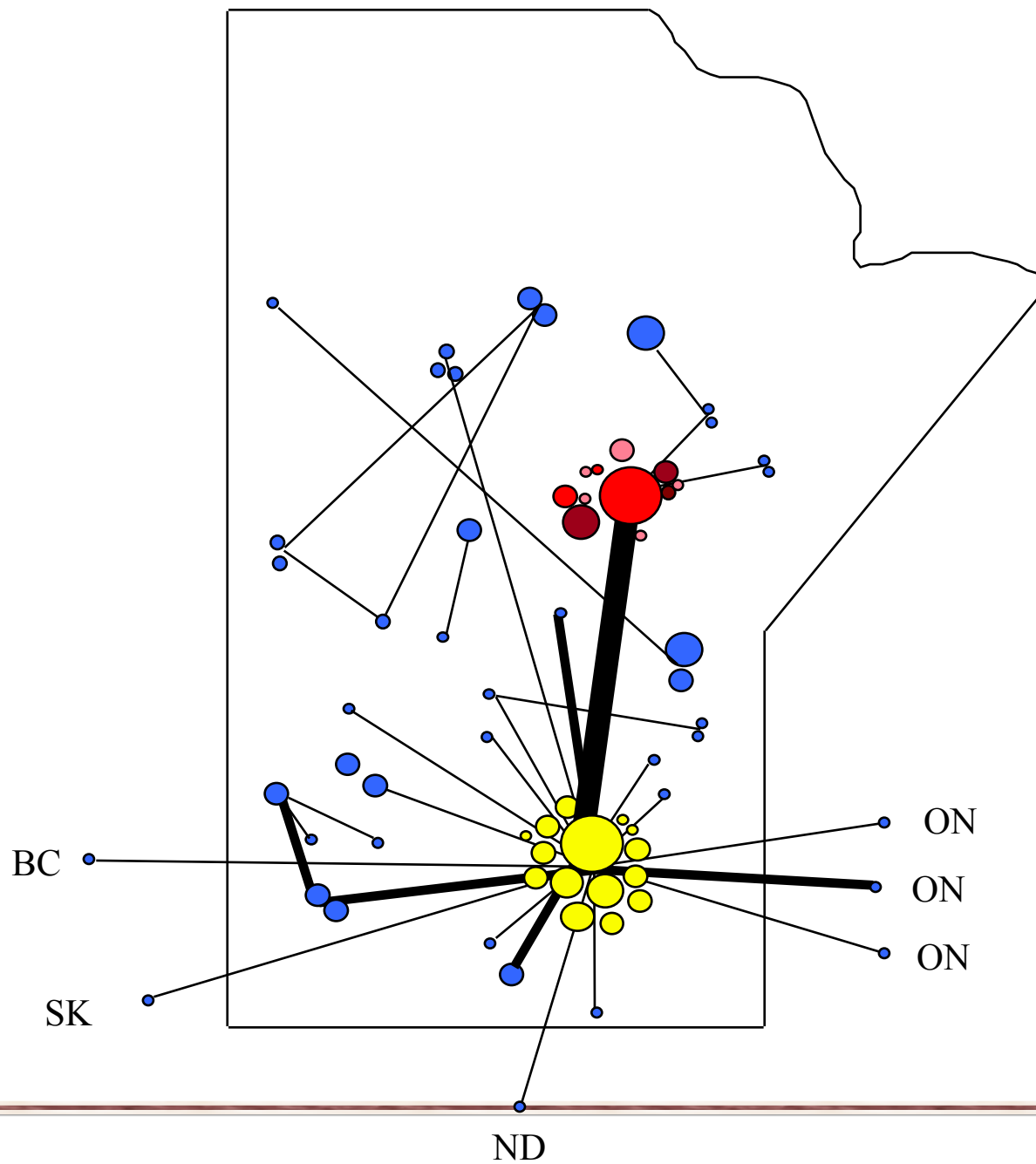
- Characterization of uncertain relationships (Jolly & Wylie, 2001)
- Assessment of interventions in different network scenarios (Kiss et. Al., 2005)
- Retrospective analysis of epidemics and interventions (Shirley & Rushton, 2005)
- Hypothesis generation

STI Networks - Jolly & Wylie, 2001

- Subjects infected with gonorrhoea and/or chlamydia in MB Aug. 1997 to May 1998
- Decreasing effectiveness of screening and population based prevention
- “Core group” with large number of partners and long infectious periods
- Under-reported sex partners



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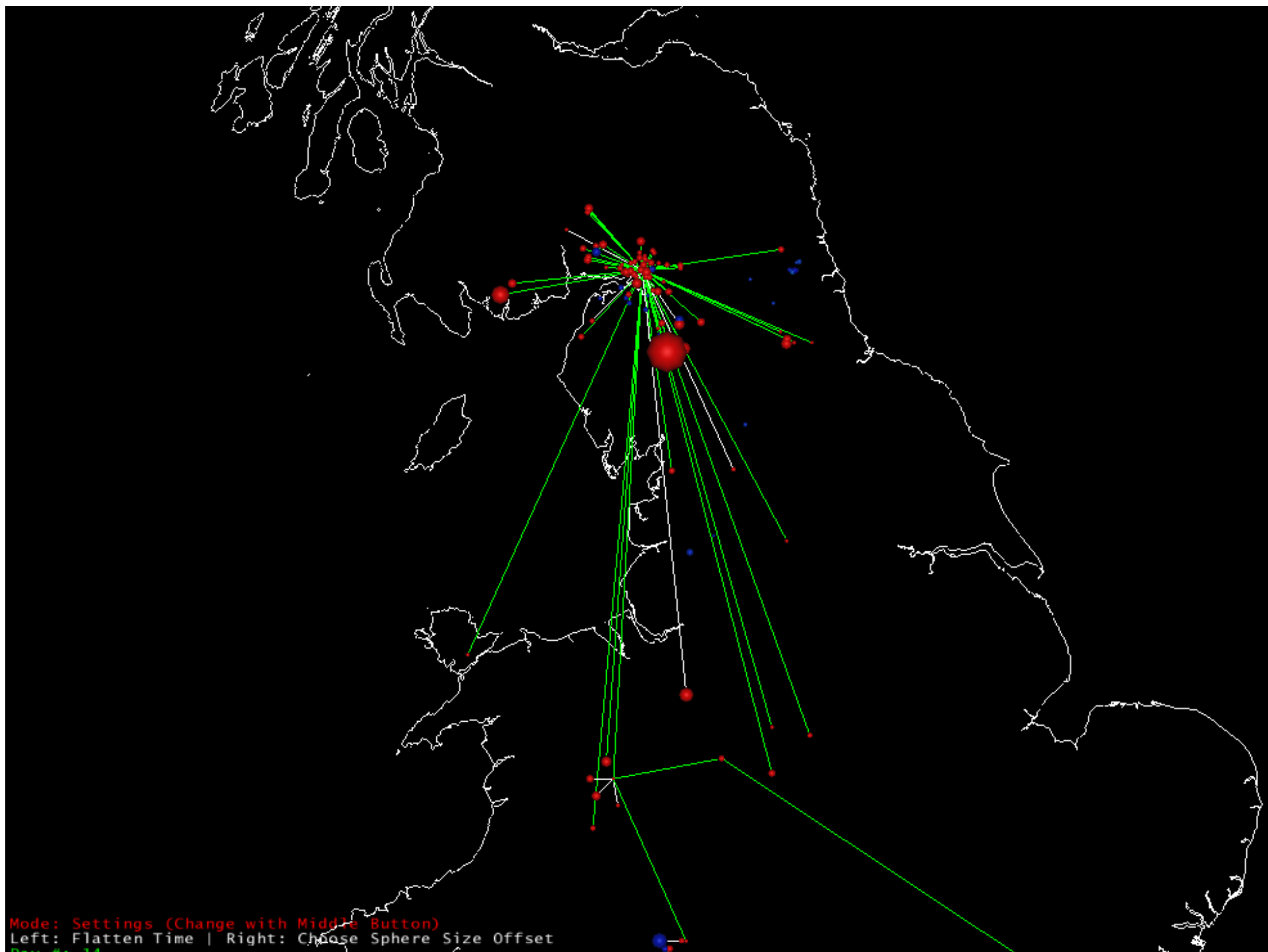


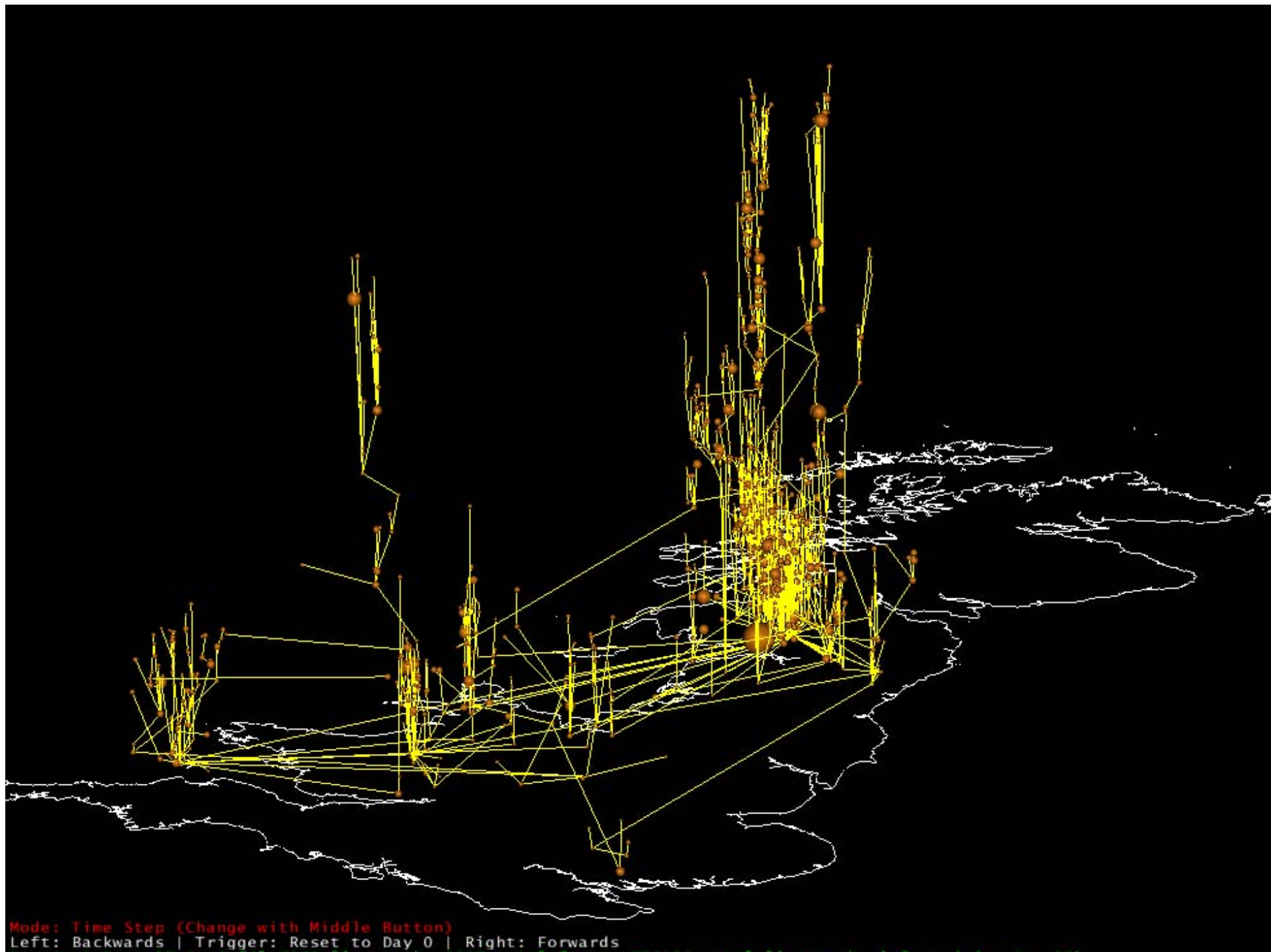
STI Networks - Jolly & Wylie, 2001

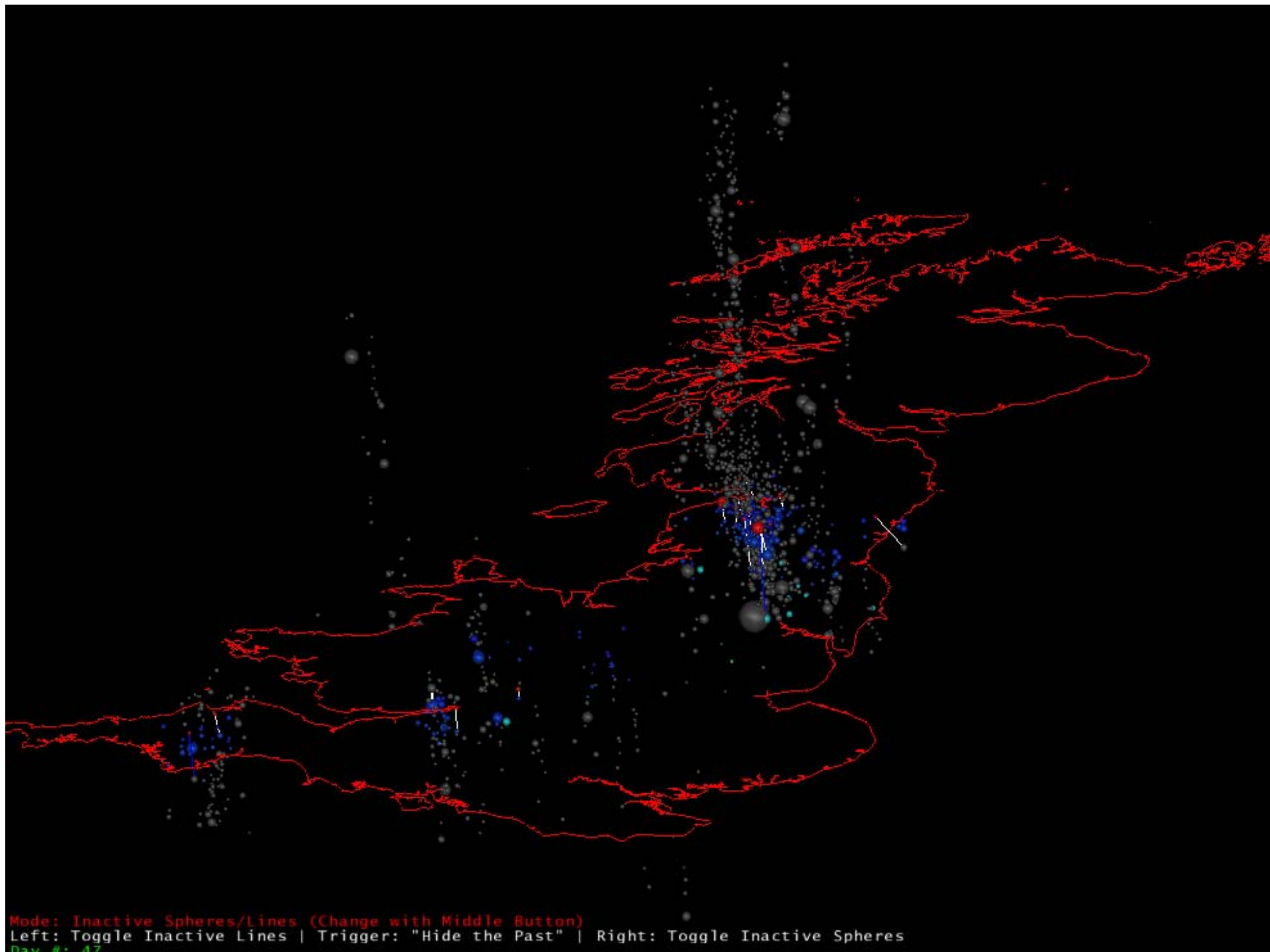
- Geographical bridges in the network
- Sexual networks as “ecological niches”
- Sexual network similar to layers of an onion with most effective transmitters at the centre
- “Upstream contacts” of case who had contact just before the onset of symptoms have greater chance of spreading and should prioritized for F/U

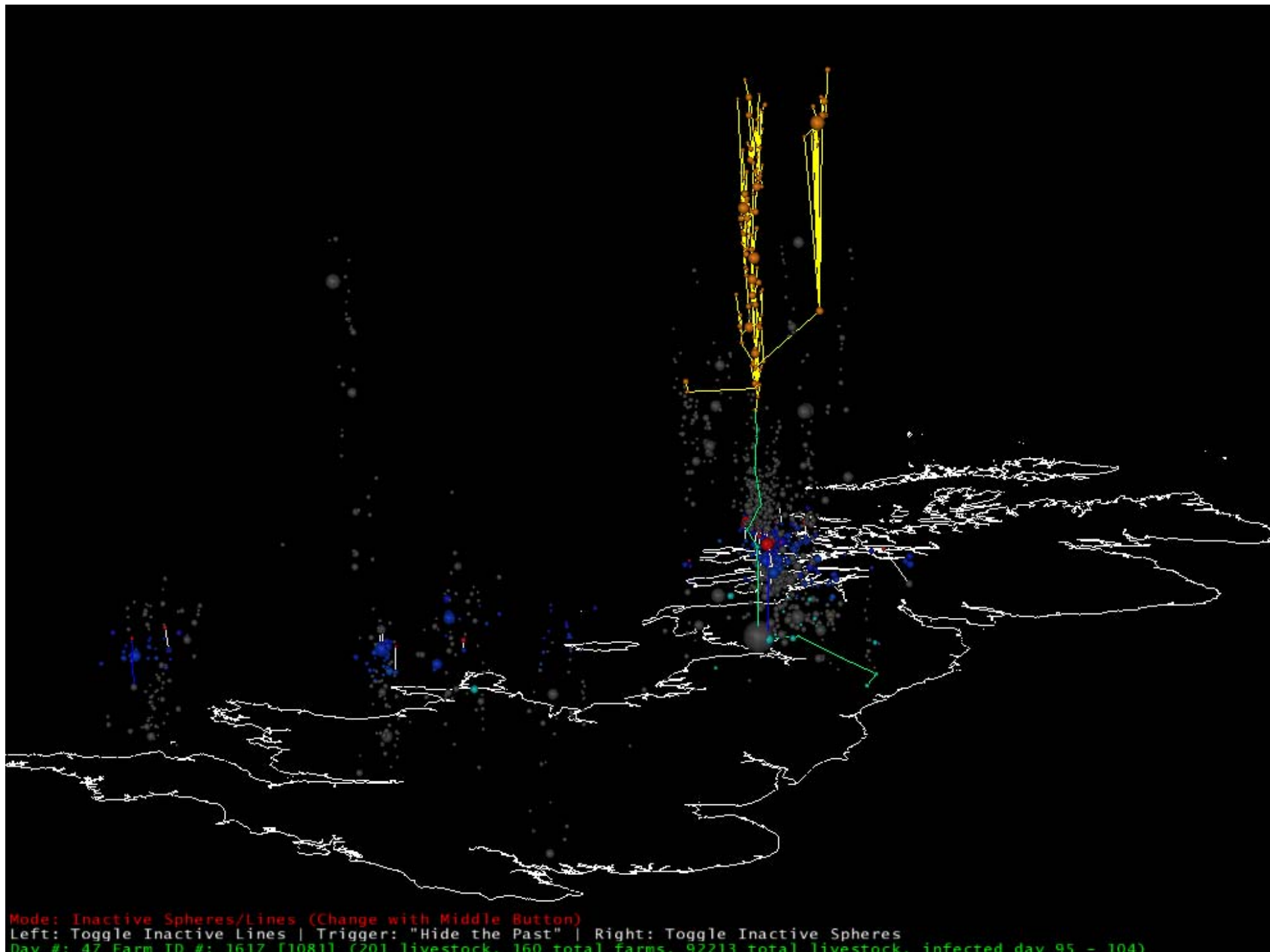
UK Foot-and-mouth Disease Epidemic, 2001

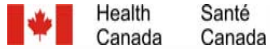
- Highly infectious picornavirus, may be wind-borne
- Pigs, sheep, goats and cattle
- Painful blisters in mouth, feet, teats
- Lameness, decreased milk production
- In 2001 epidemic, 2030 premises had confirmed outbreaks of FMD
- Resulted in the destruction of livestock on over 10,000 premises
- Economic ramifications











Shirley & Rushton, 2005

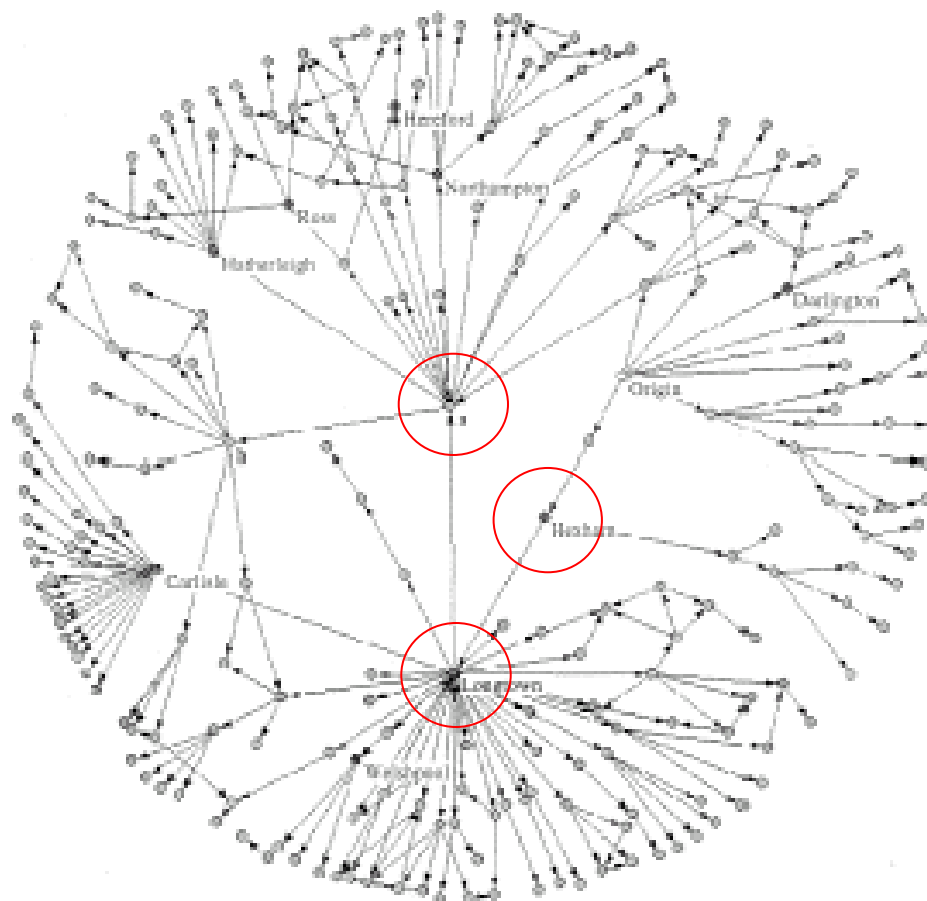
Ministry of Agriculture and Veterinary Laboratory Agency traced the origin of all confirmed outbreaks of the disease.

- Over 1500 vertices.
- Edges defined as being between an infected vertex and its traced source
- Global heterogeneity seen in network
- a few vertices (markets) monopolized a large proportion of the total edges in the network
- Approximation of a scale free degree distribution



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Shirley & Rushton, 2005



Epidemiologic Considerations in Visualization of CD events

Agent

- Pathogenicity: drift, shift, jump
- Infectious co-factors (super-spreaders)
- →Edge pattern and density

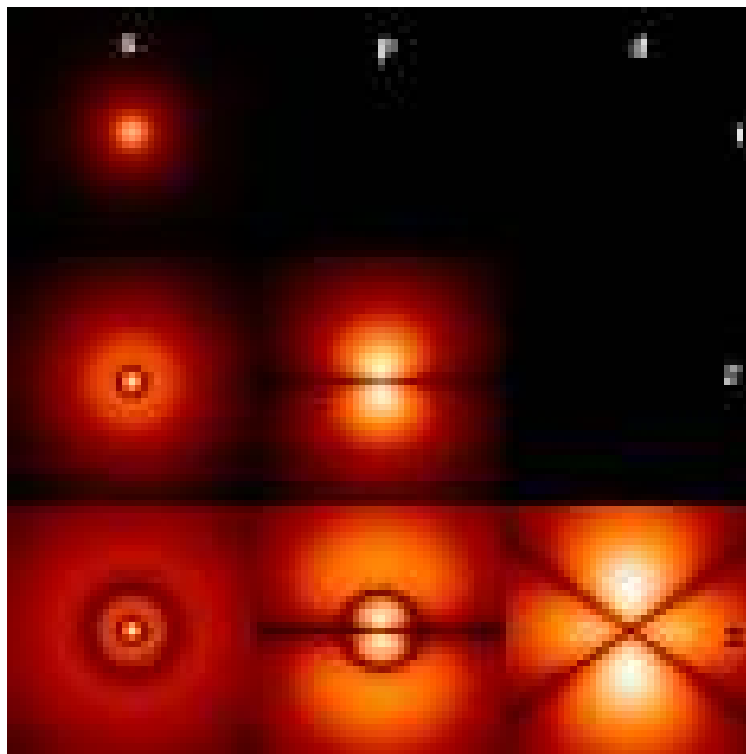
Host

- Susceptibility: modifiable, non-modifiable, intermittent
- Genetic co-factors (eg Leprosy)
- →Node colour gradient

Environment

- Spread by person-to-person, food, water, air, fomite
- Environmental co-factors (eg Parkinson's disease)
- →Orbital interaction model

Electron Orbital Model

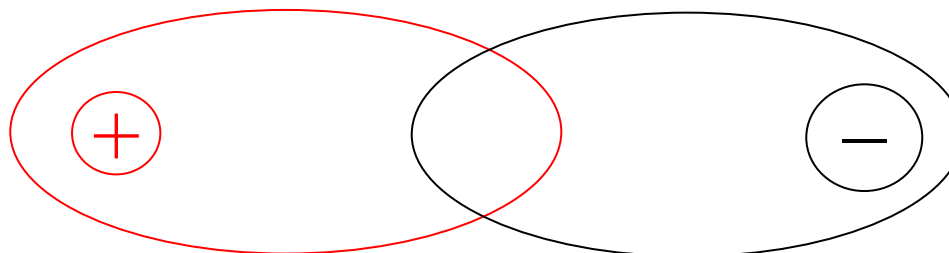


- Model for molecular bonds
- Represent probabilities
- Uncertainty
- Fuzziness
- Interaction or exclusion
- Broadcasting
- Optimal visual distribution and stripiness (charge)
- Hypothesis generation



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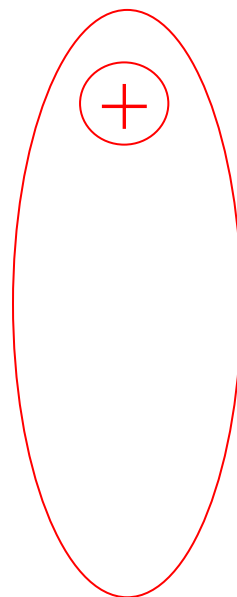
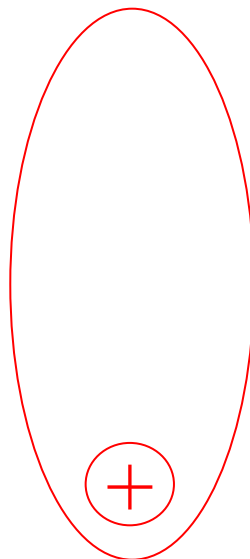


Edge formation,
Stripiness



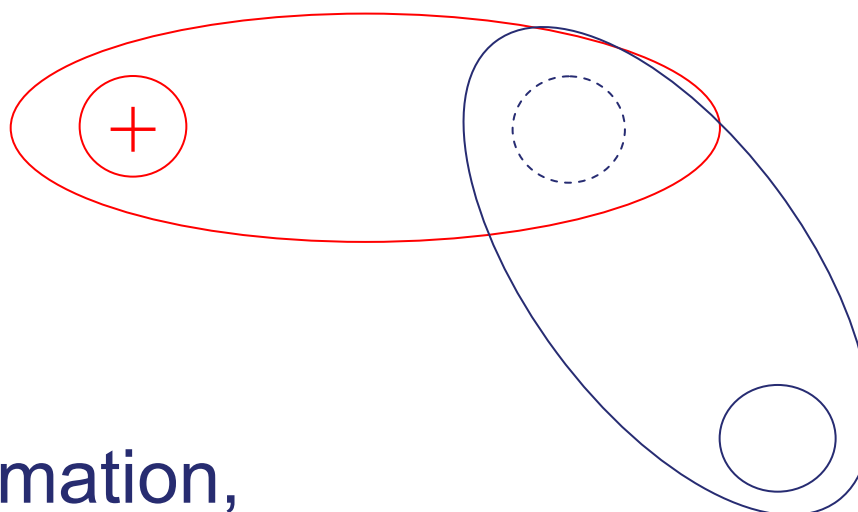
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Exclusion,
Stripiness





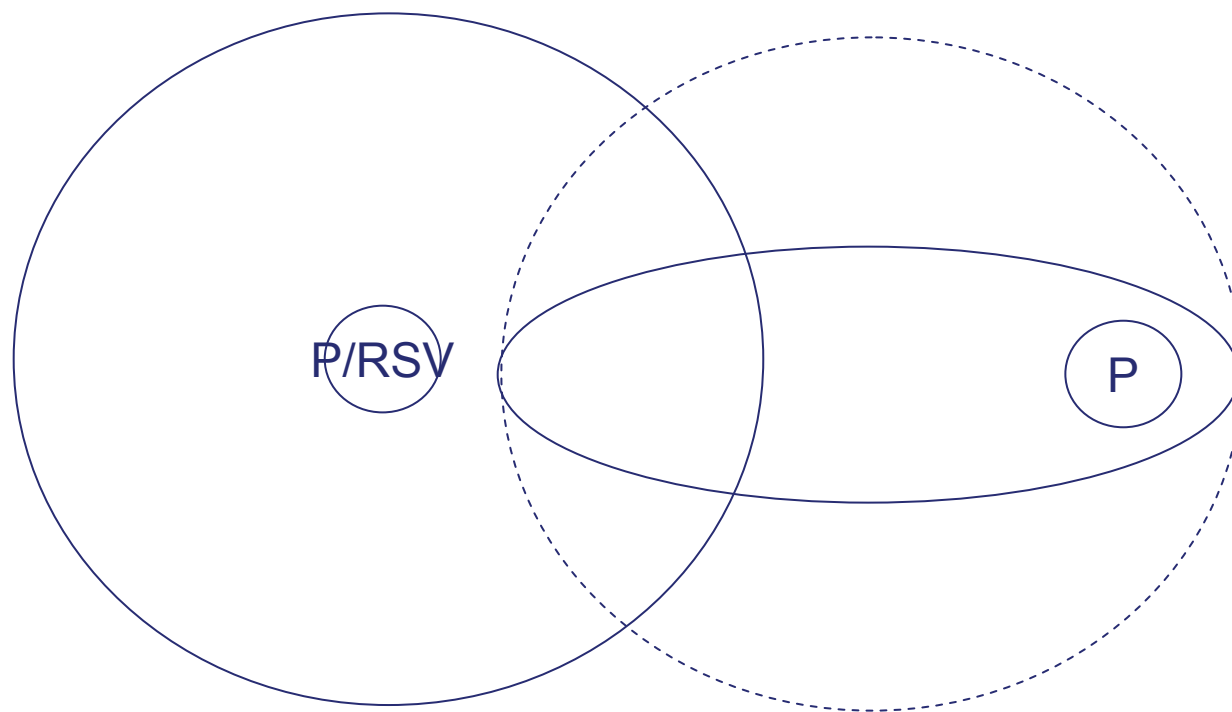
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Node formation,
Environmental-CD overlap
Fuzziness



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Broadcasting

Environmental contamination,

Super spreader creation

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Command and Control

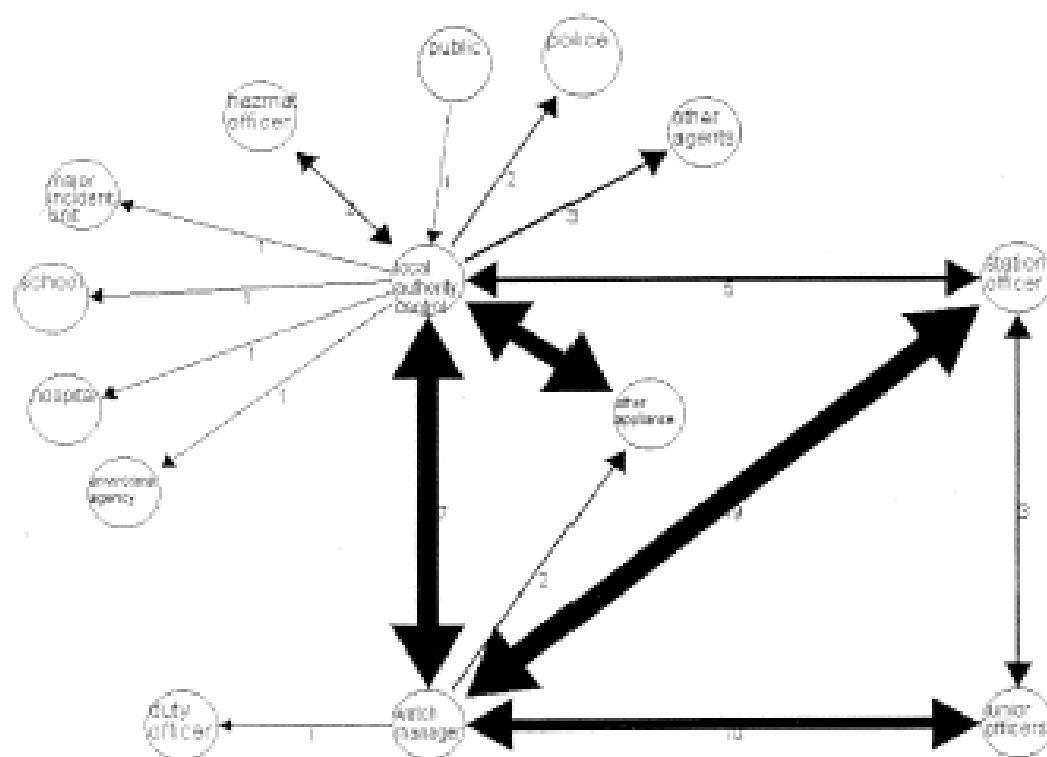
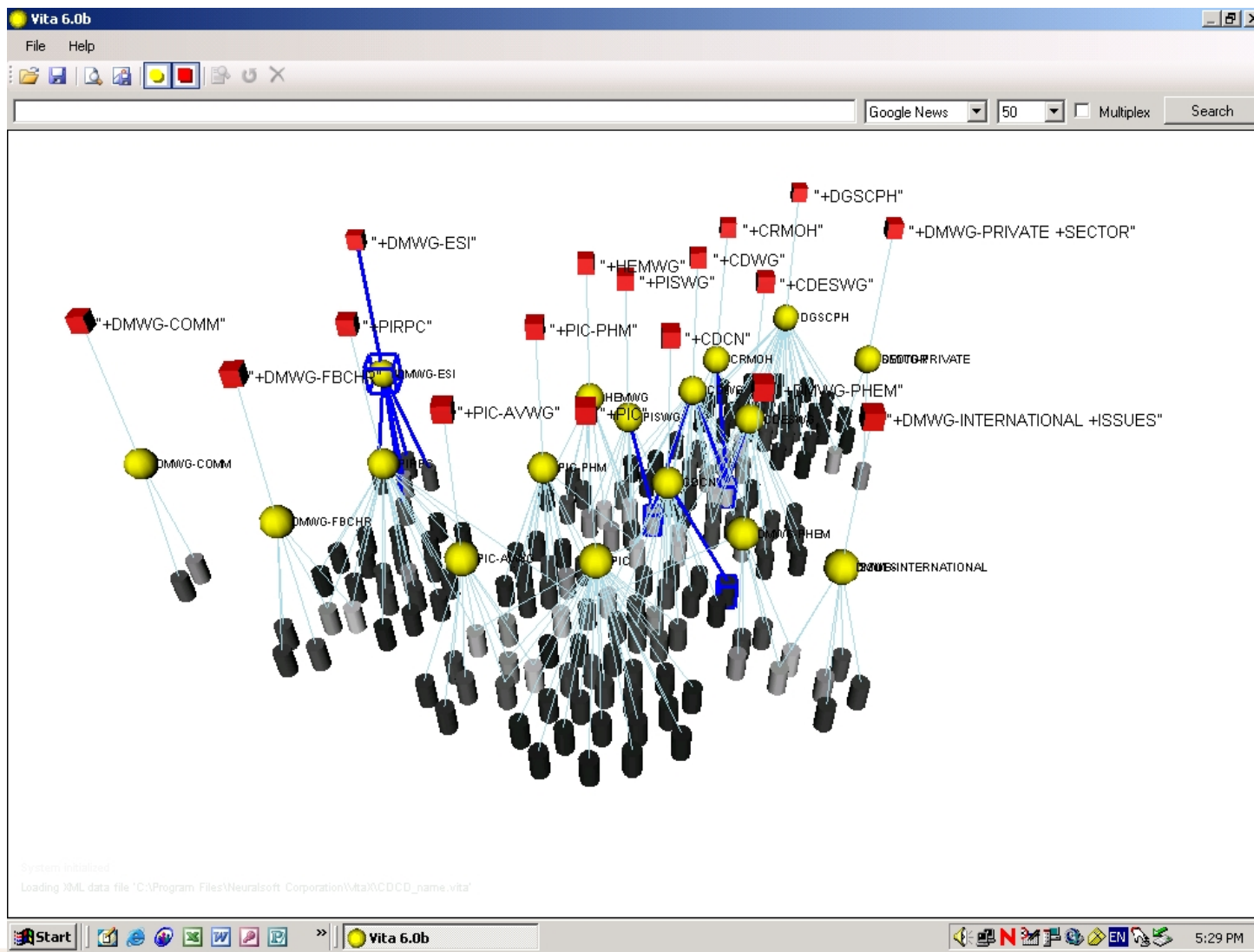


Figure 5. Social network for fire incident 2.



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Organizational Structure



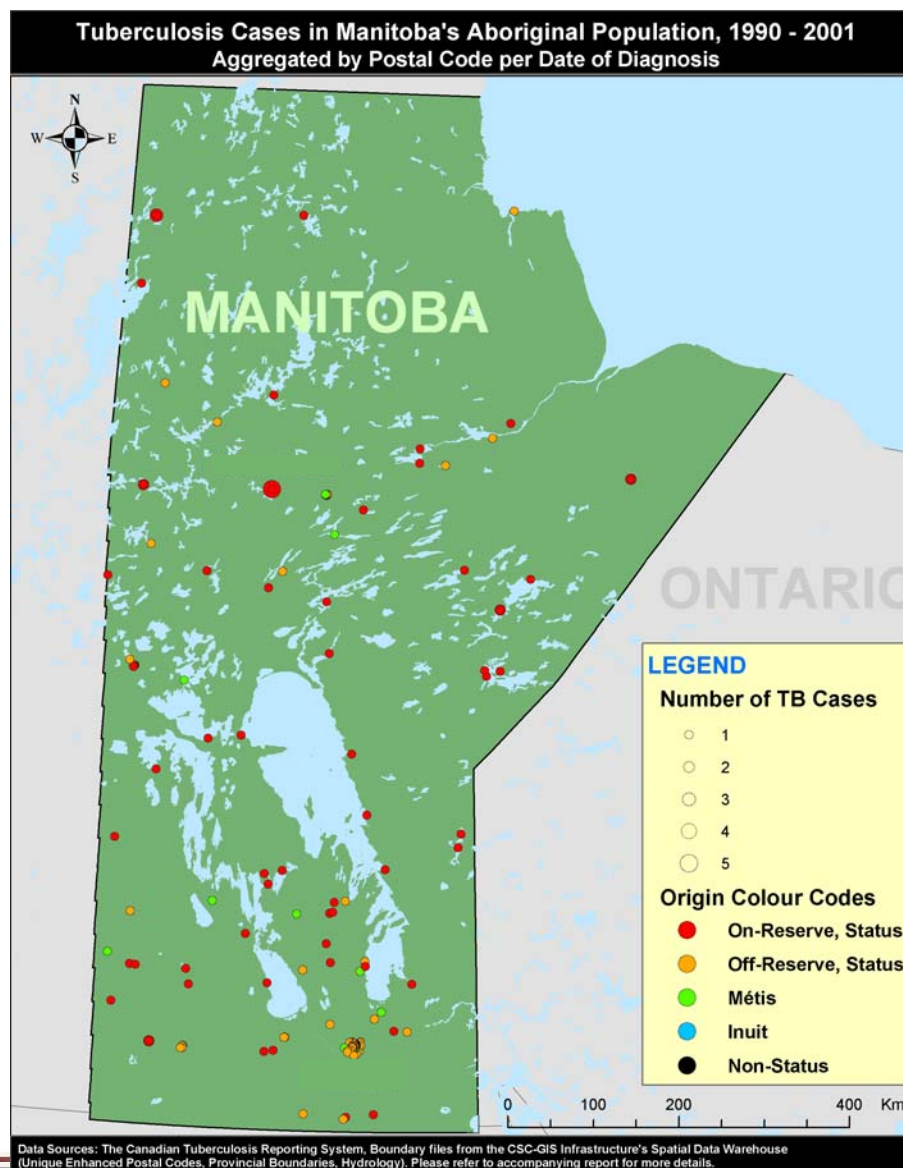
Privacy Issues

- Medical/public health context vs. military context
- Increased information density and resolution leads to greater potential for unintended disclosure of personal information
- Geospatial, temporal, familial, social information
- Media - ATIP requests
- MLA, MP
- Other departments, agencies



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Sample Maps



Centre de
surveillance
et de
surveillance

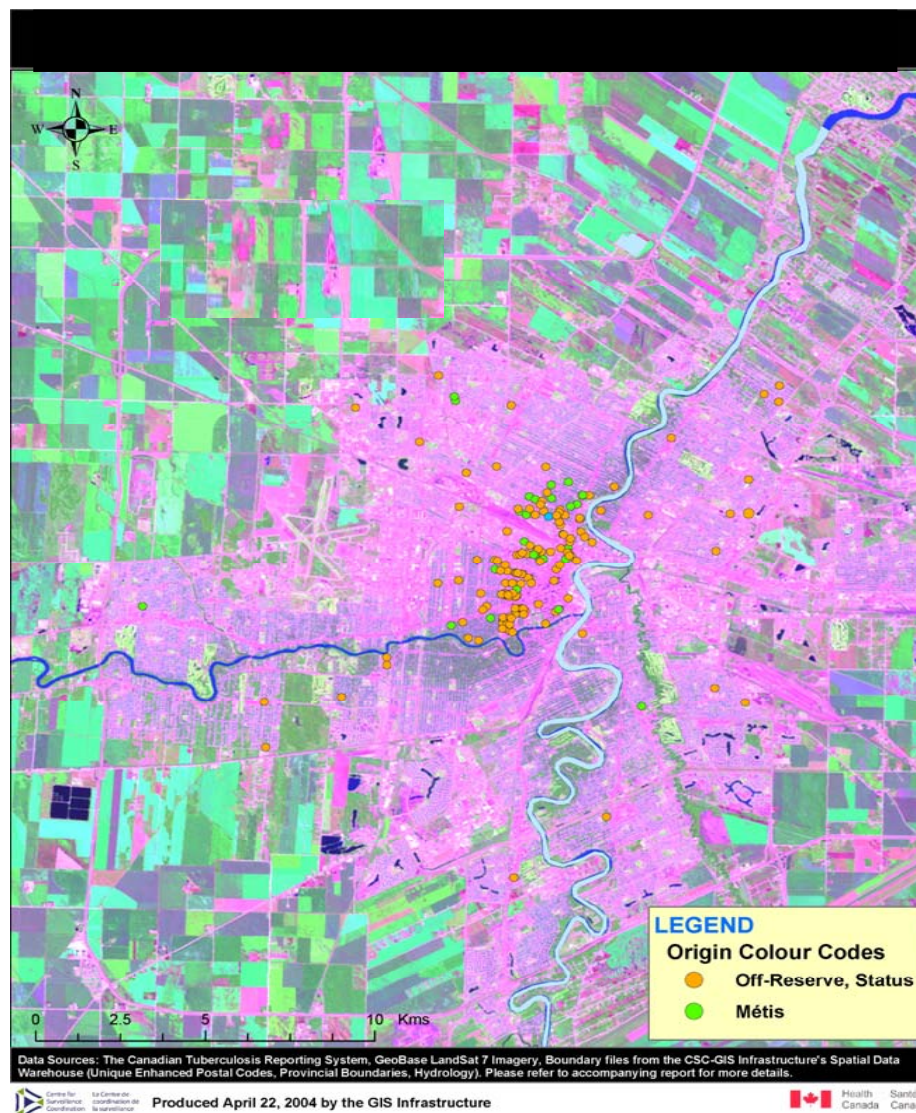
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Conclusions

- Need for *a priori* network analyses of vulnerabilities in public health
- New or emergent pathogens may modelled as theoretical events with a range of epidemiologic properties
- Visualization of CD networks may lead to breeches in confidentiality and privacy techniques should be explored
- New visualization techniques may be useful for understanding CD networks and hypothesis generation



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<http://www.iri-vr.ncl.ac.uk/projects/fmd.html>



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Questions?

