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Building an Ontology of Community Resilience

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Abstract

Background: Community resilience to a disaster is a complex phenomenon studied using a variety of research lenses, such as psychological and ecological, resulting in a lack of consensus about what the key factors are that make a community resilient. Formally representing this knowledge will allow researchers to better understand the links between the knowledge generated using different lenses and help to integrate new findings into the existing body of knowledge.

Objective: Using ontology engineering methods to represent this knowledge will provide a tool to aid researchers in the field.

Methods: An ontology is a structured way of organizing and representing knowledge in the field of community resilience to a disaster. The model created using this method can be read by a computer, which allows a reasoner to manipulate and infer new knowledge.

Results: When using these methods to structure community resilience knowledge some of the complexities and ambiguities were identified. These included semantic ambiguities, such as two distinct factors being used interchangeably or two terms being used to describe the same factor, making the distinction between what are the factors and the characteristics of those factors, and finally, the inherited characteristics and relationships associated with hierarchical relationships.

Conclusions: Having the knowledge about community resilience to a disaster represented in an ontology will aid researchers when operationalizing this knowledge in the future.

CHAPTER 1: Introduction

1.1: Background

The increasing numbers of natural disasters and the interdependency of national economies amplify the need for better response to these unexpected events (Berkes & Ross, 2013). Natural disasters have been growing in frequency of events, people affected, and costs of recovery (EM-DAT, 2009), resulting in an increased economic burden nationally and locally. The limited financial capacity to respond to disasters and their increasing frequency has created the incentive for nations and communities to prepare prior to a disaster to mitigate its effects. While much of the research on community resilience to a disaster focuses on response, it is necessary to develop interventions to build community resilience prior to a disaster (O'Sullivan, Kuziemsky, Toal-Sullivan, & Corneil, 2013). In order to leverage resilience in advance, it is important to know the key factors that contribute to this phenomenon so effective interventions can be designed to build community resilience prior to a disaster.

Community resilience has been defined as *a community's ability to resist, absorb, and recover from a disturbance, such as a disaster* (Holling, 1973). Research has shown that no single factor contributes to community resilience; rather, it is a combination of factors that together make a community resilient to a disaster. The way in which different communities are structured and function prior to a disaster are unique; the impacts a disaster can have on a community vary depending on a number of factors including the type, severity, and extent of disaster damage.

However, when operationalizing this knowledge about community resilience to a disaster, it is important to determine which factors are universal, and which factors are specific to a given context (community type and/or disaster). To study such a complex topic, researchers have used theoretical lenses such as the ecological and psychological approaches.

The factors that are considered essential to the definition of community resilience to a disaster depend on the community studied, the type of disaster, and the theoretical approach. Given this complexity, there is a lack of consensus about how to operationalize knowledge about community resilience to a disaster, which ultimately hinders disaster planning (Berkes & Ross, 2013; Norris, Stevens, Pfefferbaum, Wyche, & Pfefferbaum, 2008a). While there is a substantial body of research about the key factors that make a community resilient to a disaster, these factors have not been integrated and structured into one framework or model in an organized manner. Structuring this knowledge base should help stimulate debate about which factors need to be represented and how these factors synergistically contribute to the resilience of a community. By representing multiple research perspectives in one model and capturing the interrelatedness of these perspectives, researchers will be able to better identify how multiple theories can be integrated and applied in practice.

'Ontology' is usually defined as a structured way of organizing a knowledge composed of concepts or factors (the main constructs or building blocks of a knowledge base) and the relationships between these factors (Fox, Barbuceanu, Gruninger, & Lin, 1998; Lin & Sakamoto, 2009). Ontology engineering is a method that has been successfully used in biomedicine and computer sciences to organize and represent knowledge (Noy & McGuinness, 2001). Prior research using this method has largely involved disaster management rather than community resilience (Grolinger, 2013; Sotoodeh, 2007; Xu, 2007; Joshi, Seker, Bayrak, Ramaswamy, & Connelley, 2007). Current ontologies, such as those representing disaster mitigation and planning knowledge (Joshi, Seker, Bayrak, Ramaswamy, & Connelley, 2007), would be important to link to a community resilience ontology in the future. Using ontological engineering, a model can be created to systematically represent key factors of community resilience that exist across different research approaches, and the relationships between those factors.

In the field of community resilience, researchers focus on developing theoretical frameworks to support interventions aimed at increasing a community's capacity to respond to a disaster. Having current knowledge in this field organized and represented using ontology engineering will, through the integration of the various concepts discussed in the literature, aid in the application of this knowledge when developing community-based interventions. This thesis research will demonstrate how this can be accomplished, based on a subsection of the knowledge about community resilience to a disaster. Disaster researchers are the intended audience for the results of this research.

1.2: Benefits of Using an Ontology

The two main benefits of using an ontology to represent community resilience knowledge are: 1) the formalizing of knowledge in the field and 2) the ability to reason or manipulate that knowledge. Representing the community resilience knowledge in such a formal way will encourage researchers to consider adopting this method when reporting future results to expand the knowledge base contained in the model. By continuously expanding a single ontology, researchers will be able to integrate new concepts with ease into the existing knowledge base using the approach proposed in this thesis. This will ensure that the knowledge does not become static; rather, it will evolve along with the field.

The second benefit of using ontology engineering methods to represent community resilience knowledge is the ability to reason using this model to manipulate and infer new knowledge. With the aim of incorporating new research results into an ontology, researchers will also be forced to consider the implications of adding new factors or relationships within the existing model. One of the advantages of an ontology is the ability to infer new relationships based on those that are asserted in the model. Therefore, when adding new factors or relationships, it is important to consider the implications of such changes. For example, when describing a new relationship between disaster and environment, is the link between these two factors, or between specific types of disasters and environments? The difference is illustrated using the following possible relationships: 1) natural disasters affect the ecological environment; versus 2) disasters affect the ecological environment. The implication in the second relationship is that all types of disasters affect the ecological environment; however, is this true of pandemics, such as Ebola? It is this emphasis on the implications of linking one factor to another that will benefit researchers when integrating new factors and relationships into the existing body of knowledge.

1.3 Research Objective

The formalizing of knowledge and ability to reason are both benefits for researchers, however, using ontology engineering methods to represent the entire body of knowledge is a significant undertaking. As such, the first step is demonstrating the importance of using an ontology and how such a representation can benefit researchers. This thesis aims to discuss this first step through describing some of the complexities in the knowledge about community resilience and explaining how an ontology can be used to help unpack some of these complexities.

Building a complete ontology of community resilience to a disaster knowledge is outside of the scope of this research. Considering that systematic representation of domain knowledge about community resilience to a disaster benefits researchers in this field, these benefits are illustrated through a number of the examples. Thus, the objective of this research is to use of these examples to illustrate potential benefits and advantages of using ontology engineering methods to represent the knowledge.

1.4: Research Hypothesis and Research Questions

There are many different theories about what makes a community resilient to a disaster. The factors that make up knowledge developed from these theories are often categorized as the ecological (or socio-ecological) perspective and the psychological perspective (Berkes & Ross, 2013; Norris et al., 2008a), amongst others. While there are some overlapping factors between these two perspectives, there are also differences. This diversity of viewpoints is a testimony to the complexity of this field. For this thesis, an illustrative ontology was developed to show how complexities could be represented. When building the illustrative ontology, both the ecological and psychological perspectives were considered.

The research hypothesis is: *Structuring the knowledge about community resilience to a disaster using ontology engineering will provide a tool to facilitate the use of such knowledge in practice*.

Answers to the following research questions will verify this hypothesis:

1. How can knowledge about community resilience to a disaster be defined?
2. How can the complexities of this knowledge be identified and represented?
3. How can First Order Logic (FOL), as an ontological engineering method, be used to identify and address ambiguities/complexities in the knowledge?

1.5: Plan of Thesis

This thesis begins with a literature review that describes the current state of knowledge with respect to the various approaches to community resilience to a disaster. Also included in this section is a brief review concerning what is knowledge and how knowledge can be represented. Next, the Methods section describes ontological engineering and its role in developing a systematic representation of the knowledge about community resilience to a disaster. This section details how the knowledge sources for this thesis were defined and how the factors and relationships were extracted to answer research question 1. The second part of the Methods section describes how the knowledge was organized and represented in an ontology using first order logic (FOL). Next, the Results section describes the sources of complexity in this field and how with a help of FOL and ontology they can be addressed. This section is primarily concerned with Research Questions 2 and 3, through identifying and addressing complexities in the knowledge caused by semantic ambiguity, as well as using FOL to identify logical inconsistencies that must be addressed.

The Discussion section describes the potential uses of ontology to represent community resilience knowledge. The thesis finishes with the limitations of this study and areas of future research. The appendix lists the articles selected as the source for knowledge extraction, definitions of concepts used in the ontology, lists of the relationships (with reference to the articles from which they were derived), the hierarchies of terms, and the model and output of the reasoner algorithm used to derive at the results presented in the Discussion section.

CHAPTER 2: Literature Review

2.1: Community Resilience to a Disaster

There are many different types of resilience (Norris et al., 2008a), and in this research we focus on community resilience to a disaster, which is often defined as the adaptive capacity of a community to respond to a disaster (Berkes & Ross, 2013; Castleden, McKee, Murray, & Leonardi, 2011; Collier et al., 2009; Gunderson, 2010a; Ireland, 2010; Klein, Nicholls, & Thomalla, 2003a; Norris et al., 2008a; Obrist, Pfeiffer, & Henley, 2010; Wallace & Wallace, 2008a). Having this research focus allows the operationalization of local knowledge to inform the process of disaster planning, the use of local social networks to identify those individuals or groups at higher risk, and to develop local responses that can be tailored to the unique needs of a community (Andrew, 2012).

Using multiple research approaches to studying community resilience to a disaster has led researchers to disagree about what the key factors are when describing this phenomenon. This is best illustrated by looking at community resilience from the ecological and psychological perspectives.

The ecological approach examines the community as a complex socio-ecological system that focuses on the interactions between society and its environment. Due to its origins in ecology, this approach considers how changes in the natural environment affect society and the adaptations in response to changes that occur both in nature and within human societies. Many researchers in the ecological field (Bahadur, Ibrahim, & Tanner, 2013; Gunderson, 2010a; Klein, Nicholls, & Thomalla, 2003b; Kuhlicke, 2013; Obrist et al., 2010) reference the following definition of community resilience as "a measure of (1) the amount of change the system can undergo and still retain the same controls on function and structure, (2) the degree to which the system is capable of self-organization, and (3) the community's ability to build and increase its capacity for learning and adaptation" (Berkes & Jolly, 2002, pg 2-3). Researchers using this approach, for example, examine how climate change affects animal populations and how those diminishing numbers affect communities reliant on hunting for survival (Berkes & Jolly, 2001). In justification for the use of this particular definition, Berkes & Jolly (2001) state that factors such as self-organization, social learning, and adaptation, cited in the definintion, emerged in their research. While this definition fits within this particular research setting, it does not include such factors as social support, economic development, or community competence, concepts emphasized by other researchers (Bahadur et al., 2013; Berkes & Ross, 2013; Gunderson, 2010b; Klein et al., 2003b; Norris et al., 2008a; Obrist et al., 2010)

In comparison, the psychological approach focuses on the interaction between individuals within a community. This approach recognizes that while the natural environment and its impacts on society are important, the ability of individuals and communities to adapt to a wide range of resources in the face of adversity is important (Norris et al., 2008a); for example, using social networks to learn about food safety following a power outage.

In addition to the ecological and psychological approaches, researchers also study resilience using an urban resilience approach, which focuses specifically on how cities or urban centres (not rural areas) resist and recover in response to a disaster (Castleden et al., 2011; Wallace & Wallace, 2008a). Moreover, community resilience is also studied using an organizational lens in an effort to understand how the survival or collapse of various public and private organizations affects the overall resilience of a community (Castleden et al., 2011; Thomas, 2007). These various theoretical approaches have led researchers to develop different understandings about which factors a community must possess to become resilient to a disaster. Table 1 below gives examples of how the factors vary across the two research approaches, while many of the factors are shared, it is often the emphasis and how they are used that differs. For example, social capital is a key factor for both research approaches, however, in the ecological view this functions an umbrella term while the psychological view examines it more in depth. Having an organized representation of these factors across perspectives in a single ontology will help to integrate the findings.

Table 1: Comparison of Ecological and Psychological Approaches

Ecological Approach	**Psychological Approach**
Resources (Tyler & Moench, 2012)	Resource Equity (Harte, Childs, & Hastings, 2009; Kulig, Edge, & Joyce, 2008; Landau, 2007; Norris et al., 2008a; Onstad et al., 2012; Paturas, Smith, Smith, & Albanese, 2010; Pfefferbaum, Reissman, Pfefferbaum, Klomp, & Gurwitch, 2007; Rogerson & Emes, 2008)
Adaptation (Berke, Cooper, Salvesen, Spurlock, & Rausch, 2011; Cox, 2012; Goldstein, 2008; Greene & Greene, Dec 2009; Gunderson, 2010b; Tyler & Moench, 2012)	Adaptive Capacity (Harte, Childs, & Hastings, 2009; Kulig, Edge, & Joyce, 2008; Landau, 2007; Norris et al., 2008a; Onstad et al., 2012; Paturas, Smith, Smith, & Albanese, 2010; Pfefferbaum, Reissman, Pfefferbaum, Klomp, & Gurwitch, 2007; Rogerson & Emes, 2008)
Social Learning (Goldstein, 2008; Tyler & Moench, 2012)	Collective Action (Harte, Childs, & Hastings, 2009; Kulig, Edge, & Joyce, 2008; Landau, 2007; Norris et al., 2008a; Onstad et al., 2012; Paturas, Smith, Smith, & Albanese, 2010; Pfefferbaum, Reissman, Pfefferbaum, Klomp, & Gurwitch, 2007; Rogerson & Emes, 2008)
Social Capital (Goldstein, 2008; Mayunga, 2007; Poortinga, 2012)	Social Support (Harte, Childs, & Hastings, 2009; Kulig, Edge, & Joyce, 2008; Landau, 2007; Norris et al., 2008a; Onstad et al., 2012; Paturas, Smith, Smith, & Albanese, 2010; Pfefferbaum, Reissman, Pfefferbaum, Klomp, & Gurwitch, 2007; Rogerson & Emes, 2008)

While using different approaches and having different sets of factors is normal in research, this creates the potential for semantic ambiguity and logical inconsistency in the knowledge. Semantic ambiguity may be caused by the use of many different terms to describe the same factor; leading to confusion regarding whether these terms are equivalent or different. The opposite is also true: ambiguous use of terms can lead to two terms being used synonymously when they describe distinct factors. Semantic ambiguity also contributes to potential logical inconsistencies; a lack of understanding about which factors are equivalent or different can lead to conflicts in the relationships described.

2.2: Knowledge Representation

2.2.1: What is knowledge?

According to knowledge management researchers, there are two types of knowledge: explicit and tacit knowledge (Grant, 2007). It was Polanyi who first made this distinction between knowledge that can be expressed using language (explicit knowledge) and tacit knowledge, which is more challenging to verbally articulate (Zhenhua, 2003). The concept of tacit knowledge is complex, with some researchers arguing that it is any un-articulable knowledge, while others claim it is knowledge that is challenging to articulate but not impossible (Zhenhua, 2003). For example, a person can be taught all the steps required to perform a ballet dance; however, this explicit knowledge is not enough, truly great dancers possess tacit knowledge of the movements which allows them to perform beautifully.

This discussion of tacit and explicit knowledge is important when considering what knowledge can be represented and what cannot be captured. Specifically, a knowledge engineer can represent explicit knowledge about community resilience to a disaster, but she/he often lacks abilities to elicit and represent the tacit knowledge. However, when confronted with semantic ambiguity or logical inconsistencies in the knowledge, a knowledge engineer must rely on the domain expert's tacit knowledge to resolve these problems. When conducting this thesis research only explicit knowledge is considered and it is extracted from the journal articles.

Another important consideration when describing knowledge is context. Any knowledge is context specific (Grant, 2007). For example, knowledge about community resilience to an acute, unexpected event is different from the response to a long-term disaster situation such as civil war. If asked how best to build the resilience of a community it is important to consider the type of disaster and the unique characteristics of the community before applying current knowledge regarding interventions. This is why, when conducting this research, all of the factors that contribute to community resilience and their relationships to one another are considered within the research context of the knowledge base articles selected through the literature search process (described later). Here, a notion of context refers to the specific situation in which the research is being conducted. However, future research should consider the larger context of community resilience knowledge (the wider body of knowledge) when expanding the ontology as this is important.

2.2.2: What is knowledge representation?

There are many methods that can be used to represent knowledge, such as taxonomies or semantic networks. In deciding which to use, a knowledge engineer must consider the roles of knowledge representation in general (Davis, Shrobe, & Szolovits, 1993) One of the purposes of representing knowledge is to apply various computer software programs in order to perform tasks. For example, representing medical decision-making knowledge allows clinician decision support systems to be created to aid in diagnostics. Related to this purpose, the first role is to increase the computational efficiency in order to speed this process (generating a decision). While not within the scope of this thesis, this is a consideration when designing future research.

The second role of knowledge representation is as a surrogate or model of reality. In order to reason about a topic, there needs to be a model or understanding of the knowledge (such as a model describing what is a disaster) that can be manipulated to answer certain questions (Davis et al., 1993). Any knowledge representation is only a model of reality. As such, certain choices must be made when choosing a method regarding what is important for the body of knowledge and the end users (Davis et al., 1993). These choices are called ontological commitments and are the third role of knowledge representation. These commitments provide guidance for the researcher about how to build the knowledge representation, which allows the complexity of representing a knowledge to become a more manageable process (Davis et al., 1993). Ontological commitments for this thesis research included: the decision not to represent the entire knowledge, rather the knowledge contained in a set of journal articles; the inclusion of both psychological and ecological approaches; and focusing on factors at a higher abstraction level, to name a few.

The fourth role is as a fragmentary theory of intelligent reasoning, which highlights the fact that the knowledge representation will only include a fragment of the insight into intelligent reasoning that inspired it; this insight is only part of the larger phenomenon known as intelligent reasoning (Davis et al., 1993). When considering the fragmentary theory role within the context of this thesis, all knowledge cannot be represented. In this case the part of knowledge being represented is that pertaining to community resilience to a disaster. In addition, for this research it was knowledge extracted from journal articles that was represented, leading to an incomplete representation of community resilience knowledge.

The final role that is pertinent to this thesis is as a medium of human expression. A knowledge representation functions as a way of providing information to a machine (Davis et al., 1993), in this case creating an ontology that can be used by an algorithm, called a reasoner, to help identify semantic ambiguity and logical inconsistencies. This role of knowledge representation emphasizes how the model selected impacts its use. When considering this final role, a knowledge engineer must consider how general or specific the model must be, how expressive it needs to be, etc. For this thesis, the method chosen needed to be capable of representing the complex relationships contained in the community resilience body of knowledge.

All these roles must be considered when selecting the method for representing knowledge about community resilience to a disaster. There are four basic methods from which a researcher can choose: semantic networks, frame representations, rule representations, or logical representations (Colton, 2007).

Semantic network is based on human natural tendency to organize knowledge based on associations and hierarchies (Colton, 2007). This knowledge representation method uses nodes and links to represent concepts (or objects) and the connections between them (Colton, 2007; Sowa, 2014). This method would not capture the complexity of the relationships between factors in community resilience knowledge through nodes and links.

The frame representation method, based on semantic networks, has nodes and links with procedural information attached to each node (García, 2006). In frame representations, each node (or frame) represents a situation (or object) and information about related processes that can be attached (Colton, 2007; Davis et al., 1993). This knowledge representation method can be used to organize knowledge or dictate action (Colton, 2007). For the purposes of this research, process information was not considered important to capture, as a result frame representations were not used.

The next method, production rule representation, uses a set of condition-action (if-then) statements, which facilitate plausible inferences by determining if the conditions are met by the facts contained in the knowledge base (Colton, 2007; Davis et al., 1993; García, 2006). If conditions are met then the rule is activated in order to derive at the action (Colton, 2007; García, 2006). An example of using this method would be the following statements: if you are hungry then go to the kitchen, if there are leftovers in the fridge then put them in the microwave, etc. This method was not used as the relationships between concepts, such as hungry and kitchen, were capable of capturing the complexity of the community resilience field.

Finally, the logical representation method uses different types of logical formalism, such as first order logic (FOL), propositional logic (PL), higher order logic (HOL), or fuzzy logic, to represent knowledge (Colton, 2007). These types of logic have varying degrees of expressivity and different functions, which are considerations used when choosing which formalism to use (Colton, 2007; García, 2006). The ontology method, using FOL as the language, was chosen because it is capable of representing the complex relationships involved in community resilience knowledge, unlike the nodes and links of semantic networks for example. Further, while FOL is expressive enough for this purpose, the interpretation of a model using this logic does not suffer from semantic ambiguities. In addition, the development of hierarchies that infer the inheritance of characteristics and relationships that is part of ontology engineering is important when representing community resilience knowledge. Researchers in this field already use hierarchies to organize knowledge, making this an important consideration when organizing and representing the knowledge for this thesis. The following section will describe how this method was used when creating the sample ontology, which illustrates the benefits to researchers in the field of having such a representation.

CHAPTER 3: Methods

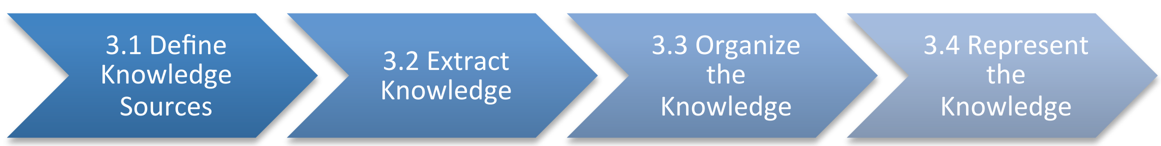
The following section describes the methods used to build the illustrative (or sample) ontology. The study methods used for this thesis research are borrowed from METHONTOLOGY, ontology development methods proposed by Fernandez, Gomez-Perez, and Juristo (1997). This method was selected as it is targeted at less experienced ontology engineers (Pinto & Martins, 2004) and it has been used in similar fields, such as health care (Zeshan & Mohamad, 2012). METHONTOLOGY uses the following development process when building an ontology:

- Planning the ontology steps,
- Specifying the requirements or scope of the ontology,
- Conceptualization of the problem,
- Formalization of the knowledge in form of an ontology,
- Integration with other ontologies,
- Implementation of the ontology using some formal language, evaluation and documentation of what was created,
- Mainteinance of the ontology.

This section outlines the plan used to build the ontology, as summarized in Figure 1, this thesis also serves as a documentation of how this ontology was built and the actual sample ontology in the appendix. The scope of the ontology knowedge being represented in the research was defined in the literature review as describing community resilience to a disaster knowledge across multiple research approaches. Conceptualizing the problem encompases both defining the knowledge source and extracting the knowledge, as described further in this section. For this thesis, fist order logic (FOL) was used to formalize the knowledge and is described further in 3.4.1. For the purposes of this research, the last two phases of METHONTOLOGY were not conducted.

As outlined in Figure 1, the first section describes how the knowledge sources were defined and the literature search strategy used. Next, the method used for extracting knowledge from journal articles is outlined, followed by a brief description of how the factors were initially organized. Finally, the ontology methods are outlined, followed by a description of how this method was applied to knowledge in this field.

Figure 1: Research Process



3.1: Define knowledge sources

For the purpose of this research, the knowledge was extracted from the academic articles describing, from different perspectives, community resilience to a disaster. A structured literature search was conducted and 31 journal articles (referenced in Appendix A) were selected as the knowledge source to be represented in the illustrative ontology.

3.1.1: Literature Search Strategy

A semi-structured literature search was conducted in December 2013 with the assistance of a librarian. The following six databases were searched: Ovid MEDLINE (US National Library of Medicine), PsycINFO (American Psychological Association), EBSCO (EBSCOhost Online Research Databases), Global Health (Public Health Database, EBSCO), Engineering Village (Elsevier), and SCOPUS (Elsevier). Table 2 below outlines the Boolean search terms, limitations, and exclusions used for each database and the number of results from each search.

Table 2: Literature Search Strategy

Database	Boolean Search	# Articles
OVID	[Community OR residence characteristics] AND [ecosystem OR 'adaptation, psychological' OR 'resilience, psychological' OR resilience] AND [disasters OR disaster planning OR emergencies] -Limit to English Language	231
PsycINFO	Resilience (psychological)[i] AND [disasters OR emergency management OR emergency preparedness] AND communities -Limit to English Language	34
OVID & PsycINFO	[Communit* OR residence characteristics OR (socio* AND ecologic*)] AND disaster AND resilien* -Limit to humans and English Language	304
EBSCO	Community AND resilience AND disasters -Limit to Peer Reviewed, English Language Subject limitations[ii] Thesaurus term limitations[iii]	187
Global Health	[Community OR socio ecological] AND resilience AND disaster -Limit to English Language, journal articles	32
Engineering Village	[Socio ecologic* OR communit*] AND resilien* AND disaster -Limit to English Language, journal articles Exclude Risk Assessment and Geologic Hazards	230
SCOPUS	[Socio ecologic* OR communit*] AND resilien* AND disaster AND NOT [organizational OR business] -Limit to English Language, journal articles and reviews Exclude business articles	229
Total Articles		1,247

These searches yielded 1,247 journal articles that were compiled and duplicates removed. Titles and abstracts were then reviewed, applying the following exclusion criteria:

1) Eliminate articles that only discuss individual or organizational resilience,
2) Eliminate articles in which the authors' definition of disasters is not: having acute onset, being time delimited, collectively experienced and potentially traumatic with human, natural, or technological causes (Norris et al., 2008a).

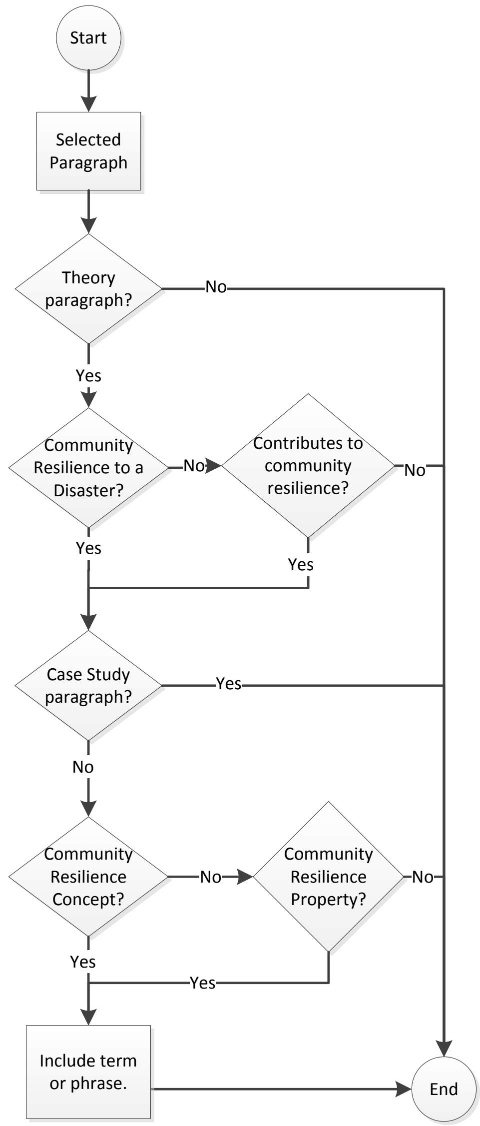
Articles that discuss community resilience from both the psychological or ecological approach were included. Application of the exclusion/inclusion criteria produced a list of 180 articles. Finally, from this list, only articles concerned with a theoretical discussion about community resilience to a disaster were considered. This is because case studies were found to be too specific and limiting in terms of the number of factors and relationships; this produced a final list of 31 articles published between 1998-2013 in 28 different academic journals, these articles were used for knowledge extraction.

3.2: Extract knowledge from the articles

A knowledge extraction framework was developed to ensure that the same process of extracting the knowledge was consistently applied to all 31 articles. The proposed knowledge extraction framework was based on the PICO method used by The Cochrane Collaboration and others, as part of their systematic review process (Cochrane Collaboration, 2013). Application of the PICO method allows the extraction of information from each article about **P**atient (or Population), the **I**ntervention applied to that patient group, **C**ontrol used, and the **O**utcomes reported (Higgins & Green, 2011). For the purposes of our research, this method was adapted to extract the following information from each article: **C**oncepts - information describing factors impacting community resilience, **A**bstraction level of information (or granularity) – information describing the scope at which these factors are discussed, and **P**roperties – information describing the relationships identified between different factors. The acronym for this knowledge extraction method is CAP.

The CAP method was applied to the entire article and it was part of an iterative process that relied on the researcher and domain expert's (Dr. O'Sullivan) knowledge about community resilience to a disaster, to ensure that all the key factors and relationships were extracted and were at the same level of abstraction. Figure 2 outlines how the CAP method was applied to each paragraph to enhance the objectivity of this process.

Figure 2: Use of the CAP Method to extract data from each paragraph



As seen in Figure 2, when reviewing each paragraph, it was important to take into consideration the larger context of the section or article when determining whether this paragraph contains important information to extract. Some paragraphs did not explicitly use the words 'community resilience to a disaster'; however, within the context of the article it was implied. For example, the following excerpt from Gunderson (2010b) does not use the words 'community resilience to a disaster,' however; *capital* is a key factor when representing knowledge:

> "*Different forms of capital are critical to post- disturbance recovery in both types of systems. These include natural capital (Folke et al. 2002) and social capital (Putnam 2000) as well as other economically defined forms of capital. Natural capital in this sense refers to the stocks (or goods) in ecosystems that provide service or use to humanity. One example is the release of organic matter from coastal vegetation associated with hurricanes. Hurricane-force winds defoliate trees, and storm surges and tides dislodge organic soils. As a result, estuaries and coastal systems receive large inputs of organic matter, which in turn fuels a post-disturbance pulse in the estuarine production of shrimp, fish, and other organisms* (Day et al. 2007)" (pg. 5).

Within the context of the article, it is evident that the term 'post-disturbance recovery' refers to *resilience* and 'both types of systems' refers to *community* as well as *ecological systems*; making this a relevant paragraph for knowledge extraction. Table 3 illustrates the results of applying the CAP method to this paragraph.

Table 3: Example of the Application of the CAP Method

Concepts	Abstraction level	Properties
Capital	Concept	"critical to" recovery
Natural capital Social capital Economic capital	Subconcepts of capital	"is-a" or hierarchical relationship to 'capital'

The other consideration when applying the CAP method pertains to how factors unfamiliar to the researcher were handled. For example, 'reactive capacity' was considered a new concept and as a result I consulted the domain expert about its relevance to the overall knowledge about community resilience to disaster. In this study, new or unfamiliar factors were documented and either, through review of the other articles these factors became clear, or the domain expert (Dr. O'Sullivan) was asked to clarify. This process of applying the CAP method to the knowledge base articles was applied twice to ensure that no factors were missed in the first review, as familiarization with these articles allowed new factors to emerge.

3.3: Organizing the knowledge

The factors extracted from all of the articles were compiled and any duplicates were removed resulting in a list of 648 factors. The next step in the research process was to cluster these and eliminate similar ones as the first step in organizing the knowledge.

3.3.1: Clustering Factors and Building the Relationships

When faced with the task of representing 648 factors and the relationships between them it was important to develop a way of organizing the factors first before linking them. With the goal of creating a hierarchy of factors to allow for inheritance, the first step was to group similar factors into clusters that would eventually become the hierarchies. The word cluster is being used because at this phase in the research no consideration was being taken to the relatedness of these factors other than hierarchical. When beginning the clustering process, the model of community resilience to a disaster presented by Norris et al (2008) was used to make it more manageable for the researcher. In their model, Norris et al (2008) list the following factors as being key to community resilience knowledge and which were used as labels for clusters during this process: resources, disaster, environment, capacities, and resilience types. Adjustments to their model were made as other factors were added, leading to 10 clusters in total, which are each captured in the figures in Appendix D. Each factor from the original list was considered within the context of the article from which they were derived to determine to which cluster they belong.

Once the clustering was completed, relationships between the factors within the clusters were investigated, forming 10 silos of knowledge that were connected later. These relationships were written using FOL formulas to establish the connections between the factors within each of the 10 clusters. An important consideration in this stage is the idea of inheritance. In a hierarchy, more specific factors inherit the characteristics of the more general factors to which they belong. As a result, it was important to define these factors as part of this process to ensure correct positioning within the hierarchy. Definitions for each factor were used to determine differences, as well as the generality or specificity within the model. FOL was used to define the *Social Capital* and *Community Competence,* which then allows a reasoner to infer the relationship between *Community Participation* and *Social Capital* using the inherited characteristics (discussed further in the results). An example of using FOL to represent hierarchical relationships is the following axiom which states that community participation is a type of social capital:

$$\forall x \text{ Community\_Participation}(x) \rightarrow \text{Social\_Capital}(x)$$

The definitions for the factors included in this thesis are captured in Appendix B while the hierarchy of factors can be found in Appendix D.

3.4: Representing the Knowledge

When developing the hierarchies in section 3.3 relationship between these distinct clusters are not representing, forming silos of knowledge. The next step is to represent the connections between these silos of knowledge. While other methods can represent the hierarchical relationships captured thus far, the notion of inheritance that was emphasized in ontology engineering was a driver in choosing this method. Section 3.4.1 below gives an overview of general ontology methods while section 3.4.2 illustrates how these methods were applied to the community resilience to a disaster literature for the purposes of this thesis.

3.4.1: Ontology Methods

An ontology is a structured way of formalizing and organizing knowledge about a particular topic, such as community resilience to a disaster. This knowledge is not only composed of concepts, but also the relationships between them (Fox et al., 1998; Lin & Sakamoto, 2009). For example, ontology engineering is used to identify factors such as *adaptation, change,* and *resources* when representing knowledge about community resilience to a disaster. However, representing factors is not enough, FOL is used to establish the relationships between these factors. It is the ability to represent complex knowledge using an ontology that distinguishes this method from others, such as a hierarchy of terms.

First Order Logic

As discussed in the literature review, first order logic (FOL) is the formalized logic used to build a knowledge representation, such as this thesis ontology. The role of FOL is as a language used to logically represent the concepts and relationships within the model. FOL is a formal language that uses syntax – symbols that can be combined to create axioms (statements) – and semantics – the interpretations of syntax, to represent knowledge (García, 2006). Syntax includes logical and non-logical symbols; non-logical symbols are the labels used to represent the relationships between concepts which are tailored to fit the field being represented, for example, 'enhances' was a relationship between social capital and community resilience which was created for this thesis. Logical symbols, by comparison, have the same meaning across fields (García, 2006). These include quantifiers such as ∀ representing *for all* relation, and ∃ representing *there exists* relation, logical connectives such as ∧ representing *and* relation ∨ representing *or* relation, → representing *implies* relation ↔ representing *biconditional* relation and ¬ representing a *negation*, brackets (), variables, and the equality symbol (=) (García, 2006). The use of FOL will be demonstrated further in the results section below.

FOL uses a set of axioms, statements or arguments, to capture the knowledge within a field. The community resilience field contains complexities that are best represented using the expressive nature of FOL, as represented by the number of logical symbols and the inclusion of non-logical symbols as part of this formal system of representation. Much of the expressive nature of FOL versus other logics, such as propositional logic, is derived from the ability to use quantifiers. This was particularly important within the community resilience field as relationships were not always linear, changes in the size of a social network or its connectedness with information sources affects whether this factor increases or decreases a community's resilience to a disaster, for example (Wallace & Wallace, 2008a).

3.4.2: Application of Ontology Methods

After the hierarchical relationships were written in FOL, the relationships between the various hierarchies were added. Relationships between factors extracted using the CAP method were written using FOL, as well as implicit ones that were used when building the ontology (such as 'a community has an environment'). When adding the other relationships (non-hierarchical) extracted using the CAP method, the knowledge base articles were consulted for context of the article to ensure the FOL relationships accurately represented the knowledge. As illustrated in Table 3, when applying the CAP method to extract factors and relationships, notes were taken about potential labels for the relationships between factors given the sentence or paragraph of that article. When compiling the relationships used to link factors, an effort was made to use the same label for similar situations, such as using only 'increases' rather than increases, enhances, improves, and builds, etc. When writing the FOL axioms linking factors, the original sentence or paragraph from the data sources was reviewed to ensure that the label selected accurately represented the knowledge contained in that article.

Once the relationships from previous applications of the CAP method were exhausted, the knowledge base articles were reviewed again with a specific focus on extracting relationships between factors contained in the literature. This step was important as previous reviews using the CAP method were focused on extracting the factors to build the hierarchies, resulting in some relationships being overlooked. Oversight occurred when the same factor was used multiple times in the same article, such as more than 10 times, in these instances the factor was noted however, one of the subtleties of how it related to others were missed in the first review. Once the relationships between factors were extracted from the articles they were written in FOL and can be found in Appendix C, Tables 14, 15, and 16.

CHAPTER 4: Results

4.1: Illustrative Ontology

When conducting this research, a sample ontology was created to represent the knowledge contained in the 31 selected journal articles. However, as this model was not tested it serves as an illustration of how an ontology can be built and the advantages of using this method, for researchers in this field. The illustrative ontology can be found in Appendix C shown as tables which list the English language relationships, how they appear in FOL, and a reference to the journal article each relationship was extracted from. The ontology also contains relationships that are important for the functioning of the ontology but which are not explicitly stated in articles. For example, articles describing community resilience to a disaster do not explicitly state that 'a community has community resilience to a disaster'; however, this type of relationship is important to accurately and appropriately represent the knowledge in the field. These relationships are also contained in Appendix C in a separate table.

An ontology using FOL represents knowledge using a set of logical formulas or axioms. These FOL axioms are used to describe the relationships between various factors, as described in the methods section. The advantage of having this set of logical formulas is the ability to query the knowledge being represented. This allows researchers to both determine possible questions that can be used to query the knowledge, and determine what conclusions can be derived. When querying the knowledge, these FOL axioms are entered into a reasoner, such as Z3, to create a model which an algorithm can use to reason about the knowledge (query the knowledge). In order to illustrate this process, consider the relationship: Communities that have a small range/diversity of resources are less resilient. The FOL axiom used to represent this relationship is the following:

$$\forall\ x,y,z,w\ (Community(x) \wedge Resource(y) \wedge hasResource(x,y) \wedge Diversity\ (z) \wedge hasDiversity(y,z) \wedge hasValue(z,low) \wedge CRtD(w) \wedge\ hasResilience(x,w)) \rightarrow hasValue(w,low)$$

When using the Z3 reasoner the input for creating this relationship is:

```
 // For the Classes
func_decl Community = function("Community", Variable, Predicate);
func_decl Resource = function("Resource", Variable, Predicate);
//For the relations
func_decl hasResource = function("hasResource", Variable, Variable, Predicate);
func_decl hasValue = function("hasValue", Variable, Variable, Predicate);
func_decl hasDiversity = function("hasDiversity", Variable, Variable, Predicate);
func_decl hasResilience = function("hasResilience", Variable, Variable, Predicate);
//Constants
    expr high = c.int_const("high");
expr low = c.int_const("low");
expr medium = c.int_const("medium");
expr veryhigh = c.int_const("veryhigh");
//Instances
expr Ottawa = c.int_const("Ottawa");
expr CRtDO = c.int_const("CRtDO");
expr ResourceO = c.int_const("ResourceO");
expr DiversityO = c.int_const("DiversityO");
//Declaration of the logical variables used in the FOL formula
expr x = c.int_const("x");
expr y = c.int_const("y");
expr z = c.int_const("z");
expr v = c.int_const("v");
  solver s(c);
//Assertion
s.add(Community(Ottawa));
    s.add(CRtD(CRtDO));
```

```
    s.add(Resource(ResourceO));
        s.add(Diversity(DiversityO));
    s.add(hasResilience(Ottawa,CRtDO));
        s.add(hasDiversity(Ottawa,DiversityO));
        s.add(hasResource(Ottawa,ResourceO));
    s.add(hasValue(DiversityO,low));
    //Datatypes
    s.add(Datatype(high));
    s.add(Datatype(veryhigh));
    s.add(Datatype(low));
    s.add(Datatype(medium));
    //For axioms
    // Communities that have a small range/diversity of resources are less resilient
    s.add(forall(x,y,z,v, implies((Community(x) and Resource(y) and
hasResource(x,y) and Diversity (z) and hasDiversity (y,z) and hasValue(z,low) and
CRtD(v) and hasResilience(x,v)), hasValue(v,low))));
```

The model above lists the possible classes, relations, constants, specific instance and assertions that will be used to query the knowledge (Ottawa), logical variables and datatypes used to build the axiom, and the axiom that is being queried. In this example we are defining 'Ottawa' as an example of 'community' and asserting that it's value for resource diversity is 'low'. Using these assertions and the relationship stated in the model, the Z3 reasoner states that 'low' is the value for Ottawa's resilience, as seen in the output below (for this example and the results section, only the part of the reasoner output applicable to the example will be shown):

```
(define-fun CRtD ((x!1 Int)) Bool
  (CRtD!174 (k!171 x!1)))
(define-fun hasValue!181 ((x!1 Int) (x!2 Int)) Bool
(ite (and (= x!1 6) (= x!2 22)) true
veryhigh = 24
low = 22
high = 21
medium = 23
ResourceO = 8
Ottawa = 0
CRtDO = 6
```

The highlighted portion of the output above states that, according to the model and assertions contained in Z3, CRtDO (Ottawa's community resilience to a disaster) is low.

The following results sections will use portions of the illustrative ontology to demonstrate how having an ontology and using a reasoner can be used to identify challenges in representing community resilience knowledge and how they were addressed for this thesis. These examples will allow researchers in the field to better understand the advantages of having such a representation and the potential uses for such an ontology. Section 4.2 gives examples of how the second research question was answered when building the illustrative ontology. The third research question is addressed in sections 4.3-4.5 through the use of a reasoner to detect logical inconsistencies in the ontology.

4.2: Semantic Ambiguities

One of the major sources of complexity in the knowledge about community resilience to a disaster is the ambiguous use of terms to describe factors. In some cases, many different terms are used to describe the same factors, due in large part to having different approaches (eg. ecological or psychological) used to study community resilience. This creates difficulties when representing knowledge from multiple sources in a single ontology. In addition, readers may misinterpret a factor when multiple terms are used. The opposite is also true: ambiguous use of terms can lead to two terms being used synonymously when describing two distinct factors. This confusion, caused by semantic ambiguity, ultimately hinders the field by detracting from the question of how these various factors affect community resilience to a disaster.

4.2.1: Two factors to describe the same concept

In many cases, researchers using different approaches use different terminology to describe the same factor, leading readers to question whether these are equivalent or distinct? When building an ontology, it is important to define each factor using FOL statements and axioms to avoid semantic ambiguities being incorporated into the model. Using FOL axioms to define terms included in the ontology also allows equivalent terms to be identified. While the reasoner cannot automatically identify semantic ambiguities, a knowledge engineer reading it's output is able to determine when the model is using two factors as if they are equivalent, as demonstrated in the following example.

When developing the illustrative ontology, one example of semantic ambiguity from the selected articles was the use of the terms natural disaster and ecological disaster. Some of the knowledge base articles used the term "natural disaster", while others used "ecological disaster", both without explicitly stating whether these factors of community resilience were equivalent or different. However, a Z3 reasoner using FOL axioms to define these factors can assert their equivalence in the reasoner output, as will be illustrated through this example. When building the illustrative ontology, a definition (axiom) was created stating that 'disasters that have a natural cause and affect a community are a type of natural disaster' (Axiom 1). A second definition stated that 'disasters that have a natural cause and affect a community are a type of ecological disaster' (Axiom 2).

Axiom 1: $\forall$x, y (Disaster (x) $\wedge$ Natural_Cause (y) $\wedge$ has_Cause (x, y) $\wedge$ Community (z) $\wedge$ has_Affect_On (x, z)) $\rightarrow$ Natural_Disaster (x)

Axiom 2: $\forall$x, y (Disaster (x) $\wedge$ Natural_Cause (y) $\wedge$ has_Cause (x, y) $\wedge$ Community (z) $\wedge$ has_Affect_On (x, z)) $\rightarrow$ Ecological_Disaster (x)

In FOL axioms such as axiom 1, 'Disaster (x)' states that every time the variable x is used in that axiom it is referring to the factor 'disaster' (with each new axiom the meaning of the variables is reset). FOL uses these variables to allow logical statements to be created with ease. Once these relationships have been described as FOL formulas, an instance of disaster, such as 2012 Alberta Flood, can be created to query the relationships contained in the ontology, allowing equivalences to be identified. The following FOL axioms define '2012 Alberta Flood' as being a disaster with a natural cause:

Axiom 3: $\forall$x, y (Disaster (x) $\wedge$ Natural_Cause (y) $\wedge$ has_Cause (x, y) $\wedge$ Community (z) $\wedge$ has_Affect_On (x, z)) $\rightarrow$ 2012_Alberta_Flood (x)

When using the Z3 reasoner on this model, the output would state the following:

```
(define-fun NaturalDisaster!174 ((x!1 Int)) Bool
  (ite (= x!1 8) true
(define-fun EcologicalDisaster!174 ((x!1 Int)) Bool
  (ite (= x!1 8) true
2012AlbertaFlood = 8
```

This output states that 2012 Alberta Flood is a type of Natural Disaster and a type of Ecological Disaster, indicating to the knowledge engineer reading this output that these factors are logically equivalent. A FOL axiom can be added to the model to represent this equivalence:

Axiom 4: $\forall$ x (Ecological_Disaster (x)) $\leftrightarrow$ Natural_Disaster (x)

The inclusion of this axiom ensures that relationships using the term 'Ecological Disaster' would also be applied to 'Natural Disaster,' and vice versa, without the knowledge engineer having to specify these relationships separately.

4.2.2: Two distinct factors being used equivalently

Another aspect of semantic ambiguity is the interchangeable use of factors that are not equivalent. Due to authors describing factors in their research without explicit definitions, these factors are used differently depending upon the author of the article; in this case one author implies that two factors are different while another uses them interchangeably as if equivalent. An example from the illustrative ontology is the use of the factors *community engagemen*t and *community participation* interchangeably by some researchers, and as distinct factors by others. This creates confusion within the field about how these factors should be treated. In this example there are two ways this complexity can be identified using the reasoner: 1) the model contains an instance of only one factor rather than both (as in the 2012 Alberta Flood example), or 2) inconsistency is determined.

The first instance is similar to the example about natural versus ecological disasters. If a domain expert theorizes that two concepts are equivalent then a query, such as in section 4.1.1, will yield similar results. In the example above, these factors are defined as different: community engagement is defined as a community that is empowered in using their resources, while community participation is considered a community that has meaningful use of resources, as stated in Axioms 5 and 6:

Axiom 5: ∀x, y (Community (x) ∧ Resource (y) ∧ has (x, y) ∧ has_Characteristic (y, empowering)) → Community_Engagement (y)

Axiom 6: ∀x, y (Community (x) ∧ Resource (y) ∧ has (x, y) ∧ has_Characteristic (y, meaningful use)) → Community_Participation (y)

An instance of community engagement, called 'political campaigning,' could be added with the characteristic of 'empowerment' as part of the definition:

Axiom 7: ∀x, y (Community (x) ∧ Resource (y) ∧ has (x, y) ∧ has_Characteristic (y, empowerment) ∧ has_Characteristic (y, political goal)) → Political_Campaigning (y)

Based on Axiom 5 and 7 the reasoner would infer that campaigning is a type of community engagement, as shown in the following output:

```
(define-fun CommunityEngagement!174 ((x!1 Int)) Bool
  (ite (= x!1 9) true
PoliticalCampaigning = 9
```

This output demonstrates that community engagement and community participation are different factors according to the knowledge represented in the model. If a researcher considers these factors equivalent then, either the model needs to be changed to reflect that, or the researcher needs to alter their theory about community engagement and participation given this representation of the knowledge. Revising the model to incorporate the fact that these concepts are different requires adding the following FOL formula:

Axiom 8: $\forall$ x (Community_Participation (x) $\rightarrow$ $\neg$ Community_Engagement (x))

By including axiom 8 in the ontology this ensures that the reasoner will generate an error if a new relationship is added which implies that community participation and engagement are equivalent.

The second method to identify semantic ambiguity is exploring logical inconsistencies in the model. In this case, the knowledge engineer would need to specific relationships that are implied in the knowledge base articles, not just those explicitly stated. The articles used when building the sample ontology did not explicitly state that community engagement and community participation were equivalent or not, however, it was the way in which these factors were described that indicated how they should be interpreted. For example, in one article, an author listed community engagement and community participation along with other factors that were included in the concept of social capital – implying they are distinct. When representing the knowledge from this article, axiom 8 applies. When analyzing a second article, which uses the factors community engagement and community participation interchangeably, the following axiom should be created:

Axiom 9: $\forall$ x (Community_Participation (x)) $\leftrightarrow$ Community_Engagement (x)

Clearly these two axioms are contradictory and, as a result, the Z3 reasoner would generate the following error:

```
sarahs-mbp:build sarahnewell26$ ./cpp_example
unsat
```

unexpected error: invalid usage

This error message indicates to the knowledge engineer that there exist unsatisfiable relationships in the model (Axioms 8 and 9) that need to be resolved before Z3 can reason using the model.

4.3: Characteristics vs. concepts

When building an ontology, factors retrieved from the articles are the building blocks of the knowledge – they are those concepts that must be represented in order to represent the knowledge. Factors exist independently of the characteristics used to quantify or qualify the concept, however, the opposite is not true. For example, “environment” is a factor while “harsh” is a characteristic of an environment, because the concept of “environment” exists independently from the concept of “harsh”.

When reviewing the articles, there were many examples of concepts that consisted of both a factor and characteristic. For example, researchers also describe good policy (Etkin & Stefanovic, 2005), good outcomes (Obrist et al, 2010), strong leadership (Walsh, 2007), engaged governance (Berkes & Ross, 2012), community strengths (Berkes & Ross, 2012; Barr & Devine-Wright, 2012; Haque & Burton, 2005), and community assets (Mayunga, 2007; Berkes & Ross, 2012; Andrew, 2012; Obrist et al, 2010; Burkle, 2011). The problem with representing these phrases together as a factor is that often these concepts which are described as “assets” or “strengths” can also be seen as “threats” or “challenges” in different circumstances.

The problems caused by qualified or quantified factors are evident in the Wallace and Wallace (2008) article, which stated that dense social ties are not always seen as an asset to a community. If the social network is large and connected to the political structure, then it promotes rapid flow of information, whereas social networks that are small and isolated actually have a slow flow of information, which reduces the resilience of the community. Therefore, representing social networks as a community asset would be problematic as social networks can be both assets and challenges. When representing the knowledge in the ontology, neutral terms were selected to represent each factor and relationships were used to qualify or quantify these factors given certain situations, as illustrated in the example below.

In this example, one article might describe good governance as decentralized organizations using local knowledge, as represented in the FOL axiom below:

Axiom 10: ∀x, y, z (Community (x) ∧ Decentralized_Organizations (y) ∧ has (x, y) ∧ Local_Knowledge (z) ∧ Uses (x, z)) → Good_Governance (x)

However, in order to represent the knowledge from a second article arguing that good governance is local knowledge and public/private partnerships, the following axiom needs to be created:

Axiom 11: ∀x, y, z (Community (x) ∧ Public_Private_Partnerships (y) ∧ has (x, y) ∧ Local_Knowledge (z) ∧ Uses (x, z)) → Good_Governance (x)

In this model good governance is defined in two different ways, this will not create an error using the Z3 reasoner until instances of good governance are created. For example, an instance of good governance called Good Governance Ottawa is added to the model and it is asserted that Ottawa has local knowledge and decentralized organizations:

Axiom 12: $\forall$x, y, z (Community (x) $\wedge$ Decentralized_Organizations (y) $\wedge$ has (x, y) $\wedge$ Local_Knowledge (z) $\wedge$ Uses (x, z)) $\rightarrow$ Ottawa (x)

The reasoner output would state the following:

```
(define-fun GoodGovernance ((x!1 Int)) Bool
 true)
(define-fun Disaster ((x!1 Int)) Bool
 true)
(define-fun Datatype ((x!1 Int)) Bool
 (Datatype!284 (k!278 x!1)))
(define-fun PublicPrivatePartnership ((x!1 Int)) Bool
 false)
(define-fun isDisaster ((x!1 Int) (x!2 Int)) Bool
 false)
(define-fun SocialNetwork!285 ((x!1 Int)) Bool
 (ite (= x!1 2) true
 (ite (= x!1 12) true
 (ite (= x!1 18) true
 (ite (= x!1 22) true
```

This output states that good governance is true, however, there are no instances of good governance being true, as compared to social network (at the bottom of the output) that has 4 instances that are true. Therefore, the knowledge engineer would need to review the model to determine that Axioms 10 and 11 are the problem and consult with a domain expert to determine if both statements are indeed true when describing governance. If so, than "good" is a characteristic of "governance", consequently the axioms should be rewritten as:

Axiom 13: $\forall$x, y, z, v (Community (x) $\wedge$ Governance (y) $\wedge$ has_Governance (x, y) $\wedge$ Public_Private_Partnerships (z) $\wedge$ has (x, z) $\wedge$ Local_Knowledge (v) $\wedge$ Uses (x, v)) $\rightarrow$ has_Value (y, good)

Axiom 14: $\forall x, y, z, v$ (Community (x) $\wedge$ Governance (y) $\wedge$ has_Governance (x, y) $\wedge$ Decentralized_Organizations (z) $\wedge$ has (x, z) $\wedge$ Local_Knowledge (v) $\wedge$ Uses (x, v)) $\rightarrow$ has_Value (y, good)

While axioms 13 and 14 are similar to axioms 10 and 11, the main difference is the effect of these relationships on an instance. In axioms 13 and 14, an instance of governance can have the characteristic 'good' in either situation without causing a conflict. This demonstrates the ability of formal knowledge representation to help to establish differences between the concepts and their characteristics, further clarifying how knowledge is being represented.

4.4: Inherited Characteristics

The concept of inheritance applies both to relationships and characteristics. Inheritance is the notion that a subconcept shares the relationships and characteristics of the more general concept to which it belongs, however, there exists certain relationships and characteristics that are not shared with the general concept– making the subconcept more specific. For example, ecological environment shares the relationships and characteristics attributed to the concept environment, while still possessing attributes that make it distinct. If the relationship 'environment is affected by a disaster' exists than as a subconcept of environment, ecological environment is also affected by a disaster.

Inheritance of characteristics within an ontology can be used to represent multiple theories in a single model. When creating the illustrative ontology, there were two theories regarding how to categorize the subconcepts of resources. When representing both theories, using the characteristics of each category and the principle of inheritance, these two theories were integrated using inferences made by Z3. This process is explained in the following example.

In the illustrative ontology, the issue of resource was the most difficult when developing the hierarchy of terms. For example, when writing about resources two researchers described different ways of categorizing the various types. According to Hobfoll (2012), resources fall under the following categories: *condition resources* which are defined as "structures or states that allow access to or the possession of other resources" (Alvaro et al., 2010); *personal resources* which are those skills and traits of the individual that bolster community resilience; *object resources* which are any resources with a physical presence; and *energy resources* which are "those whose value is derived from their ability to be exchanged for other resources" (Alvaro et al., 2010). In comparison, Norris et al (2008b) argue that resources are divided into the categories of *social capital*, *community competence*, *economic development*, and *information & communication*. The integration of these two ways of categorizing 'resource' can be done automatically and the reasoner can infer hierarchical relationships that can be used to integrate these two categorizations. For example, the following axioms need to be created for the illustrative ontology to define all the possible categorizations of a 'resource':

Axiom 15: $\forall x$ (Resource (x) $\wedge$ has_Value (x, state_of_Community)) $\rightarrow$ Condition_Resource (x)

Axiom 16: $\forall x$ (Resource (x) $\wedge$ has_Value (x, exchangeable)) $\rightarrow$ Energy_Resource (x)

Axiom 17: ∀x (Resource (x) ∧ has_Value (x, state_of_Community) ∧ has_Value (x, network_of_relationships)) → Social_Capital (x)

Axiom 18: ∀x (Resource (x) ∧ has_Value (x, state_of_Community) ∧ has_Value (x, capacity_for_action)) → Community_Competence (x)

Axiom 19: ∀x (Resource (x) ∧ has_Value (x, state_of_Community) ∧ has_Value (x, transmit_information)) → Communication (x)

Axiom 20: ∀x (Resource (x) ∧ has_Value (x, exchangeable) ∧ has_Value (x, facts)) → Information (x)

Axiom 21: ∀x (Resource (x) ∧ has_Value (x, exchangeable) ∧ has_Value (x, financial)) → Economic_Development (x)

Based on the seven axioms above, the reasoner will determine that social capital, community competence, and communication are all subconcepts of condition resource because they share the characteristic of 'state of community resources'. However, they are all unique subconcepts because the other characteristics are not shared amongst them. The reasoner will also determine that information and economic development are subconcepts of energy resource because they share the characteristic of being 'exchangeable resources'. The following Z3 output shows how the reasoner infers the hierarchy based on inheritance:

```
(define-fun ConditionResource!285 ((x!1 Int)) Bool
  (ite (= x!1 3) true
  (ite (= x!1 4) true
  (ite (= x!1 5) true
 (define-fun EnergyResource!285 ((x!1 Int)) Bool
  (ite (= x!1 6) true
  (ite (= x!1 7) true
SocialCapital = 3
CommunityCompetence = 4
Communication = 5
```

Information = 6
EconomicDevelopment = 7

This ability of an ontology to infer knowledge is one of the advantages when using this method to represent multiple research approaches.

4.5: Inherited relationships

When connecting two factors, (eg. Using a characteristic to quantify or qualify a factor), it is important to consider the abstraction level of these factors, because both characteristics and relationships are inherited within the hierarchy, as described in 4.4. As a result of inheritance, a knowledge engineer must consider the implications of relating one concept versus another, for example, relating community to environment as compared to ecological environment.

When building the illustrative ontology, 'resource' was the most complex concept to represent. As such, it is an excellent example of the challenge in capturing the notion of the inheritance of relationships between factors and their implications. For example, Norris et al (2008) state "*Communities that are dependent on a narrow range of resources are less able to cope with change that involves the depletion of that resource*" (pg 134). Here Norris et al (2008) are using the term range to describe the quantity of different resources, also known as diversity. In the illustrative ontology there are over 180 subconcepts of *Resource* that would all inherit this relationship. When making a statement like this, it is unclear whether the authors considered whether all 180 types of resources have the characteristic 'diverse'. If so, the authors are arguing that "Communities that are dependent on a narrow range of [social capital, community competence, information & communication, and economic development] are less able to cope with change that involves the depletion of that resource" (pg 134) (as these are the categories of resources stated earlier in their article). While on the surface this may seem an appropriate statement, is it accurate to state that a wide range of information regarding how to respond in a disaster is beneficial? It is likely that they are referring to a specific type of resource when making such a statement. The notion of inheritance when representing the knowledge about community resilience to a disaster using an ontology forces researchers to consider the implications of statements before including them in the model. The example below demonstrates how the use of FOL emphasizes the need to address this issue regarding inherited relationships by making the hierarchy, and as a result the inheritance patterns, explicit.

Axiom 22: ∀ x Social_Capital (x) → Condition_Resource (x)

Axiom 23: ∀ x Community_Competence (x) → Condition_Resource (x)

Axiom 24: ∀ x Communication (x) → Condition_Resource (x)

Axiom 25: ∀ x Information (x) → Energy_Resource (x)

Axiom 26: ∀ x Economic_Development (x) → Energy_Resource (x)

Axiom 27: ∀ x Condition_Resource (x) → Resource (x)

Axiom 28: ∀ x Energy_Resource (x) → Resource (x)

Axiom 29: ∀x, y, z (Community (x) ∧ Resource (y) ∧ has_Resource (x, y) ∧ has_Value (y, diverse) ∧ Community_Resilience_To_A_Disaster (z) ∧ has_Resilience (x, z)) → has_Value (z, high)

Axiom 30: $\forall x$ Resources $(x) \rightarrow (\exists$ y Datatype $(y) \wedge$ has_Value $(x, y))$

Axiom 31: Range constraint for Resources: $\forall x, y$ (Resources $(x) \wedge$ Datatype $(y) \wedge$ has_Value $(x, y)) \rightarrow (y =$ narrow $\vee$ y = diverse$)$

Axioms 22-24 state that social capital, community competence, and communication are subconcepts of condition resource, axioms 25 and 26 state that information and economic development are subconcepts of energy resource, and axioms 27 and 28 state that condition and energy resources are subconcepts or resource. The 29th axiom describes the problematic relationship that ‘communities with resources that are diverse have high levels of community resilience to a disaster. Axiom 30 specifies that ‘resource’ can be measured, and Axiom 31 defines possible values as either ‘narrow’ or ‘diverse’. As part of the ontology, a statement specifying that ‘information diversity does not lead to community resilience’ (axiom 32) needs to be added, so that relationships such as the one written in axiom 29 would generate an error due to the conflict between these two relationships as information is a type of resource but does not have the characteristic ‘diverse’.

Axiom 32: $\forall$ x Information $(x) \rightarrow \neg$ has_Value (x, diverse)

Axiom 32 specifies that information cannot have the characteristic of being diverse, which allows a researcher to check for unsatisfiable axioms, and determine that axiom 25 and 28 combined with axiom 29 conflicts with axiom 32, making the model unsatisfiable.

CHAPTER 5: Discussion

5.1.1: Integrating new knowledge in the field

As a result of the limited of structure in the knowledge of community resilience to a disaster, integrating new findings into the existing body of knowledge is challenging. Currently when a researcher is integrating results, they have the potential for semantic misinterpretation, and may neglect a key area of the knowledge. When representing knowledge using an ontology and integrating new knowledge into a single ontology, these semantic ambiguities and potential misinterpretations are limited. It is important when modeling a complex phenomenon, such as community resilience to a disaster, to include as much of the knowledge as possible to fully represent the field and enhance the ability of the reasoner. For example, there would be a problem if new research results regarding the impact of different aspects of social capital on community resilience did not acknowledge the work of Wallace & Wallace (2008b) regarding the impact social networks and information flow have on resilience. As social networks are a type of social capital, the researchers would need to consider this link when describing the overall phenomenon observed in their research. By representing the knowledge using an ontology, researchers are able to avoid such problems when incorporating the results within the wider body of knowledge, as all the knowledge would be contained in a single ontology.

5.1.2: Using the reasoner to find new areas of research

One of the advantages of representing the knowledge using an ontology is the ability to use a computer to reason about the knowledge in order to identify problems, such as the ones mentioned in the results section. For the purposes of this thesis research, reasoning offers two potential functions that would be advantageous for community resilience researchers: the ability to determine if a model has any contradictions, as demonstrated in the results section, and the ability to query the knowledge. In order to query the knowledge, the ontology must include instances and values for these instances. Once instances are included in the ontology, a reasoner can be used to query the knowledge or determine values associated with individual communities or disaster instances.

There are two main ways that the application of a reasoner can benefit community resilience researchers, the first being through identifying potential new areas of expertise. In this case, data measuring the levels of community resilience factors for specific instances can be used to indicate when knowledge is incomplete. When all the known relationships between factors that are considered indicators of community resilience to a disaster are represented in a single ontology, data can be associated with this model to determine whether there are unexplained phenomena occurring which require further study. This concept is best understood using the example described below:

The relationships of interest for this example are those described by Wallace & Wallace(2008b): 1) 'If a community has a large, dense social network then their information flow is rapid resulting in high levels of community resilience to a disaster', and 2) 'If a community has a small, dense social network then their information flow is slow resulting in low levels of community resilience to a disaster'. Using the following four communities as instances, a gap in knowledge can be identified using the Z3 reasoner discussed earlier:

- Ottawa - large, dense social network, rapid information flow, and high community resilience;
- Owen Sound - small, dense social network, slow information flow, and low community resilience;
- Toronto - large, dense social network, slow information flow, and low community resilience; and
- Port Elgin - small, dense social network, rapid information flow, and high community resilience.

The this case, the reasoner would state that, given the two relationships contained in the model, the community resilience values for Ottawa and Owen Sound are true while the values for Port Elgin and Toronto are false. This would indicate to the researcher that something unusual must be happening to cause Port Elgin and Toronto not to represented by the model – Port Elgin was selected for this mock case study to demonstrate that other factors need to be considered because, while it is a small community in southwestern Ontario, it is home to Bruce Nuclear Power Plant, causing it to have rapid information flow within the community and high levels of community resilience.   However, this is not the only way the reasoner can be applied to these relationships.

5.1.3: Using the reasoner to predict values for community resilience

The second application of the reasoner that is beneficial to researchers in this field is in determining the values for community resilience when given values for certain factors. In this case, the same communities from the previous example could be used, however, the values for community resilience would be excluded. Given the two relationships contained in the ontology, the reasoner would be able to state that Ottawa has high community resilience to a disaster and Owen Sound has low community resilience to a disaster. However, in the case of Port Elgin and Toronto, two more relationships would need to be added to handle these different situations as the reasoner would simply not give values for these communities. For the purposes of this example, the following relationships were added: 'If a community has large, dense social network and slow information flow then it has medium levels of community resilience to a disaster' and 'If a community has small, dense social network and rapid information flow then it has very high levels of community resilience to a disaster'. This would allow the reasoner to assign the community resilience value of 'medium' to Toronto and 'very high' to Port Elgin. This example of the use of a reasoner can be found in Appendix E; the first part of Appendix E is the ontology modeled using C++ and the second part is the Z3 reasoner output giving the community resilience values for the 4 sample communities.

This ability to query the knowledge would allow researchers to further understand the impact of representing and integrating the knowledge from various research approaches.

5.2: Limitations

There were two main limitation of this thesis research: 1) the CAP method, and 2) the inability to test the model given the constraints of the thesis.

5.2.1: Limitations in capturing and representing knowledge

When designing this research project it became apparent that having a way to objectively extract factors and relationships from the articles was important. The goal when creating the CAP method was to ensure that the process of extracting knowledge was the same for all articles so that no factors or relationships were neglected. The CAP method was developed based on the existing PICO method; however, it was not tested for validity. When developing the CAP method an important decision involved defining what information was important to extract. This is a limitation of the thesis, as a flaw in the data extraction process could cause certain factors or relationships to be overlooked.

5.2.2: Limitation of not representing the complete knowledge

The second limitation for this thesis was the lack of evaluation of the model created. When designing an ontology, researchers often develop a set of goals, or tasks, which the ontology must be able to perform – called competency questions. These competency questions are used to define the scope of the ontology and determine when it is complete. Competency questions are very specific and are regarding instances of each factor, such as the ability to perform the task described in the discussion section. For the purposes of this thesis, inclusion of instances was not appropriate given the focus on representing the overall knowledge rather than instances of concepts. As a result of the lack of instances and the demonstrative nature of this thesis, the ontology could not be evaluated to determine if the knowledge is represented accurately.

5.3: Future Research

An important area of future research involves rigorous testing of the CAP method used to extract the data. Validating the data extraction method used would ensure that any expansion of this thesis ontology in the future would accurately represent the knowledge. Ideally a number of researchers would be asked to apply the CAP method to the same set of articles and the number of factors and relationships extracted that were the same would be tallied against those that were different – similar to the inter-rater reliability test used in qualitative coding. This testing of the CAP method would be important to determine if the Concept, Abstraction level, and Properties are the appropriate items to extract and whether the flow diagram describing the application of the CAP method is complete.

As mentioned in the introduction, this thesis functions as a demonstration of how ontology methods can be applied to this field and the benefits of having such a representation. Future research would ideally expand the scope of this research to represent the entire body of knowledge. As described in the CAP method, all factors included were at a higher abstraction level – such as resources, community, and disaster, rather than Salvation Army, Calgary, and 2012 Alberta Flood. By definition these decisions cause only part of the knowledge about community resilience to a disaster to be represented in this thesis research. The first area for future research would be to include all conceptual levels in the ontology, which would greatly expand the ontology and allow for enhanced reasoning capacity.

The second method to expand the model would be to include more or different articles as knowledge sources. A challenge in the community resilience to a disaster field is that literature is published in a variety of journals and stored in a variety of databases, as a result of the variety of approaches used to study community resilience to a disaster. Another method to use when representing all the knowledge would be consulting experts in the field of community resilience to a disaster. These individuals could either be interviewed, or participate in a focus group to provide consensus about what are the key factors and relationships needed to represent the knowledge. Using either an expanded literature search or expert opinion as the knowledge source is the next step towards developing a complete ontology of community resilience to a disaster knowledge. Having a complete representation increases the ability of the reasoner and allows evaluation of the model created.

5.4 Contributions to the Field

The following represent the contributions that this thesis research makes to the field:

- Demonstration how ontology engineering methods can be applied to social science research, such as the study of community resilience to a disaster.

- Demonstration of how reasoning on the ontology can help with indentification of complex concepts and their explanation.
- Proposal of CAP method - a new method for annotating knowledge from journal articles.

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Appendices

Appendix A – Articles used in the study

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Appendix B – Concept definitions

Table 4: Capacity

Term	Definition	Citation
Capacity	"The combination of all the strengths, attributes and resources available within a community, society or organization that can be used to achieve agreed goals."	(UNISDR, 2007)
	"The ability or power to do or understand something"	(Oxford University Press, 2014h)
Adaptive Capacity	"Adaptive capacities are resources with dynamic attributes. "	Norris et al, 2008, pg 130
Community Capacity	"(1) the characteristics of communities that affect their ability to identify, mobilize, and address social and public health problems and (2) the cultivation and use of transferable knowledge, skills, systems, and resources that affect community- and individual-level changes consistent with public health-related goals and objectives."	Norris et al, 2008, pg 136
Adapt (Human Capacity)	Human ability to "become adjusted to new conditions"	(Oxford University Press, 2014c)
Agency (Human Capacity)	"capacity to affect things and is therefore linked to power"	Obrist et al, 2010, pg 290
Anticipate (Human Capacity)	"Guess or be aware of (what will happen) and take action in order to be prepared"	(Oxford University Press, 2014d)
Cope (Human Capacity)	Ability to "deal effectively with something difficult"	(Oxford University Press, 2014l)
Recover (Human Capacity)	"The action or process of regaining possession or control of something stolen or lost" or "A return to a normal state of health, mind, or strength"	(Oxford University Press, 2014ag)
Resist (Human Capacity)	"Withstand the action or effect of"	(Oxford University Press, 2014ah)
Transformabi lity	"capacity 'to create untried beginnings from which to evolve a new way of living'"	Walker et al, 2004, 7, in Berkes & Ross, 2012, pg 5

Table 5: Resource

Term	**Definition**	**Citation**
Resource	"a host of objects, conditions, characteristics, and energies that people value"	Norris et al, 2008, pg 134
Condition Resource	structures or states that allow access to or the possession of other resources (eg. Status at work, good health, employment, marriage)	Alvaro et al, 2010
Capital	"Wealth in the form of money or other assets owned by a person or organization or available for a purpose such as starting a company or investing"	(Oxford University Press, 2014i)
Cultural Capital	"legitimate knowledge of one kind or another, that is skills and education"	Obrist et al, 2010, pg 288
Embodied Cultural Capital	"personal dispositions and habits"	Obrist et al, 2010, pg 288
Institutional Cultural Capital	"educational qualification"	Obrist et al, 2010, pg 288
Objectified Cultural Capital	"knowledge and tradition stored in material forms"	Obrist et al, 2010, pg 288
Ecological Capital	"land, water and wildlife"	Obrist et al, 2010, pg 287
Economic Capital	"command over economic resources, mainly cash and assets"	Obrist et al, 2010, pg 288
Human Capital	"ability to work, health and knowledge"	Obrist et al, 2010, pg 287
Physical Capital	"transport, shelter, and energy"	Obrist et al, 2010, pg 287
Social Capital	network of relationships linked to resources	Characteristic defined for thesis
Collective Consciousness (SC)	"set of shared beliefs, ideas, and moral attitudes that unify a community"	*Collins Dictionary of Sociology*, p93
Community Engagement (SC)	"community is empowered to apply it's collective skills and resources"	(Tasmanian Department of Health and Human Services, 2014)
Community Participation (SC)	ensuring meaningful engagement with communities	(Tasmanian Department of Health and Human Services, 2014)
Coordinate (SC)	bring different elements of a community into a relationship to ensure efficiency	(Oxford University Press, 2014k)

Empowerment (SC)	"a process through which people lacking an equal share of valued resources gain greater access to and control over those resources"	Norris et al, 2008, pg 142
Formal Empowerment (SC)	"mechanisms for citizen input"	Norris et al, 2008, pg 142
Instrumental Empowerment (SC)	"ability to participate in and influence decision, as determined by knowledge, material resources, and persuasiveness"	Norris et al, 2008, pg 142
Intrapersonal Empowerment (SC)	"feelings of personal competence and confidence"	Norris et al, 2008, pg 142
Substantive Empowerment (SC)	"ability to reach decisions that solve problems"	(Norris et al, 2008, pg 142)
Place Attachment (SC)	"emotional connection to one's neighborhood or city, somewhat apart from connections to the specific people who live there"	(Norris et al, 20008, pg 139)
Sense of Belonging (SC)	feeling connected to one's surroundings (people, places, and things)	composite for thesis
Sense of Community (SC)	"an attitude of bonding (trust and belonging) with other members of one's group or locale"	(Norris et al, 2008, pg 139)
Community Pride (Sense of Community)	satisfied sense of attachment to one's community	composite for thesis
Sense of Security (SC)	feeling safe from attack, having confidence that your needs will be met, sense that everything will be alright	composite for thesis
Social Network (SC)	"a network of social interactions and personal relationships"	(Oxford University Press, 2014ak)
Connectedness (SN)	"associated with or related to others, the state of being connected"	(Princeton University, n.d.)
Organizational Linkages (Connectedness)	connections between organizations within the community	composite for thesis
Social Embeddedness (Connectedness)	"Frequency and intensity of interactions"	(Norris et al, 2008, pg 139)

Knowledge Network (SN)	networks that aim to share information and create knowledge	composite for thesis
Social Cohesion (SN)	"Self-help and mutual support"	(Norris et al, 2008, pg 139)
Social Support (SC)	"social interactions that provide individuals with actual assistance and embed them into a web of social relationships perceived to be loving, caring, and readily available in times of need"	(Barrera, 1986, in Norris et al, 2008, pg 138)
Perceived Social Support	"the belief that help would be available if needed"	(Norris et al, 2008, pg 138)
Received Social Support	"actual receipt of help"	(Norris et al, 2008, pg 138)
Symbolic Capital	"power-related resources"	(Obrist et al, 2010, pg 288)
Communication	"the creation of common meanings and understandings and the provision of opportunities for members to articulate needs, view, and attitudes"	(Norris et al, 2008, pg 140)
Awareness	"The extent of common knowledge about disaster risks, the factors that lead to disasters and the actions that can be taken individually and collectively to reduce exposure and vulnerability to hazards."	(UNISDR, 2007)
Communal Narrative	story that creates meaning for the community to deal with the disaster	Norris et al, 2008
Communication Infrastructure	Infrastructure: "The basic physical and organizational structures and facilities (e.g. buildings, roads, power supplies) needed for the operation of a society or enterprise"	(Oxford University Press, 2014u)
Information Flow	"path information takes to get from it's origin to end users"	(Business Dictionary, 2014a)
Information Technology Use	as a channel for information	composite created for thesis
Information Use Skills	ability or capability to use information in an effective way	composite created for thesis
Organizational Communication	communication within and between organizations	composite created for thesis
Trusted Information Sources	a member of the community whom you rely on for information	composite created for thesis

Understanding Skill	being able to accurately interpret information	composite created for thesis
Community Competence	networked sense of capacity for action	characteristic defined for thesis
Capacity Building	understanding obstacles and enhancing abilities	characteristic defined for thesis
Capacity for Failure	omission of expected or required action	characteristic defined for thesis
Collaboration	The capacity to work with others in order to accomplish a shared goal.	characteristic defined for thesis
Collective Efficacy	"reflects trust in the effectiveness of organized community action"	(Norris et al, 2008, pg 141)
Community Action	acting collectively, define needs and determine action to be taken	composite created for thesis
Community Development	action taken by citizens to build stronger, more resilient communities	(Peer Net BC, n.d.)
Community Ownership	assets or organizations that are owned and controlled by the community	Characteristic defined for thesis
Community Planning	"technical and political process [of] … design of the urban environment"	(Harvard Law School, 2014)
Community Self-Organization	action of organizing, spontaneously arrange components (people or resources)	(Business Dictionary, 2014c)
Coping	"The ability of people, organizations and systems, using available skills and resources, to face and manage adverse conditions, emergencies or disasters."	(UNISDR, 2007)
Critical Reflection Capacity	deciding on the action to be taken to respond to a disaster	composite created for thesis
Problem Solving Capacity	finding a solution to a difficult problem	(Business Dictionary, 2014b)
Sense of Agency	capacity of agent to act in the world	Norris et al, 2008
Governance	process and decisions that define actions	characteristic defined for thesis
Leadership	"action of leading a group of people"	(Oxford University Press, 2014x)
Learning	"acquisition of knowledge or skills through experience"	(Oxford University Press, 2014y)
Episodic Learning	"involves the creation of new policies or approaches to solve the problems that were revealed by [a disaster]"	(Gunderson, 2010, pg 6)

Transformational Learning	"solving problems in identified problem domains among sets of difficult and complex variables"	(Gunderson, 2010, pg 6)
Power	"the capacity to direct or influence the behavior of others"	(Oxford University Press, 2014ad)
Public Trust	"belief in the reliability, truth, ability, or strength of someone"	(Oxford University Press, 2014am)
Social Infrastructure	Infrastructure: "The basic physical and organizational structures and facilities (e.g. buildings, roads, power supplies) needed for the operation of a society or enterprise"	(Oxford University Press, 2014u)
Public Education	Government funded education - "The process of receiving or giving systematic instruction, especially at a school or university"	(Oxford University Press, 2014p)
Public Health	"The health of the population as a whole, especially as monitored, regulated, and promoted by the state"	(Oxford University Press, 2014ae)
Public Policy	"The principles, often unwritten, on which social laws are based"	(Oxford University Press, 2014af)
Community Status	measurement of the state of the community at a given time point	characteristic created for thesis
Political Structure	institutions and groups and their relations to each other, patterns of interaction within political systems	Characteristic created for thesis
Political Support	to aid the cause, policy, or interest of	composite created for thesis
Political Will	"unconditional use of political power to benefit the public welfare"	composite created for thesis
Energy Resource	those whose value is derived from their ability to be exchanged for other resources (eg. Money, knowledge, credit)	(Alvaro et al, 2010, pg 3)
Knowledge	"Facts, information, and skills acquired through experience or education; the theoretical or practical understanding of a subject"	(Oxford University Press, 2014w)
Information	"Facts provided or learned about something or someone"	(Oxford University Press, 2014t)
Economic Development	economic development refers to actions of policy makers and communities to promote the standard of living and economic health	composite

Access	to obtain or retrieve something	(Oxford University Press, 2014b)
Alternative Livelihood	diversifying livelihoods to mitigate the effect of a disaster	composite
Business Opportunity	opportunity to build a business (either a new business or expand on an existing one)	composite
Workforce	"people engaged or available for work"	(Oxford University Press, 2014an)
Personal Resources	skills and traits (eg. Occupational skills, self-esteem)	(Alvaro et al, 2010. pg 3)
Object Resources	have physical presence (eg. Clothing, shelter, car, house)	(Alvaro et al, 2010, pg 3)
Physical Infrastructure	Infrastructure: "The basic physical and organizational structures and facilities (e.g. buildings, roads, power supplies) needed for the operation of a society or enterprise"	(Oxford University Press, 2014u)
Intervention Resources	tools that "prevent or alter a result or course of events"	(Oxford University Press, 2014v)
Emotional Sharing	recount and share emotional experiences with others	composite
Adaptation	"'building resilience' and 'increasing capacity' within ecosystems to cope with change"	(Haque & Burton, 2005, pg 341)
Adaptation Process	Relieve adversity, restore basic needs, and rekindle hope	Klein et al, 2003
Anticipatory Adaptation	Enhance adaptability, improve physical infrastructure, increase flexibility, and reverse vulnerability: public awareness and preparedness	Klein et al, 2003
Climate Change Adaptation	Climate-proofing, climate-resilient crops, climate-resilient infrastructure, promoting better information, and improved planning	Klein et al, 2003
No-risk Adaptation	"used to argue that linking DRR with adaptation is beneficial as it addresses existing climate variability while building resilience for future uncertainty"	Ireland, 2010, pg 339
Community Based Approach	approaches taken that include the community in both the planning and execution of the intervention	created for thesis

Disaster Management	Thinking and planning effectively, situational knowledge, knowledge about what to do, human-computer interaction, and media	Masten & Obradovic, 2008
Disaster Risk Reduction	Information development, awareness raising, planning, design, implementation, and monitoring	Klein et al, 2003
Emergency Preparedness Planning	plan for: scale, resilience, sustainable response, and for post-disaster operation	Manyena, 2006
Mitigation	"The lessening or limitation of the adverse impacts of hazards and related disasters."	(UNISDR, 2007)
Disaster Mitigation	refers to all kinds of disasters	(Haque & Burton, 2005)
Participatory Approach	Integrated emergency institutions and communication, nature of institution, culture of collaboration, public-private, public health systems, and local inclusion: knowledge, resources, climate moderation areas	Collier et al, 2009
Prevention Approach	Planning, vulnerability reduction, capacities, knowledge, and skills	Klein et al, 2003
Recovery Model	Long-term rehabilitation process, re-accumulation of capital and physical infrastructure, policies and programs of government and private, resource distribution, and program coordination	Tobin, 1999
Vulnerability Approach	Wealth, public policy and administration, condition of infrastructure, and organized abilities of disaster and risk management	Klein et al, 2003

Table 6: Community Response

Term	Definition	Citation
Absorb	"Take up and reduce the effect or intensity of (sound or an impact)"	(Oxford University Press, 2014a)
Adapt	Community ability to "become adjusted to new conditions"	(Oxford University Press, 2014c)
Buffer	"A person or thing that reduces a shock or that forms a barrier between incompatible or antagonistic people or things"	(Oxford University Press, 2014g)
Clean Up	"Make things or an area clean or neat"	(Oxford University Press, 2014j)

Table 7: Vulnerability

Term	**Definition**	**Citation**
Vulnerability	"pre-existing condition or state defined by a set of negative attributes that cause people or communities' susceptibility to loss"	(Berry 2002 in Haque & Burton, 2005, pg 344)
	"The characteristics and circumstances of a community, system or asset that make it susceptible to the damaging effects of a hazard."	(UNISDR, 2007)
Structural Vulnerability	"such as poorly built, or insufficiently strong or resilient systems"	(Etkin & Stefanovic, 2005, pg 470)
Socio-political Vulnerability	"such as no or limited accessibility to information, limited control over resource allocation and pertinent decisions"	(Etkin & Stefanovic, 2005, pg 470)
Social Vulnerability	vulnerability at a society level "exposure to a hazard that is difficult to cope with"	(Apa et al, 2012, pg 393)
Psychological Vulnerability	"dread, avoidance, denial"	(Etkin & Stefanovic, 2005, pg 470)
Physical Vulnerability	"such as living in a location exposed to hazard"	(Etkin & Stefanovic, 2005, (Etkin & Stefanovic, 2005, pg 469)
Personal Vulnerability	"such as age"	(Etkin & Stefanovic, 2005, pg 469)
Institutional Vulnerability	"such as enforcement of standards and codes, type of governance"	(Etkin & Stefanovic, 2005, pg 470)
Economic Vulnerability	"such as wealth distribution, economic diversity"	(Etkin & Stefanovic, 2005, pg 470)
Ecological Vulnerability	"natural environment vulnerability"	Etkin & Stefanovic, 2005, pg 470
Eco-ethical Vulnerability	"values that lead to a loss of ecological resilience"	(Etkin & Stefanovic, 2005, pg 470)
Cultural Vulnerability	“such as how risks are perceived and responded to”	Etkin & Stefanovic, 2005, pg 470

Table 8: Resilience

Term	Definition	Citation
Resilience	"The ability of a system, community or society exposed to hazards to resist, absorb, accommodate to and recover from the effects of a hazard in a timely and efficient manner, including through the preservation and restoration of its essential basic structures and functions."	(UNISDR, 2007)
Ecological Resilience	"allows for many possible desirable states that match the environment"	(Norris et al, 2008, pg 130)
Engineering Resilience	system returns to pre-designated state or function after a disturbance	(Norris et al, 2008)
Infrastructure Resilience	"capcity of built infrastructure to continue functioning during disasters"	(Castleden et al, 2011, pg 370)
Organizational Resilience	"capacity of...organizations to resist and recover from disturbances"	(Castleden et al, 2011, pg 373)
Psychological Resilience	"capacity of individuals or groups of people to cope with adversity and continue functioning"	(Castleden et al, 2011, pg 370)
Social Resilience	"capacity of actors to access capitals in order to – not only cope with and adjust to adverse conditions (that is, reactive capacity) – but also search for and create options (that is, proactive capacity), and thus develop increased competence (that is, positive outcomes) in dealing with a threat"	Obrist et al, 2010, pg 289
Socio-ecological Resilience	"resilience is the capacity of a system to absorb disturbance and reorganize while undergoing change so as to still retain essentially the same function, structure, identity, and feedbacks"	(Walker et al, in Castleden et al, 2011, pg 371)
Urban Resilience	"capacity of a city/urban area...to resist and recover from disturbances"	(Castleden et al, 2011, pg 373)

Table 9: Environment

Term	Definition	Citation
Environment	"The surroundings or conditions in which a person, animal, or plant lives or operates"	(Oxford University Press, 2014q)
Ecological Environment	Part of the environment "Relating to or concerned with the relation of living organisms to one another and to their physical surroundings"	(Oxford University Press, 2014n)
Economic Environment	Part of the environment "Relating to economics or the economy"	(Oxford University Press, 2014o)
Physical Environment	Part of the environment "Relating to things perceived through the senses as opposed to the mind; tangible or concrete" (built rather than natural)	(Oxford University Press, 2014ab)
Social Environment	Part of the environment "Relating to society or its organization"	(Oxford University Press, 2014aj)

Table 10: Disaster Cycle

Term	Definition	Citation
Anticipation	"The action of anticipating something; expectation or prediction" - "Guess or be aware of (what will happen) and take action in order to be prepared"	(Oxford University Press, 2014e)
Assessment	"The action of assessing someone or something" - "Evaluate or estimate the nature, ability, or quality of"	(Oxford University Press, 2014f)
Preparedness	"The knowledge and capacities developed by governments, professional response and recovery organizations, communities and individuals to effectively anticipate, respond to, and recover from, the impacts of likely, imminent or current hazard events or conditions."	(UNISDR, 2007)
Prevention	"The outright avoidance of adverse impacts of hazards and related disasters."	(UNISDR, 2007)
Recovery	"The restoration, and improvement where appropriate, of facilities, livelihoods and living conditions of disaster-affected communities, including efforts to reduce disaster risk factors."	(UNISDR, 2007)
Response	"The provision of emergency services and public assistance during or immediately after a disaster in order to save lives, reduce health impacts, ensure public safety and meet the basic subsistence needs of the people affected."	(UNISDR, 2007)

Table 11: Disaster

Term	**Definition**	**Citation**
Disaster	"a serious disruotion affecting a community or population, causing deaths, injuries, or damage to property, livelihoods, or the evironment, that exceeds the ability of the affected community to cope using its own resources"	(UNISDR 2004, pg 17 in Boon et al, 2012, pg 383)
Acute Disaster	short-term, unexpected disaster (ie a single flood)	composite for thesis
Chronic Disaster	long-term, could be expected (ie annual flooding)	composite for thesis
Ecological Disaster	"Natural process or phenomenon that may cause loss of life, injury or other health impacts, property damage, loss of livelihoods and services, social and economic disruption, or environmental damage."	(UNISDR, 2007)
Economic Disaster	collapse of the economic systems upon which we rely	created for thesis
Human Disaster	a hazard that has a human origin	created for thesis
Technical Disaster	"A hazard originating from technological or industrial conditions, including accidents, dangerous procedures, infrastructure failures or specific human activities, that may cause loss of life, injury, illness or other health impacts, property damage, loss of livelihoods and services, social and economic disruption, or environmental damage."	(UNISDR, 2007)

Table 12: Outcome

Term	**Definition**	**Citation**
Outcome	"The way a thing turns out; a consequence"	(Oxford University Press, 2014aa)
Resilience Outcome	Results of a resilient population	created for thesis
Population Wellness	"community-level outcome indicative of successful adaptation, defined as high and non-disparate levels of mental and behavioral health, role functioning, and quality of life in constituent populations"	(Norris et al, 2008, pg 131)
Positive Adaptation	Adapting that results in an improvement in situation - window of opportunity	created for thesis
Psycholgocial Wellness	"individual-level outcome indicative of sucessful adaptation defined according to four criteria: (1) absence fo stress-related psychological disorders; (2) healthy patterns of behavior; (3) adequate role functioning at home, school and/or work; and (4) high quality of life"	(Norris et al, 2008, pg 131)
Resistance Outcome	Results of a resistant system	created for thesis
Same State	Return to the same state that existed before the disaster	created for thesis
Vulnerability Outcome	Result of a vulnerable system	created for thesis

Table 13: Population

Term	Definition	Citation
Population	"All the inhabitants of a particular place"	(Oxford University Press, 2014ac)
Community	"geographic boundaries and shared fate"	(Norris et al, 2008, pg 128)
Complex Adaptive System	"characterized by emergent properties, self- organization, historical patterns of abrupt, non- linear change, and unpredictable dynamics"	Gunderson, 2010, pg 2
Complex Social System	adaptation, social innovation, creative transformation, self-organization, complex learning, flexibility, and adaptive capabilities	Francis, 2010
Corporation	"A large company or group of companies authorized to act as a single entity and recognized as such in law"	(Oxford University Press, 2014m)
Family	"A group of people related by blood or marriage"	(Oxford University Press, 2014r)
Individual	"A single human being as distinct from a group"	(Oxford University Press, 2014s)
Neighbourhood	"A district or community within a town or city"	(Oxford University Press, 2014z)
School	"An institution for educating children"	(Oxford University Press, 2014ai)
Social-ecological System	social system embedded in the larger environmental context	composite created for thesis
Society	"The community of people living in a particular country or region and having shared customs, laws, and organizations"	(Oxford University Press, 2014al)
Chronosystem	transitions over the life course and environmental events	(Boon, Cottrell, King, Stevenson, & Millar, 2012)
Exosystem	environmental settings that have an indirect, but profound influence on the individual	(Boon et al., 2012)
Macrosystem	includes cultural context that the individual currently lives in	(Boon et al., 2012)
Mesosystem	interactions between two microsystems	(Boon et al., 2012)
Microsystem	individual's immediate surroundings	(Boon et al., 2012)

Appendix C – Relationships in Ontology

Table 14: Relationships Created for Ontology

English Language Relationship	First Order Language Axiom
Environment has a community	∀ x,y Environment (x)∧Community (y) ↔ has (x, y)
Community enhances community resilience	∀ x,y Community (x)∧CRtD (y) → Enhances (x, y)
Community has community resilience	∀ x,y Community (x)∧CRtD (y) → has (x, y)
Community has community status	∀ x,y Community (x)∧Community_Status (y) ↔ has (x, y)
Community has vulnerability	∀ x,y Community (x)∧Vulnerability (y) → has (x, y)
Community is affected by disasters	∀ x,y Community (x)∧Disaster (y) → Affected_By (x, y)
Corporation enhances community resilience	∀ x,y Corporation (x)∧CRtD (y) → Enhances (x, y)
Corporation is part of community	∀ x,y Corporation (x)∧Community (y) → Part_Of (x, y)
Corporation is part of society	∀ x,y Corporation (x)∧Society (y) → Part_Of (x, y)
Family is part of corporation	∀ x,y Family (x)∧Corporation (y) → Part_Of (x, y)
Family is part of society	∀ x,y Family (x)∧Society (y) → Part_Of (x, y)
Family is part of school	∀ x,y Family (x)∧School (y) → Part_Of (x, y)
Individual is part of the corporation	∀ x,y Individual (x)∧Corporation (y) → Part_Of (x, y)
Individual is part of the family	∀ x,y Individual (x)∧Family (y) → Part_Of (x, y)
Individual is part of the school	∀ x,y Individual (x)∧School (y) → Part_Of (x, y)
Individual is part of the society	∀ x,y Individual (x)∧Society (y) → Part_Of (x, y)
Neighbourhood is part of the school	∀ x,y Neighbourhood (x)∧School (y) → Part_Of (x, y)
Neighbourhood is part of society	∀ x,y Neighbourhood (x)∧Society (y) → Part_Of (x, y)
Community resilience has a community	∀ x,y Community_Resilience (x)∧Community (y) ↔ has (x, y)
Communication requires the ability to communicate	∀ x,y Communication (x) ∧Ability_To_Communicate (y) → Requires (x,y)
Community action is equivalent to capacity building	∀ x Community_Action (x) ↔ Capacity_Building (x)
Community development is part of community action	∀ x,y Community_Development (x) ∧Community_Action (y) → Part_Of (x,y)

Community planning is part of community action	∀ x,y Community_Planning (x) ∧Community_Action (y) → Part_Of (x,y)
Adaptation is equivalent to vulnerability reduction	∀ x Adaptation (x) ↔ Vulnearbility_Reduction (x)

Table 15: Simple Relationships in FOL

English Language Relationship	First Order Language Axiom	Reference
Adaptive capacity is enacted by an individual	∀ x,y Adaptive_Capacity (x)∧Individual (y)→ Enacted_By (x, y)	Boon et al, 2012
Community has a community response	∀ x,y Community (x)∧Community_Response (y) → has (x, y)	Boon et al, 2012
Community is part of microsystem	∀ x,y Community (x)∧Microsystem (y) → Part_Of (x, y)	Masten & Obradovic, 2008
Community is part of society	∀ x,y Community (x)∧Society (y) → Part_Of (x, y)	Masten & Obradovic, 2008
Family is part of community	∀ x,y Family (x)∧Community (y) → Part_Of (x, y)	Masten & Obradovic, 2008
Family is part of the microsystem	∀ x,y Family (x)∧Microsystem (y) → Part_Of (x, y)	Masten & Obradovic, 2008
Individual is part of community	∀ x,y Individual (x)∧Community (y) → Part_Of (x, y)	Masten & Obradovic, 2008
Individual is part of the microsystem	∀ x,y Individual (x)∧Microsystem (y) → Part_Of (x, y)	Masten & Obradovic, 2008
Individual is part of the neighbourhood	∀ x,y Individual (x)∧Neighbourhood (y) → Part_Of (x, y)	Wallace & Wallace, 2008
Neighbourhood is part of the community	∀ x,y Neighbourhood (x)∧Community (y) → Part_Of (x, y)	Masten & Obradovic, 2008
Neighbourhood is part of the mesosystem	∀ x,y Neighbourhood (x)∧Mesosystem (y) → Part_Of (x, y)	Masten & Obradovic, 2008
Neighbourhood supports public health	∀ x,y Neighbourhood (x)∧Public_Health (y) → Supports (x, y)	Wallace & Wallace, 2008
School is part of the community	∀ x,y School (x)∧Community (y) → Part_Of (x, y)	Masten & Obradovic, 2008
School is part of the microsystem	∀ x,y School (x)∧Microsystem (y) → Part_Of (x, y)	Masten & Obradovic, 2008
School is part of the neighbourhood	∀ x,y School (x)∧Neighbourhood (y) → Part_Of (x, y)	Wallace & Wallace, 2008
Social-ecological system is the same as complex adaptive system	∀ x Social-Ecological_System (x) ↔ Complex_Adaptive_System (x)	Berkes & Ross, 2012
Society is part of the exosystem	∀ x,y Society (x)∧Exosystem (y) → Part_Of (x, y)	Masten & Obradovic, 2008
Resilience requires a community to adapt	∀ x,y,z Community (x)∧Adaptability (y) ∧has (x,y) ∧CRtD (z) → has_Resilience (x, z)	Norris et al, 2008
Resilience decreases	∀ x,y Resilience (x)∧Vulnerability (y)	Klein et al, 2003

vulnerability	→ Decreases (x, y)	
Resilience requires adaptation, learning, and self organization	∀ x,y,z,v,w Community (x)∧Adaptation (y) ∧has (x,y) ∧Learning (z) ∧has (x,z))∧Self-Organization (v) ∧has (x,v) ∧CRtD (w) → has_Resilience (x, w)	Francis, 2010
Community resilience requires adaptation, adaptive capacity, and disaster	∀ x,y,z,v,w Community (x)∧Adaptation (y) ∧has (x,y) ∧Adaptive_Capacity (z) ∧has (x,z))∧Disaster (v) ∧Affected_By (x,v) ∧CRtD (w) → has_Resilience (x, w)	Norris et al, 2008
Community resilience results in resilience outcome	∀ x,y,z,v,w Community (x)∧CRtD (y) ∧has (x,y) ∧Resilience_Outcome (z) → has_Outcome (x, z)	Norris et al, 2008
Community resilience is influenced by cultural capital, experience, historical background, and local knowledge	∀ x,y,z,v,w,k Community (x)∧Cultural_Capital (y) ∧has (x,y) ∧Experience (z) ∧has (x,z))∧Historical_Background (v) ∧has (x,v) ∧Local_Knowledge (k) ∧has (x,k) ∧CRtD (w) → has_Resilience (x, w)	Tobin, 1999
Community resilience promotes preparedness and response	∀ x,y,z,v Community (x)∧CRtD (y) ∧has (x,y) ∧Preparedness (z) ∧Response (v) → (Promotes (x,z) ∧ Promotes (x,v))	Boon et al, 2012
Community resilience requires some awareness and political will and public policy	∀ x,y,z,v,w Community (x)∧Awareness (y) ∧has (x,y) ∧Public_Will (z) ∧has (x,z) ∧ Public_Policy(v) ∧CRtD (w) → has_Resilience (x, w)	Etkin & Stefanovic, 2005
Community resilience requires capacity for failure	∀ x,y,v Community (x)∧Capacity_For_Failure (y) ∧has (x,y) ∧CRtD (v) → has_Resilience (x, v)	Etkin & Stefanovic, 2005
Ecological resilience has an ecological environment, is recovery from a disaster, and multiple states possible to return to	∀ x,y,z,v,w Community (x)∧Ecological_Environment (y) ∧has (x,y) ∧Disaster (z) ∧Affected_By (x,z) ∧ Multiple_States (v) ∧Returns_To (x,v) ∧Ecological_Resilience (w) → has_Resilience (x, w)	Norris et al, 2008
Ecological resilience influenced by biodiversity, community ecological environment, and historical background	∀ x,y,z,v,w Community (x)∧Biodiversity (y) ∧Influenced_By (x,y) ∧Community_Ecological_Environment (z) ∧Influenced_By (x,z) ∧ Historical_Background (v)	Wallace & Wallace, 2008

	∧Influenced_By (x,v) ∧Ecological_Resilience (w) → has_Resilience (x, w)	
Engineering resilience affected by a disaster and returns to the same state	∀ x,y,z,w System (x)∧Disaster (y) ∧Affected_By (x,y) ∧Same_State (z) ∧Returns_To (x,z) ∧Engineering_Resilience (w) → has_Resilience (x, w)	Etkin & Stefanovic, 2005
Organizational resilience enhances community resilience	∀ x,y,v Community (x)∧Organizational_Resilience (y) ∧has (x,y) ∧CRtD (v) → Enhances (y,v)	Berkes & Ross, 2012
Psychological resilience enhances community resilience	∀ x,y,v Community (x)∧Psychological_Resilience (y) ∧has (x,y) ∧CRtD (v) → Enhances (y,v)	Berkes & Ross, 2012
Social resilience is equivalent to community resilience	∀ x Social_Resilience (x) ↔ Community_Resilience (x)	Boon et al, 2012
Social-Ecological resilience is defined as having ecological environment and society as population	∀ x,y,v,z Community (x)∧Ecological_Environment (y) ∧has_Environment (x,y) ∧Society (v) ∧has_Population (x,v) ∧Social-Ecological_Resilience (z) → has(x,z)	Many authors
Urban resilience enhances community resilience	∀ x,y,v Community (x)∧Urban_Resilience (y) ∧has (x,y) ∧CRtD (v) → Enhances (y,v)	Berkes & Ross, 2012
Debt decreases community resilience	∀ x,y,v Community (x)∧Debt (y) ∧has (x,y) ∧CRtD (v) ∧has (x,v) → Decreases (y,v)	Etkin & Stefanovic, 2005
Debt limits poverty alleviation	∀ x,y,v Community (x)∧Debt (y) ∧has (x,y) ∧Poverty_Alleviation (v) → Limits (y,v)	Ireland, 2010
Shared beliefs enhances sense of community	∀ x,y,v Community (x)∧Shared_Beliefs (y) ∧has (x,y) ∧Sense_Of_Community (v) → Enhances (y,v)	Barr & Devine-Wright, 2012
Shared beliefs affects community ownership	∀ x,y,v Community (x)∧Shared_Beliefs (y) ∧has (x,y) ∧Community_Ownership (v) → Affects (y,v)	Bahadur et al, 2013
Social network allows access to information and results in learning	∀ x,y,v,z Community (x)∧Social_Network (y) ∧has (x,y) ∧Information (v) ∧Allows_Access_To (y,v) ∧Learning (z) → Leads_To (x,z)	Berkes & Ross, 2012
Social network develops	∀ x,y,v Community	Gunderson, 2010

capacity	(x)∧Social_Network (y) ∧has (x,y) ∧Capacity (v) → Develops (x,v)	
Social network influences governance and happiness levels and health	∀ y,z,v,w Social_Network (y) ∧has (x,y) ∧Governance (z) ∧Happiness_Level (v) ∧ Health (w) → (Influences (y,z) ∧ Influences (y,v) ∧ Influences (y,w))	Boon et al, 2012
Social network requires some trust	∀ x,y Social_Network (x) ∧Trust (y) → Requires (x,y)	Bahadur et al, 2013
Connectedness enhances social support	∀ x,y Connectedness (x)∧Social_Support (y) → Enhances (x, y)	Walsh, 2007
Organizational linkages decreases vulnerability	∀ x,y Organizational_Linkages (x)∧Vulnerability (y) → Decreases (x, y)	Many authors
Symbolic capital requires some power balance	∀ x,y Symbolic_Capital (x) ∧Power_Balance (y) → Requires (x,y)	Obrist et al, 2010
Communication requires information	∀ x,y Communication (x) ∧Information (y) → Requires (x,y)	Burkle, 2011
Communication uses knowledge networks	∀ x,y Communication (x) ∧Knowledge_Network (y) → Uses (x,y)	Burkle, 2011
Communal narrative affects public policy	∀ x,y Communal_Narrative (x) ∧Public_Policy (y) → Affects (x,y)	Norris et al, 2008
Communal narrative requires connectedness and sense of community	∀ x,y,z,v,w Communal_Narrative (x) ∧ Connectedness (y) ∧Sense_Of_Community (z) → (Requires (x,y) ∧ Requires (x,z))	Norris et al, 2008
Mass media affects communal narrative	∀ x,y Mass_Media (x) ∧Communal_Narrative (y) → Affects (x,y)	Norris et al, 2008
Community competence empowers community	∀ x,y Community_Competence (x) ∧Community (y) → Empowers (x,y)	Berkes & Ross, 2012
Community competence requires communication and social capital	∀ x,y Community (x) ∧Communication (y) ∧has (x,y) ∧Social_Capital (z) ∧has (x,z) ∧Community_Competence (v) → has (x,v)	Norris et al, 2008
Capacity for failure leads to learning	∀ x,y Capacity_For_Failure (x) ∧Learning (y) → Leads_To (x,y)	Gunderson, 2010
Collaboration enhances community participation	∀ x,y Collaboration (x) ∧Community_Participation (y) → Enhances (x,y)	Barr & Devine-Wright, 2012
Collaboration enhances	∀ x,y Collaboration (x) ∧CRtD (y) →	Obrist et al, 2010

community resilience	Enhances (x,y)	
Collaboration enhances sense of community	∀ x,y Collaboration (x) ∧ Sense_Of_Community (y) → Enhances (x,y)	Barr & Devine-Wright, 2012
Problem solving capacity enhances sense of agency	∀ x,y Problem_Solving_Capacity (x) ∧ Sense_Of_Agency (y) → Enhances (x,y)	Berkes & Ross, 2012
Problem solving capacity promotes economic diversity and physical infrastructure diversity	∀ x,y,z,v,w Problem_Solving_Capacity (x) ∧ Economic_Capital (y) ∧ has_Value (y, diverse) ∧Physical_Infrastructure (z) ∧has_Value (z, diverse) → (Is_Promoted_By (x,y) ∧ Is_Promoted_By (x,z))	Berkes & Ross, 2012
Self-organization activates capacity	∀ x,y Self-organization(x) ∧ Capacity (y) → Activates (x,y)	Berkes & Ross, 2012
Sense of agency activates adaptive capacity	∀ x,y Sense_Of_Agency (x) ∧ Adaptive_Capacity (y) → Activates (x,y)	Berkes & Ross, 2012
Sense of Agency is influenced by information asymmetry	∀ x,y Sense_Of_Agency (x) ∧Information (y) ∧has_Value (y, asymmetry) → Influenced_By (x,v)	Brown, 2013
Poverty leads to social vulnerability	∀ x,y Poverty (x) ∧ Social_Vulnerability (y) → Leads_To (x,y)	Ireland, 2010
Governance affects vulnerability	∀ x,y Governance (x) ∧ Vulnerability (y) → Affects (x,y)	Burkle, 2011
Governance leads to adaptive capacity	∀ x,y Governance (x) ∧ Adaptive_Capacity (y) → Leads_To (x,y)	Bahadur et al, 2013
Power influences local knowledge, community engagement, community ownership, and community partnership	∀ x,y,z,v,w Power (x) ∧ Local_Knowledge (y) ∧ Community_Engagement (z) ∧Community_Ownership (v) ∧Community_Partnership (w) → (Influences (x,y) ∧ Influences (x,z) ∧ Influences (x,v)∧ Influences (x,w))	Bahadur et al, 2013
Power affects self-organization	∀ x,y Power (x) ∧ Self-Organization (y) → Affects (x,y)	Berkes & Ross, 2012
Power influences community action and sense of agency	∀ x,y,z Power (x) ∧ Community_Action (y) ∧ Sense_Of_Agency (z) → (Influences (x,y) ∧ Influences (x,z))	Brown, 2013
Social infrastructure is part of preparedness,	∀ x,y,z,v Social_Infrastructure (x) ∧ Preparedness (y) ∧ Recovery (z)	Andrew, 2012

recovery and response	∧Response (v) → (Part_Of (x,y) ∧ Part_Of (x,z) ∧ Part_Of (x,v))	
Public Policy adapts to physical environment and mitigates disaster	∀ x,y,z,v Public_Policy (x) ∧ Physical_Environment (y) ∧ Disaster (z) → (Adapts_To (x,y) ∧ Mitigates (x,z))	Miles & Chang, 2011
Local knowledge identifies personal vulnerability	∀ x,y Local_Knowledge (x) ∧ Personal_Vulnerability (y) → Used_To_Identify (x,y)	Andrew, 2012
Intervention resource are specific to culture	∀ x,y Intervention_Resource (x) ∧ Culture (y) → Are_Specific_To (x,y)	Norris et al, 2008
Intervention resource require flexibility	∀ x,y Intervention_Resource (x) ∧ Flexibility (y) → Requires (x,y)	Norris et al, 2008
Adaptation decreases vulnerability and enhances community resilience	∀ x,y,z Adaptation (x) ∧ Vulnerability (y) ∧ CRtD (z) → (Decreases (x,y) ∧ Enhances (x,z))	Ireland, 2010
Community based approach decreases vulnerability and enhances adaptive capacity and community resilience	∀ x,y,z,v Community_Based_Approach (x) ∧ Vulnerability (y) ∧ Adaptive_Capacity (z) ∧ CRtD (v) → (Decreases (x,y) ∧ Enhances (x,z) ∧ Enhances (x,v))	Collier et al, 2009
Community based approach uses local knowledge, community engagement, community ownership, and community participation	∀ x,y,z,v,w,k Community (x) ∧ Local_Knowledge (y) ∧ has (x,y) ∧ Community_Engagement (z) ∧ has (x,z) ∧Community_Ownership (v) ∧ has (x,v) ∧Community_Partnership (w) ∧ has (x,w) ∧ Community_Based_Approach (k) → Uses (x,k)	Bahadur et al, 2013
Mitigation decreases vulnerability	∀ x,y Mitigation (x) ∧ Vulnerability (y) → Decrease (x,y)	Tobin, 1999
Hazard mitigation limits physical and social vulnerability	∀ x,y,z,v Community (x) ∧ Social_Vulnerability (y) ∧ Limited (x,y) ∧ Physical_Vulnerability (z) ∧ Limited (x,z) ∧Hazard_Mitigation (v) → Uses (x,v)	Haque & Burton, 2005
Structural mitigation limits physical vulnerability	∀ x,y Structural_Mitigation (x) ∧ Physical_Vulnerability (y) → Limits (x,y)	Haque & Burton, 2005
Poverty alleviation decreases poverty level and enhances community resilience	∀ x,y,z Poverty_Alleviation (x) ∧ Poverty_Level (y) ∧ CRtD (z) → (Decreases (x,y) ∧ Enhances (x,z))	Ireland, 2010

Physical infrastructure decreases disaster impact and enhances community resilience	∀ x,y,z Physical_Infrastructure (x) ∧ Disaster_Impact (y) ∧ CRtD (z) → (Decreases (x,y) ∧ Enhances (x,z))	Andrew, 2012
Vulnerability is caused by lack of communication, corporation, information, and knowledge	∀ x,y,z,v,w,k Community (x) ∧ Vulnerability (y) ∧ Communication (z) ∧ Lacks (x,z) ∧ Corporation (v) ∧ Lacks (x,v) ∧ Information (w) ∧ Lacks (x,w) ∧ Knowledge (k) ∧ Lacks (x,k) → Causes (x,y)	Manyena, 2006
Vulnerability is affected by ecological and social environment and power	∀ x,y,z,v Vulnerability (x) ∧ Ecological_Environment (y) ∧ Social_Environment (z) ∧ Power (v) → (Affected_By (x,y) ∧ Affected_By (x,z) ∧ Affected_By (x,v))	Haque & Burton, 2005

Table 16: Complex Relationships in FOL

English Language Relationship	First Order Language Axiom	Logical Constants	Reference
Adaptive capacity enhances community resilience	∀ x,y,z Community (x)∧Adaptive_Capacity (y) ∧has (x,y) ∧CRtD (z) ∧has_Resilience (x,z) → has_Value (z, enhanced)	enhanced	many authors
Resilience occurs during preparedness, prevention, recovery or response	∀ x,y,z Community (x)∧Disaster_Timeline (y) ∧Is_In (x,y) ∧CRtD (z) ∧has_Resilience (x, z) → (has_Value (y, preparedness) ∨ has_Value (y, prevention) ∨ has_Value (y, recovery) ∨ has_Value (y, response)	Preparedness, prevention, recovery, response	Boon et al, 2012
Resilience requires some environmental diversity	∀ x,y,z Community (x)∧Environment (y) ∧Is_In (x,y) ∧CRtD (z) ∧has_Value (y, diverse) →has_Resilience (x, z)	diverse	Gunderson, 2010
Community Action is influenced by information asymmetry	∀ x,y Community_Action (x) ∧Information (y) ∧has_Value (y, asymmetry) → Influenced_By (x,v)	Asymmetry	Brown, 2013
Communities that have a small range/diversity of resources are less resilient	∀ x,y,z,w community (x)∧resource (y)∧hasResource(x,y)∧diversity(z)∧ hasDiversity(y,z)∧hasValue(z,low)∧ CRtD(w)∧ hasResilience(x,w)→ hasValue(w,low)	low	Bahadur et al
Decentralized policies and organizational structures are more resilient	∀x,y,z,w community(x) ∧ political structure(y) ∧ hasStructure(x,y) ∧ hasValue(y,decentralized) ∧ PublicPolicy(z) ∧hasPolicy(x,z) ∧ hasValue(z,decentralized) ∧ CRtD(w) ∧ hasResilience(x,w) → hasValue(w,high)	decentralized, high	Bahadur et al
Lack of failure results in a lack of resilience	∀x,y,z community(x) ∧ CapacityForFailure(y) ∧ hasCapacity(x,y) ∧ hasValue(y,low) ∧ CRtD(z) ∧ hasResilience(x,z) →	low	Bahadur et al

	hasValue(z,low)		
Community participation needs to be fair and equitable to have a resilient community	∀x,y,z community(x)∧ CommunityParticipation(y)∧ hasParticipation(x,y)∧ hasValue(y,fair) ∧ hasValue(y,equitable) ∧ CRtD(z) ∧ hasResilience(x,z) → hasValue(z,high)	fair, equitabl e, high	Bahadur et al
Planning that uses timely and relevant information increases resilience	∀x,y,z community(x) ∧ Information(y) ∧ hasInformation(x,y) ∧ hasValue(y,timely) ∧ hasValue(y,relevant) ∧ CRtD(z) ∧ hasResilience(x,z) → hasValue(z,high)	timely, relevant, high	Bahadur et al
Equitable distribution of wealth and economy increases resilience	∀x,y,z,w community(x) ∧ wealth(y) ∧ hasValue(y,equitable) ∧ EconomicEnvironment(z) ∧ hasValue(z,equitable) ∧hasResource(x,z) ∧ hasEnvironment(x,z) ∧ CRtD(w) ∧ hasResilience(x,w) → hasValue(w,high)	equitabl e, high	Bahadur et al
Learning enhances capacity, empowers people, and strengthens governance which leads to high CRtD	∀x,y,z,w community(x) ∧ capacity(y) ∧ hasCapacity(x,y) ∧ hasValue(y,enhanced) ∧ hasValue(x,empowered) ∧Governance(z) ∧ hasGovernance(x,z) ∧ hasValue(z,strengthened) ∧CRtD(w) ∧ hasResilience(x,w) → hasValue(w,high)	enhance d, empowe red, strength ened, high	Bahadur et al
Poverty and lack of access to resources decreases resilience	∀x,y,z,w community(x) ∧ PovertyLevel(y) ∧ hasStatus(x,y) ∧ hasValue(y,high) ∧Resources(z) ∧ hasResource(x,z) ∧ hasValue(z,poor access) ∧CRtD(w) ∧ hasResilience(x,w) → hasValue(w,low)	high, low, poor access	Greene & Greene

Social networks build CRtD through communication and trust	∀x,y,z,w community(x) ∧ SocialNetworks(y) ∧ hasResource(x,y) ∧ Communication(z) ∧ hasResource(x,z) ∧ hasValue(z,trust) ∧CRtD(w) ∧ hasResilience(x,w) → hasValue(w,high)	high, trust	Gunderson
OR	∀x,y,z,w,v community(x) ∧ SocialNetwork(y) ∧ hasResource(x,y) ∧Communication(z) ∧ hasResource(x,z) ∧ builds(y,z) → hasValue(z,good) ∧ Community(x) ∧ SocialNetwork(y) ∧ hasResource(x,y) ∧Trust(w) ∧ hasQuality(x,w) ∧ builds(y,w) → hasValue(w,high) → hasValue(z,good) ∧hasValue(w,high) ∧ CRtD(v) ∧ hasResilience(x,v) → hasValue(v,high)	high, good	Gunderson
Diversity enhances resilience	∀x,y,z community(x) ∧ Resource(y) ∧ hasResource(x,y) ∧ hasValue(y,diverse) ∧ CRtD(z) ∧ hasResilience(x,z) → hasValue(z,high)	diverse, high	Klein et al
Large cities have more power and resources which increases capacity to respond	∀x,y,z,w,v community(x) ∧ Power(y) ∧ has(x,y) ∧hasValue(x,large) ∧ hasValue(y,high) ∧ Resource(z)∧ hasResource(x,z)∧ hasValue(z,high) ∧ Response(w)∧ has(x,w) → hasValue(w,strong)∧ CRtD(v) ∧ hasResource(x,v) → hasValue(v,high)	large, high, strong	Klein et al
Amount of disturbance absorbed and remain in same state is resilience	∀x,y,z,v,w socio-ecological system(x) ∧ Disturbance(y) ∧ Impacts(x,y) ∧ Response(z) ∧ hasResponse(x,z)∧ hasValue(z,absorb) ∧hasValue(y,high) ∧ Outcome(w) ∧ hasOutcome(x,w)∧hasValue(w,same state) ∧ Resilience(v) ∧ hasResilience(x,v) → hasValue(v,high)	high, absorb, same state	Kuhlicke

Collaboration increases access to resources which increases resilience	∀x,y,z,w community(x) ∧ Resources(y) ∧ hasResource(x,y) ∧ hasValue(y,high access) ∧ CRtD(z) ∧ hasResilience(x,z) ∧Collaboration(w) ∧ has(x,w) → hasValue(z,high)	high, high access	Obrist et al
Symbolic capital influences access to other capitals	∀x,y,z,v,w community(x) ∧ SymbolicCapital(y) ∧ hasCapital(x,y) ∧ hasValue(y,high) ∧ SocialCapital(z) ∧ hasCapital(x,z) ∧ EconomicCapital(v) ∧ hasCapital(x,v)∧ CulturalCapital(w) ∧ hasCapital(x,w) → hasValue(z,high access) ∧ hasValue(v,high access)∧ hasValue(w,high access)	high, high access	Obrist et al
Communities provide businesses with human, physical, and natural capital	∀x,y,z,v,w community(x) ∧ HumanCapital(y) ∧ hasCapital(x,y) ∧ PhysicalCapital(z) ∧ hasCapital(x,z) ∧ NaturalCapital(v) ∧ hasCapital(x,v)∧ Business(w) ∧ hasBusiness(x,w)∧ hasValue(z,available) ∧ hasValue(v,available)∧ hasValue(y,available) → hasValue(w,exists)	available, exists	Thomas
Dense social networks facilitate resource sharing which increases resilience	∀x,y,z,v community(x) ∧ SocialNetworks(y) ∧ hasSocialCapital(x,y) ∧ hasValue(y,dense) ∧ Resources(z) ∧ hasResources(x,z) ∧ hasValue(z,shared)∧ CRtD(v) ∧ hasResilience(x,v) → hasValue(v,high)	dense, shared, high	Wallace & Wallace
Social support depends on social stability of neighbourhoods	∀x,y,z,v community(x) ∧ SocialSupport(y) ∧ hasSocialCapital(x,y) ∧ Neighbourhood(z) ∧ hasPopulation(x,z) ∧ hasValue(z,stable)∧ CRtD(v) ∧ hasResilience(x,v) → hasValue(v,high)	stable, high	Wallace & Wallace

Large social networks and dense ties result in rapid information flow and increased resilience	∀x,y,z,v community(x) ∧ SocialNetworks(y) ∧ hasSocialCapital(x,y) ∧ hasValue(y,large) ∧ hasValue(y,dense) ∧ InformationFlow(z) ∧ has(x,z) ∧ CRtD(v) ∧ hasResilience(x,v)→ hasValue(z,rapid) → hasValue(v,high)	large, dense, rapid, high	Wallace & Wallace
Small, dense networks have slow information flow and low resilience	∀x,y,z,v community(x) ∧ SocialNetworks(y) ∧ hasSocialCapital(x,y) ∧ hasValue(y,small) ∧ hasValue(y,dense) ∧ InformationFlow(z) ∧ has(x,z) ∧ CRtD(v) ∧ hasResilience(x,v)→ hasValue(z,slow) → hasValue(v,low)	small, dense, slow, low	Wallace & Wallace
Acute disasters can be ecological, technical, or human but have to be unexpected, single events	∀x,y,z,v,w community(x) ∧ EcologicalDisaster(y) ∧ hasCapital(x,y) ∧ TechnicalDisaster(z) ∧ HumanDisaster(v) ∧ (hasEvent(x,y)∨ hasEvent(x,z)∨ hasEvent(x,v))∧ hasValue(y,unexpected) ∧ hasValue(y,single)∧ hasValue(v,unexpected) ∧ hasValue(v,single) ∧ hasValue(z,unexpected) ∧ hasValue(z,single) ∧ AcuteDisaster(w) → hasEvent(x,w)	unexpec ted, single	Norris et al
Chronic Disasters are those that can be expected or are not a single event	∀x,y,z,v,w community(x) ∧ EcologicalDisaster(y) ∧ hasCapital(x,y) ∧ TechnicalDisaster(z) ∧ HumanDisaster(v) ∧ (hasEvent(x,y)∨ hasEvent(x,z)∨ hasEvent(x,v))∧ hasValue(y,expected) ∧ hasValue(y,multiple)∧ hasValue(v,expected) ∧ hasValue(v,multiple) ∧ hasValue(z,expected) ∧ hasValue(z,multiple) ∧	expecte d, multiple	Norris et al

	ChronicDisaster(w) → hasEvent(x,w)		
Vulnerable if not robust, redundant, or rapid resources resulting in persistant dysfunction	∀x,y,z,v,w community(x) ∧ Resources(y) ∧ hasResource(x,y) ∧ hasValue((y,robust) ∨(y,redundant) ∨(y,rapid)) ∧ Vulnerable(z) → has(x,z)∧ Disaster(v) ∧ hasEvent(x,v) ∧ VulnerabilityOutcome(w) → hasOutcome(x,w)	robust, redunda nt, rapid	Norris et al
Resistant if small disaster effect and either robust, redundant, or rapid resources (adaptive capacity)	∀x,y,z,v community(x) ∧ Disaster(y) ∧ hasEvent(x,y) ∧ AdaptiveCapacity(z) ∧ hasCapacity(x,z)∧ hasValue(z,high) ∧ hasValue(y,small)∧ ResistantOutcome(v) → hasOutcome(x,v)	high, small	Norris et al
Resilience if has adaptive capacity but disaster is too big	∀x,y,z,v community(x) ∧ Disaster(y) ∧ hasEvent(x,y) ∧ AdaptiveCapacity(z) ∧ hasCapacity(x,z)∧ hasValue(z,high) ∧ hasValue(y,big)∧ ResilienceOutcome(v) → hasOutcome(x,v)	high, big	Norris et al
Adaptive Capacities are resources that are robust, redundant, or rapidly mobilizable	∀y,z Resources(y) ∧ hasValue(y,robust) ∨ hasValue(y,redundant)∨ hasValue(y,rapid) → AdaptiveCapacity(z)	robust, redunda nt, rapid	Norris et al
If resources have all 3 Rs then are available and accessable	∀y Resources(y)∧ hasValue(y,robust) ∧ hasValue(y,redundant)∧ hasValue(y,rapid) → hasValue(y,available)∧ hasValue(y,accessible)	robust, redunda nt, rapid, accessibl e, available	Norris et al
Lower SES suffer more from disaster	∀x,y,z,v Family(x) ∧ Disaster(y) ∧ AffectedBy(x,y) ∧ PovertyLevel(z) ∧ hasLevel(x,z)∧ hasValue(z,high) ∧ ResilienceOutcome(v)∧ hasOutcome(x,v) → hasValue(v,low)	high, low	Norris et al

Strong social support leads to more information	∀x,y,z,v Family(x) ∧ SocialSupport(y) ∧ Information(z) ∧ hasSupport(x,y)∧ hasValue(y,strong)∧ has(x,z) → hasValue(z,increased)	strong, increased	Norris et al
Narrow range of natural resources increases variance in income and decreases CRtD	∀x,y,z,v Community(x) ∧ NaturalResource(y) ∧ hasResource(x,y) ∧ hasValue(y,low diversity)∧ Income(z)∧ has(x,z) → hasValue(z,variable) ∧ CRtD(v)∧ hasResilience(x,v) → hasValue(v,low)	low diversity, low, variable	Norris et al
Diversity is affected by politics and power	∀x,y,z,v Community(x) ∧ Resources(y) ∧ has(x,y) ∧ Politics(z)∧ Power(v)∧ has(x,z) ∧ has(x,v) ∧ hasValue(z,equality) ∧ hasValue(v,equality)→ hasValue(y,diverse)	diverse, equality	Norris et al

Appendix D – Hierarchies of Terms

Figure 3: Capacity Hierarchy

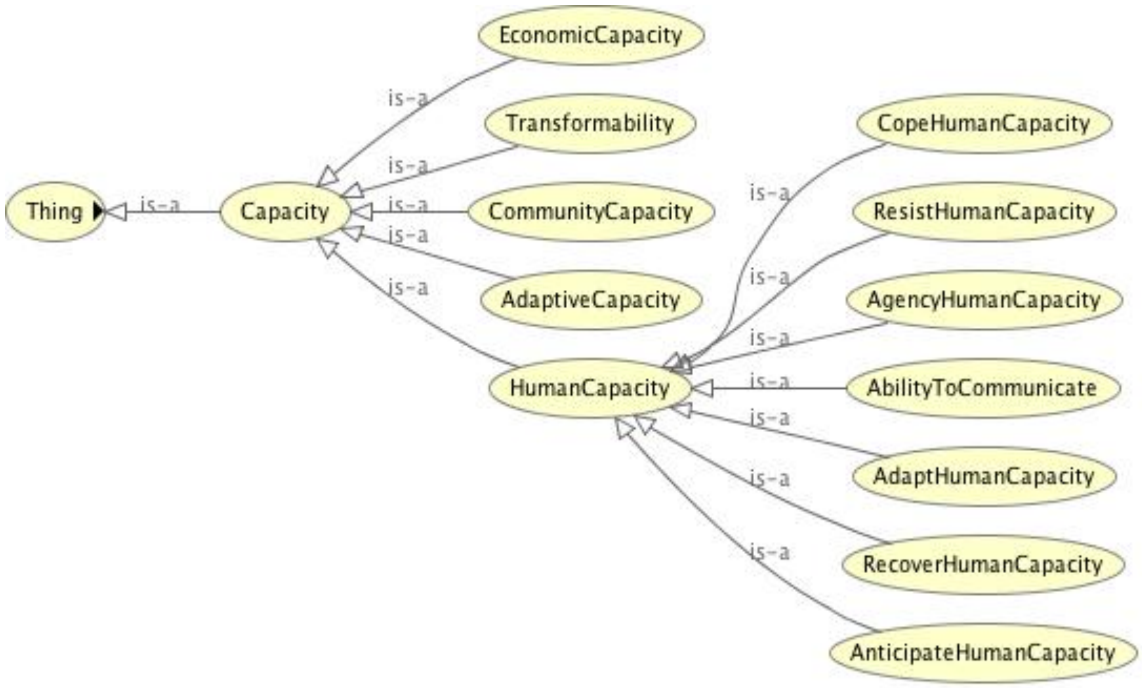


Figure 4: Community Response Hierarchy

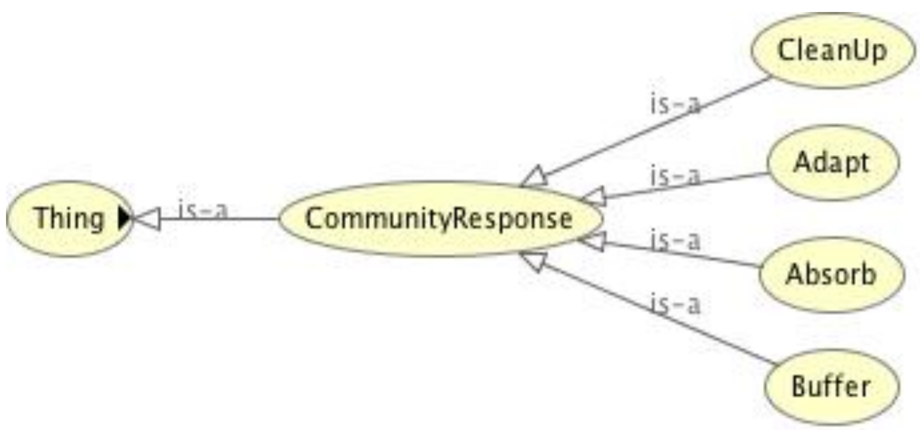


Figure 5: Disaster Cycle Hiearchy

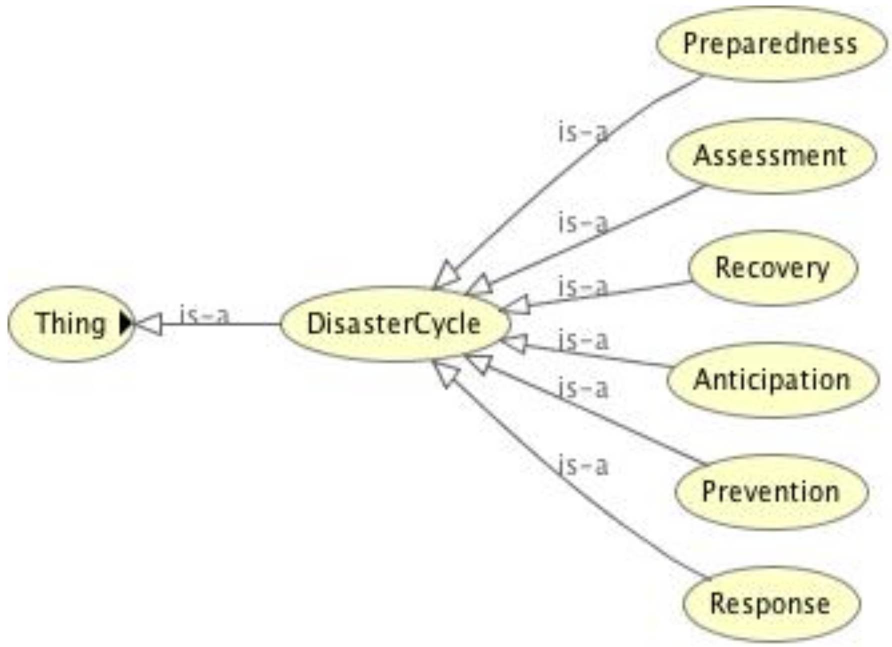


Figure 6: Disaster Hierarchy

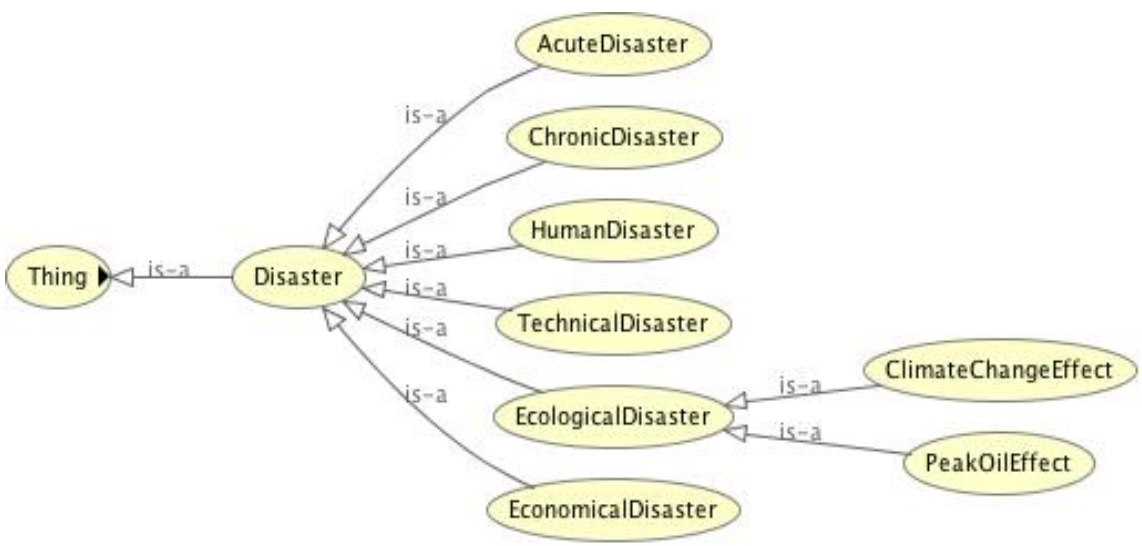


Figure 7: Environment Hierarchy

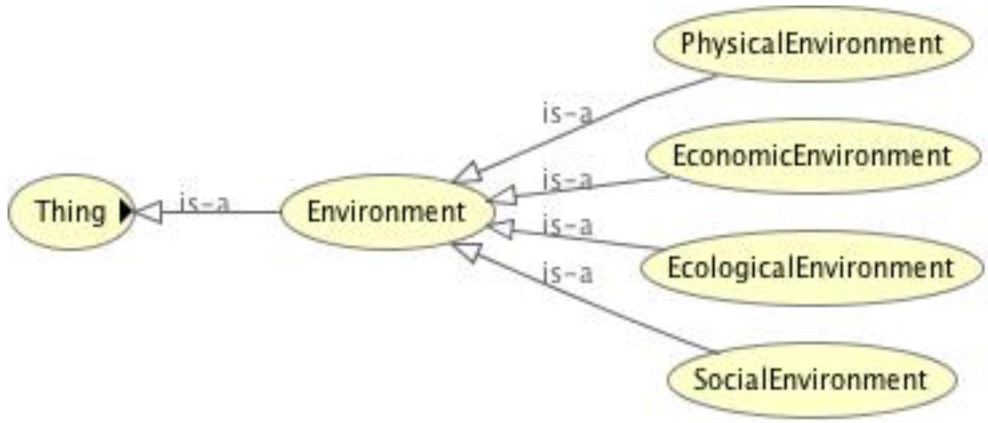


Figure 8: Outcome Hierarchy

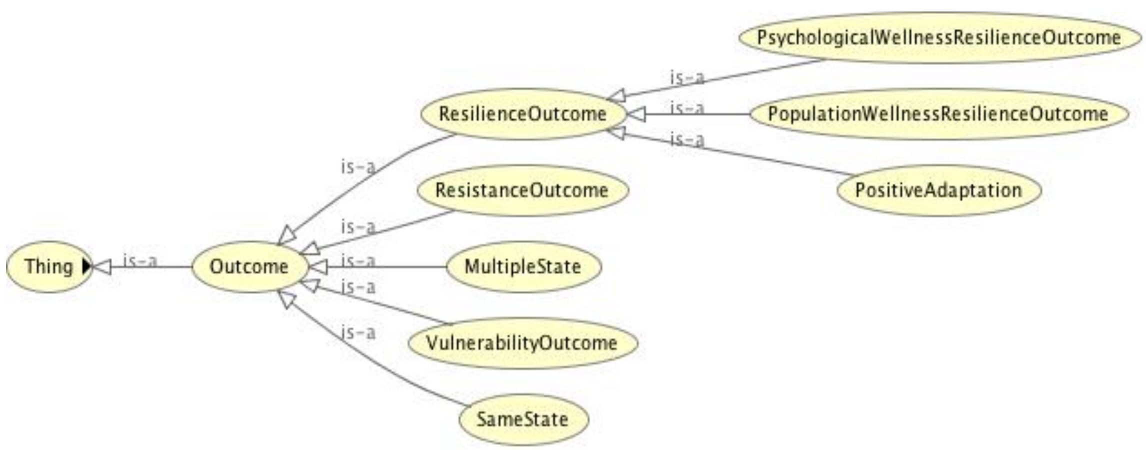


Figure 9: Population Hierarchy

Figure 10: Resilience Hierarchy

Figure 11: Resource Hierarchy

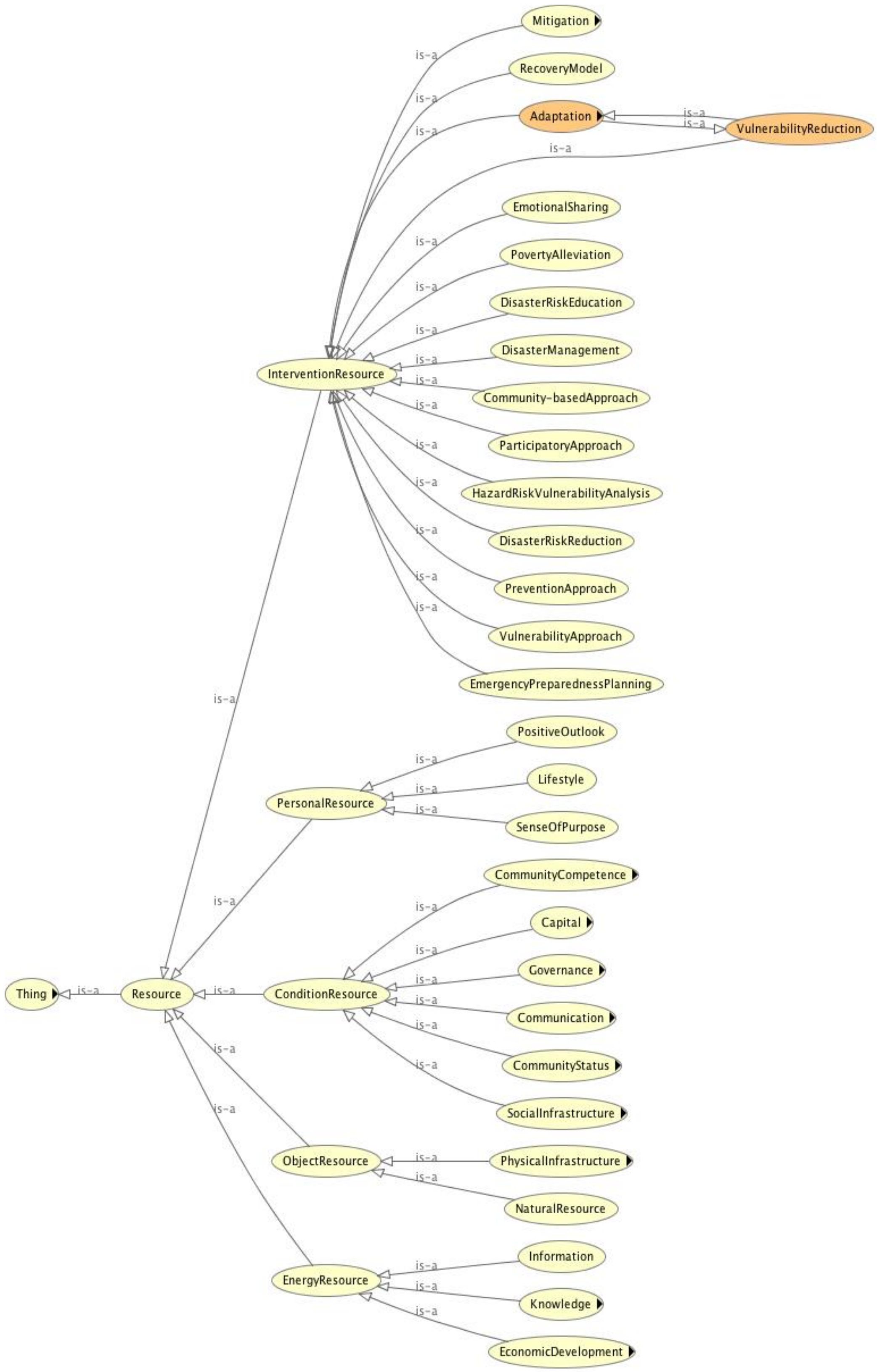
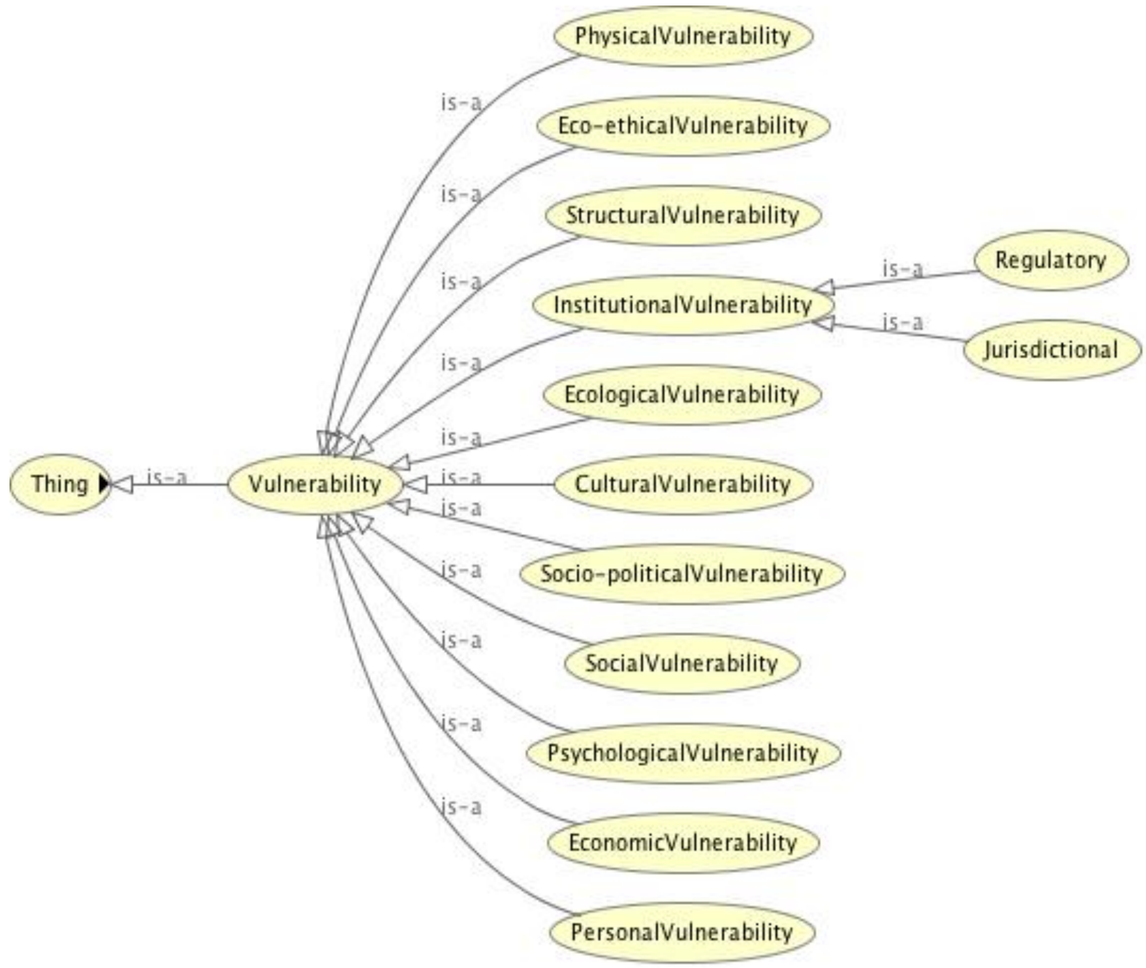


Figure 12: Vulnerability Hierarchy



Appendix E - Example Created for Discussion Section

Model

```
#include<vector>
 #include"z3++.h"
 using namespace z3;

 /**
   Ontology
   */
 void ontology() {

/*////////////////////////////////////////////////////////////////////////
//////////////////////////////////////////
            Declaration of the Z3 context: variables, constants, predicates, etc.

//////////////////////////////////////////////////////////////////////////
////////////////////////////////////////*/
      context c;
      sort Predicate = c.bool_sort();
      sort Variable = c.int_sort();
      sort Value = c.int_sort();

    // For the Classes
   func_decl Community = function("Community", Variable, Predicate);
   func_decl Resource = function("Resource", Variable, Predicate);
   func_decl Capital = function("Capital", Variable, Predicate);
   func_decl ConditionResource = function("ConditionResource", Variable,
Predicate);
   func_decl SocialCapital = function("SocialCapital", Variable, Predicate);
   func_decl SocialNetwork = function("SocialNetwork", Variable, Predicate);
   func_decl InformationFlow = function("InformationFlow", Variable, Predicate);
   func_decl EnergyResource = function("EnergyResource", Variable, Predicate);
   func_decl CRtD = function("CRtD", Variable, Predicate);
   func_decl Datatype = function("Datatype", Variable, Predicate);


   //For the relations
   func_decl hasSocialCapital = function("hasSocialCapital", Variable, Variable,
Predicate);
   func_decl hasValue = function("hasValue", Variable, Variable, Predicate);
   func_decl hasInformationFlow = function("hasInformationFlow", Variable,
Variable, Predicate);
   func_decl hasResilience = function("hasResilience", Variable, Variable, Predicate);
```

```
//Constants
expr rapid = c.int_const("rapid");
expr large = c.int_const("large");
expr dense = c.int_const("dense");
expr small = c.int_const("small");
expr slow = c.int_const("slow");
expr high = c.int_const("high");
expr low = c.int_const("low");
expr medium = c.int_const("medium");
expr veryhigh = c.int_const("veryhigh");


//Instances
expr Ottawa = c.int_const("Ottawa");
expr CRtDO = c.int_const("CRtDO");
expr SocialNetworkO = c.int_const("SocialNetworkO");
expr InformationFlowO = c.int_const("InformationFlowO");
expr OwenSound = c.int_const("OwenSound");
expr CRtDOS = c.int_const("CRtDOS");
expr SocialNetworkOS = c.int_const("SocialNetworkOS");
expr InformationFlowOS = c.int_const("InformationFlowOS");
expr PortElgin = c.int_const("PortElgin");
expr CRtDPE = c.int_const("CRtDPE");
expr SocialNetworkPE = c.int_const("SocialNetworkPE");
expr InformationFlowPE = c.int_const("InformationFlowPE");
expr Toronto = c.int_const("Toronto");
expr CRtDT = c.int_const("CRtDT");
expr SocialNetworkT = c.int_const("SocialNetworkT");
expr InformationFlowT = c.int_const("InformationFlowT");



//Declaration of the logical variables used in the FOL formula
expr x = c.int_const("x");
expr y = c.int_const("y");
expr z = c.int_const("z");
expr v = c.int_const("v");


  solver s(c);


/*//////////////////////////////////////////////////////////////////////
////////////////////////////////////////
        Axioms for hierarchy
```

```
/////////////////////////////////////////////////////////////////////////
/////////////////////////////////////////*/

   s.add(forall(x, implies((ConditionResource(x)), Resource(x))));
   s.add(forall(x, implies((EnergyResource(x)), Resource(x))));
   s.add(forall(x, implies((Capital(x)), ConditionResource(x))));
   s.add(forall(x, implies((SocialCapital(x)), Capital(x))));
   s.add(forall(x, implies((SocialNetwork(x)), SocialCapital(x))));
   s.add(forall(x, implies((InformationFlow(x)), EnergyResource(x))));

   //Assertion
    s.add(Community(Ottawa));
    s.add(SocialNetwork(SocialNetworkO));
    s.add(hasSocialCapital(Ottawa,SocialNetworkO));
    s.add(hasValue(SocialNetworkO,dense));
    s.add(hasValue(SocialNetworkO,large));
    s.add(InformationFlow(InformationFlowO));
    s.add(hasInformationFlow(Ottawa,InformationFlowO));
    s.add(hasValue(InformationFlowO,rapid));
    s.add(CRtD(CRtDO));
    s.add(hasResilience(Ottawa,CRtDO));
    //This will be a query: we infer it
    //s.add(hasValue(CRtDO,high));

    s.add(Community(OwenSound));
    s.add(SocialNetwork(SocialNetworkOS));
    s.add(hasSocialCapital(OwenSound,SocialNetworkOS));
    s.add(hasValue(SocialNetworkOS,dense));
    s.add(hasValue(SocialNetworkOS,small) and
not(hasValue(SocialNetworkOS,large)));
    s.add(InformationFlow(InformationFlowOS));
    s.add(hasInformationFlow(OwenSound,InformationFlowOS));
    s.add(hasValue(InformationFlowOS,slow) and
not(hasValue(InformationFlowOS,rapid)));
    s.add(CRtD(CRtDOS));
    s.add(hasResilience(OwenSound,CRtDOS));
  //   s.add(hasValue(CRtDOS,low));

    s.add(Community(PortElgin));
    s.add(SocialNetwork(SocialNetworkPE));
    s.add(hasSocialCapital(PortElgin,SocialNetworkPE));
    s.add(hasValue(SocialNetworkPE,dense));
    s.add(hasValue(SocialNetworkPE,small));
    s.add(InformationFlow(InformationFlowPE));
    s.add(hasInformationFlow(PortElgin,InformationFlowPE));
```

```
   s.add(hasValue(InformationFlowPE,rapid));
   s.add(CRtD(CRtDPE));
   s.add(hasResilience(PortElgin,CRtDPE));
 //   s.add(hasValue(CRtDPE,medium));

   s.add(Community(Toronto));
   s.add(SocialNetwork(SocialNetworkT));
   s.add(hasSocialCapital(Toronto,SocialNetworkT));
   s.add(hasValue(SocialNetworkT,dense));
   s.add(hasValue(SocialNetworkT,large));
   s.add(InformationFlow(InformationFlowT));
   s.add(hasInformationFlow(Toronto,InformationFlowT));
   s.add(hasValue(InformationFlowT,slow));
   s.add(CRtD(CRtDT));
   s.add(hasResilience(Toronto,CRtDT));
  // s.add(hasValue(CRtDT,medium));


   s.add(not(Ottawa==OwenSound or Ottawa==PortElgin or Ottawa==Toronto or
OwenSound==PortElgin or OwenSound==Toronto or Toronto==PortElgin or
Ottawa==high or Ottawa==low or Ottawa==dense or Ottawa==large or
Ottawa==small or Ottawa==rapid or Ottawa==slow or PortElgin==high or
PortElgin==low or PortElgin==dense or PortElgin==large or PortElgin==small or
PortElgin==rapid or PortElgin==slow or Toronto==high or Toronto==low or
Toronto==dense or Toronto==large or Toronto==small or Toronto==rapid or
Toronto==slow or Toronto==medium or Ottawa==medium or
OwenSound==medium or PortElgin==medium or PortElgin==veryhigh or
OwenSound==veryhigh or Toronto==veryhigh or Ottawa==veryhigh));


   s.add(not(OwenSound==high or OwenSound==low or OwenSound==dense or
OwenSound==large or OwenSound==small or OwenSound==rapid or
OwenSound==slow or high==low or high==dense or high==large or high==small or
high==rapid or high==slow or low==dense or low==large or low==small or
low==rapid or low==slow or dense==large or dense==small or dense==rapid or
dense==slow or large==small or large==rapid or large==slow or small==rapid or
small==slow or rapid==slow or high==medium or low==medium or
dense==medium or large==medium or small==medium or rapid==medium or
slow==medium or high==veryhigh or low==veryhigh or medium==veryhigh or
rapid==veryhigh or slow==veryhigh or large==veryhigh or small==veryhigh or
dense==veryhigh));

   s.add(not(CRtDO==CRtDOS or CRtDO==CRtDPE or CRtDO==CRtDT or
CRtDOS==CRtDPE or CRtDOS==CRtDT or CRtDPE==CRtDT));

   s.add(not(InformationFlowO==InformationFlowOS or
```

```
InformationFlowO==InformationFlowPE or InformationFlowO==InformationFlowT
or InformationFlowOS==InformationFlowPE or
InformationFlowOS==InformationFlowT or
InformationFlowPE==InformationFlowT));

    s.add(not(SocialNetworkO==SocialNetworkOS or
SocialNetworkO==SocialNetworkPE or SocialNetworkO==SocialNetworkT or
SocialNetworkOS==SocialNetworkPE or SocialNetworkOS==SocialNetworkT or
SocialNetworkPE==SocialNetworkT));

    //Datatypes
    s.add(Datatype(high));
    s.add(Datatype(veryhigh));
    s.add(Datatype(low));
    s.add(Datatype(medium));
    s.add(Datatype(rapid));
    s.add(Datatype(slow));
    s.add(Datatype(large));
    s.add(Datatype(small));
    s.add(Datatype(dense));


    //For axioms

    //If a community has a large, dense social network then their information flow is
rapid

    s.add(forall(x,y,z,v, implies((Community(x) and SocialNetwork(y) and
hasSocialCapital(x,y) and (hasValue(y,large) and hasValue(y,dense)) and
InformationFlow(z) and hasInformationFlow(x,z) and hasValue(z,rapid) and
CRtD(v) and hasResilience(x,v)), hasValue(v,high))));

    //If a community has a small, dense social network then their information flow is
slow

    s.add(forall(x,y,z,v, implies((Community(x) and SocialNetwork(y) and
hasSocialCapital(x,y) and (hasValue(y,small) and hasValue(y,dense)) and
InformationFlow(z) and hasInformationFlow(x,z) and hasValue(z,slow) and
CRtD(v) and hasResilience(x,v)), hasValue(v,low))));


//If a community has large, dense social network and slow information flow then it
has medium levels of community resilience to a disaster

    s.add(forall(x,y,z,v, implies((Community(x) and SocialNetwork(y) and
hasSocialCapital(x,y) and hasValue(y,large) and hasValue(y,dense) and
```

```
InformationFlow(z) and hasInformationFlow(x,z) and hasValue(z,slow) and
CRtD(v) and hasResilience(x,v)), hasValue(v,medium))));

    //If a community has small, dense social network and rapid information flow
then it has very high levels of community resilience to a disaster

    s.add(forall(x,y,z,v, implies((Community(x) and SocialNetwork(y) and
hasSocialCapital(x,y) and hasValue(y,small) and hasValue(y,dense) and
InformationFlow(v) and hasInformationFlow(x,v) and hasValue(v,rapid) and
CRtD(z) and hasResilience(x,z)), hasValue(z,veryhigh))));


    //Range constraint for Social Network
    s.add(forall(x,y, implies ((SocialNetwork(x) and Datatype(y) and hasValue (x,y)),
(((y == large) or (y == small) or (y == dense))))));

    s.add(forall(x,y, implies ((SocialNetwork(x) and Datatype(y) and hasValue (x,y)),
(((y == large) or (y == dense)) and not(y == small))
                        or (not(y == large) and ((y == small) or (y == dense))))));


    //Range constraint for Information Flow
    s.add(forall(x,y, implies ((InformationFlow(x) and Datatype(y) and hasValue
(x,y)), ((y == rapid) or (y == slow)))));

    s.add(forall(x,y, implies ((InformationFlow(x) and Datatype(y) and hasValue
(x,y)), (((y == rapid) and not(y == slow))
                                                        or (not(y == rapid) and (y ==
slow))))));


    //Range constraint for CRtD
    s.add(forall(x,y, implies ((CRtD(x) and Datatype(y) and hasValue (x,y)), ((y ==
high) or (y == low) or (y == medium) or (y==veryhigh)))));

    s.add(forall(x,y, implies((CRtD(x) and hasValue (x,y)), (((y==high) and
not(y==low) and not(y==medium) and not(y==veryhigh))
            or ((y==low) and not(y==medium) and not(y==high) and
not(y==veryhigh))
            or ((y==medium) and not(y==high) and not(y==low) and
not(y==veryhigh)) or ((y==veryhigh) and not(y==medium) and not(y==high) and
not(y==low))))));
```

```
    std::cout << s.check() << "\n";
    model m = s.get_model();
    std::cout << m << "\n";
    std::cout << m.size() << " model size\n";
    // traversing the model
    for (unsigned i = 0; i < m.size(); i++) {
        func_decl v = m[i];
        // this problem contains only constants
        if(v.arity() == 0)
            std::cout << v.name() << " = " << m.get_const_interp(v) << "\n";
        else
            std::cout << v.name() << " \n";
    }


    }



 int main() {
        try {
             ontology(); std::cout << "\n";
              std::cout << "done\n";
           }
        catch (exception & ex) {
              std::cout << "unexpected error: " << ex << "\n";
           }
        return 0;
    }
```

Reasoner Results:

```
Sarahs-MacBook-Pro:build sarahnewell26$ ./cpp_example
sat
(define-fun slow () Int
  11)
(define-fun SocialNetworkPE () Int
  14)
(define-fun InformationFlowPE () Int
  15)
(define-fun SocialNetworkO () Int
  1)
(define-fun SocialNetworkT () Int
  18)
```

```
(define-fun veryhigh () Int
  24)
(define-fun low () Int
  22)
(define-fun high () Int
  21)
(define-fun Toronto () Int
  17)
(define-fun CRtDPE () Int
  16)
(define-fun small () Int
  9)
(define-fun InformationFlowO () Int
  4)
(define-fun PortElgin () Int
  13)
(define-fun CRtDOS () Int
  12)
(define-fun large () Int
  3)
(define-fun medium () Int
  23)
(define-fun InformationFlowT () Int
  19)
(define-fun rapid () Int
  5)
(define-fun InformationFlowOS () Int
  10)
(define-fun SocialNetworkOS () Int
  8)
(define-fun k!2 () Int
  25)
(define-fun Ottawa () Int
  0)
(define-fun dense () Int
  2)
(define-fun CRtDT () Int
  20)
(define-fun OwenSound () Int
  7)
(define-fun CRtDO () Int
  6)
(define-fun hasResilience!176 ((x!1 Int) (x!2 Int)) Bool
  (ite (and (= x!1 0) (= x!2 6)) true
  (ite (and (= x!1 7) (= x!2 12)) true
  (ite (and (= x!1 13) (= x!2 16)) true
```

```
 (ite (and (= x!1 17) (= x!2 20)) true
  false)))))
(define-fun k!172 ((x!1 Int)) Int
 (ite (= x!1 13) 13
 (ite (= x!1 7) 7
 (ite (= x!1 0) 0
  17))))
(define-fun k!171 ((x!1 Int)) Int
 (ite (= x!1 8) 8
 (ite (= x!1 14) 14
 (ite (= x!1 1) 1
 (ite (= x!1 18) 18
 (ite (= x!1 15) 15
 (ite (= x!1 12) 12
 (ite (= x!1 16) 16
 (ite (= x!1 4) 4
 (ite (= x!1 20) 20
 (ite (= x!1 19) 19
 (ite (= x!1 6) 6
  10))))))))))))
(define-fun hasResilience ((x!1 Int) (x!2 Int)) Bool
 (hasResilience!176 (k!172 x!1) (k!171 x!2)))
(define-fun Resource ((x!1 Int)) Bool
 true)
(define-fun hasInformationFlow!175 ((x!1 Int) (x!2 Int)) Bool
 (ite (and (= x!1 0) (= x!2 4)) true
 (ite (and (= x!1 7) (= x!2 10)) true
 (ite (and (= x!1 13) (= x!2 15)) true
 (ite (and (= x!1 17) (= x!2 19)) true
  false)))))
(define-fun hasInformationFlow ((x!1 Int) (x!2 Int)) Bool
 (hasInformationFlow!175 (k!172 x!1) (k!171 x!2)))
(define-fun InformationFlow!178 ((x!1 Int)) Bool
 (ite (= x!1 4) true
 (ite (= x!1 10) true
 (ite (= x!1 15) true
 (ite (= x!1 19) true
  false)))))
(define-fun InformationFlow ((x!1 Int)) Bool
 (InformationFlow!178 (k!171 x!1)))
(define-fun CRtD!177 ((x!1 Int)) Bool
 (ite (= x!1 6) true
 (ite (= x!1 12) true
 (ite (= x!1 16) true
 (ite (= x!1 20) true
  false)))))
```

```
(define-fun CRtD ((x!1 Int)) Bool
 (CRtD!177 (k!171 x!1)))
(define-fun SocialNetwork!174 ((x!1 Int)) Bool
 (ite (= x!1 1) true
 (ite (= x!1 8) true
 (ite (= x!1 14) true
 (ite (= x!1 18) true
  false)))))
(define-fun hasSocialCapital!179 ((x!1 Int) (x!2 Int)) Bool
 (ite (and (= x!1 0) (= x!2 1)) true
 (ite (and (= x!1 7) (= x!2 8)) true
 (ite (and (= x!1 13) (= x!2 14)) true
 (ite (and (= x!1 17) (= x!2 18)) true
  false)))))
(define-fun hasSocialCapital ((x!1 Int) (x!2 Int)) Bool
 (hasSocialCapital!179 (k!172 x!1) (k!171 x!2)))
(define-fun Datatype!180 ((x!1 Int)) Bool
 (ite (= x!1 25) false
  true))
(define-fun ConditionResource ((x!1 Int)) Bool
 true)
(define-fun k!173 ((x!1 Int)) Int
 (ite (= x!1 11) 11
 (ite (= x!1 24) 24
 (ite (= x!1 22) 22
 (ite (= x!1 3) 3
 (ite (= x!1 9) 9
 (ite (= x!1 23) 23
 (ite (= x!1 2) 2
 (ite (= x!1 21) 21
 (ite (= x!1 5) 5
  25))))))))))
(define-fun Datatype ((x!1 Int)) Bool
 (Datatype!180 (k!173 x!1)))
(define-fun SocialNetwork ((x!1 Int)) Bool
 (SocialNetwork!174 (k!171 x!1)))
(define-fun hasValue!181 ((x!1 Int) (x!2 Int)) Bool
 (ite (and (= x!1 1) (= x!2 2)) true
 (ite (and (= x!1 1) (= x!2 3)) true
 (ite (and (= x!1 4) (= x!2 5)) true
 (ite (and (= x!1 8) (= x!2 2)) true
 (ite (and (= x!1 8) (= x!2 9)) true
 (ite (and (= x!1 10) (= x!2 11)) true
 (ite (and (= x!1 14) (= x!2 2)) true
 (ite (and (= x!1 14) (= x!2 9)) true
 (ite (and (= x!1 15) (= x!2 5)) true
```

```
 (ite (and (= x!1 18) (= x!2 2)) true
 (ite (and (= x!1 18) (= x!2 3)) true
 (ite (and (= x!1 19) (= x!2 11)) true
 (ite (and (= x!1 6) (= x!2 21)) true
 (ite (and (= x!1 12) (= x!2 22)) true
 (ite (and (= x!1 16) (= x!2 24)) true
 (ite (and (= x!1 20) (= x!2 23)) true
  false))))))))))))))))
(define-fun Community ((x!1 Int)) Bool
 true)
(define-fun EnergyResource ((x!1 Int)) Bool
 true)
(define-fun Capital ((x!1 Int)) Bool
 true)
(define-fun hasValue ((x!1 Int) (x!2 Int)) Bool
 (hasValue!181 (k!171 x!1) (k!173 x!2)))
(define-fun SocialCapital ((x!1 Int)) Bool
 true)
51 model size
slow = 11
SocialNetworkPE = 14
InformationFlowPE = 15
SocialNetworkO = 1
SocialNetworkT = 18
veryhigh = 24
low = 22
high = 21
Toronto = 17
CRtDPE = 16
small = 9
InformationFlowO = 4
PortElgin = 13
CRtDOS = 12
large = 3
medium = 23
InformationFlowT = 19
rapid = 5
InformationFlowOS = 10
SocialNetworkOS = 8
k!2 = 25
Ottawa = 0
dense = 2
CRtDT = 20
OwenSound = 7
CRtDO = 6
hasResilience
```

Resource
hasInformationFlow
k!172
InformationFlow
CRtD
k!171
SocialNetwork!174
hasSocialCapital
CRtD!177
Datatype!180
ConditionResource
Datatype
hasSocialCapital!179
SocialNetwork
hasValue!181
Community
hasInformationFlow!175
EnergyResource
Capital
InformationFlow!178
hasResilience!176
hasValue
k!173
SocialCapital