Ontology Summit 2022 Communiqué
Dealing with Disasters

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Abstract

The COVID-19 pandemic as well as other recent disasters have prompted an impressive, worldwide response by governments, industry, and the academic community. A newfound willingness both to share information and to improve transparency in sharing information has played a role in the success of these responses. In this article we examine the landscape of health-related, environmental, and aerospace disasters; and a framework consisting of a set of dimensions is developed to characterize the landscape. A sample of projects is presented to illustrate best practices and lessons learned for tasks such as search, data description, interoperability and harmonization of the increasingly large data sources that are relevant to disasters. It was found that there are many cross-domain linkages between the information resources needed for responding to different kinds of disasters, which offers opportunities for the reuse of information resources.

1. Introduction

The United Nations Office for Disaster Risk Reduction (UNDRR) defines a disaster to be "a serious disruption of the functioning of a community or a society at any scale due to hazardous events interacting with conditions of exposure, vulnerability and capacity, leading to one or more of the following: human, material, economic and environmental losses and impacts" (UNDRR, 2022). The International Federation of Red Cross and Red Crescent Societies (IFRC) adds the requirement that the disruption must exceed the capacity or willingness of a community or society to cope using its own resources (IFRC, 2022). By the IFRC definition, an emergency would not be a disaster if the community or society has the capacity and willingness to cope. While preventing all possible disasters is not possible, one can reduce disaster risks either by addressing the underlying causes of the emergencies that can result in disasters or by ensuring that there are adequate resources and plans for coping with foreseeable emergencies to prevent them from becoming disasters (by the IFRC definition). Information is fundamental to either way of reducing disaster risks; indeed, one can argue disasters are nearly always the result of a failure of information (West, 2022). When a disaster has occurred, information is necessary for managing the disaster.

New technologies, better sensors and greater willingness to share data have increased the quantity and complexity, as well as the timeliness, of information in general, and of information that is relevant for disaster risk reduction and disaster management in particular. As a result of the increase in volume, complexity, and creation speed of data, we increasingly rely on computational support to deal with data. The Findability, Accessibility, Interoperability, and Reuse (FAIR) principles are guidelines to ensure that data is machine-actionable with minimal or no human intervention (GO FAIR, 2022). The FAIR guidelines require data to be described with rich metadata, and both data and metadata must conform to the FAIR principles. However, to make data FAIR whilst preserving them over time requires trustworthy digital repositories with sustainable governance and organizational frameworks, reliable infrastructure, and comprehensive policies supporting community-agreed practices. The Transparency, Responsibility, User focus, Sustainability and Technology (TRUST) principles were collaboratively developed and endorsed by

Figure 1: Pictorial Representation of the Landscape of Kinds of Disaster (Ravi Sharma)

the digital repository community for the purpose of providing a common framework to facilitate discussion and implementation of best practice in digital preservation by all stakeholders (Lin, D., Crabtree, J., Dillo, I. et al., 2020). Semantic technologies (also called knowledge organization systems) can be useful for coping with the variety of sources and types of information by meaningfully harmonizing data from diverse sources and by aiding interoperability of systems for disaster risk reduction as well as disaster management systems helping to ensure that data and metadata satisfies FAIR and TRUST principles. Semantic technologies can range from simple taxonomies to formal ontologies. An ontology encompasses a representation, formal naming, and definition of the categories, properties, and relations between the concepts, data, and entities that substantiate one, many, or all domains of discourse.

In this article we begin by developing a framework for the dimensions that define disasters. A pictorial representation of the framework is shown in Figure 1. While disasters have many common features and generally follow similar lifecycles, there are differences that influence the kinds of technologies that are best suited to risk reduction and management. This is especially the case for ontologies, and we discuss the issues and make recommendations in Section 2.

The disaster that has generated the most public attention in recent times is the COVID-19 pandemic. The COVID-19 pandemic has had a massive impact on the world, in terms of human toll – economically, socially, politically and scientifically. Section 3 is devoted to pandemics with special attention to COVID-19.

There is a very wide range of environmental disasters. The most prominent are climate change, wildfires, and floods. Section 4 discusses environmental disasters and the issues that they raise. Aerospace and maritime disasters are considered in Section 5.

In Section 6, we present a representative sample of projects that have developed and use semantic technologies and ontologies for disaster monitoring and management. The projects illustrate the usefulness of semantic technologies such as ontologies for many purposes as well as provide lessons for developers who need to respond to hazards, emergencies and other disruptions.

2. Disaster Framework Dimensions

Disasters can be characterized by a number of dimensions. We organized the dimensions using the basic question words whose answers are considered foundational for information gathering, problem solving, defining an enterprise, or establishing a context (Baclawski et al, 2020b; Bennett, 2021). The questions are shown in Figure 2. In addition, we included some dimensions that are relevant to disasters: risk, severity, and supply chains. Finally, the degree to which any data or metadata conforms to FAIR and TRUST principles is an important dimension.

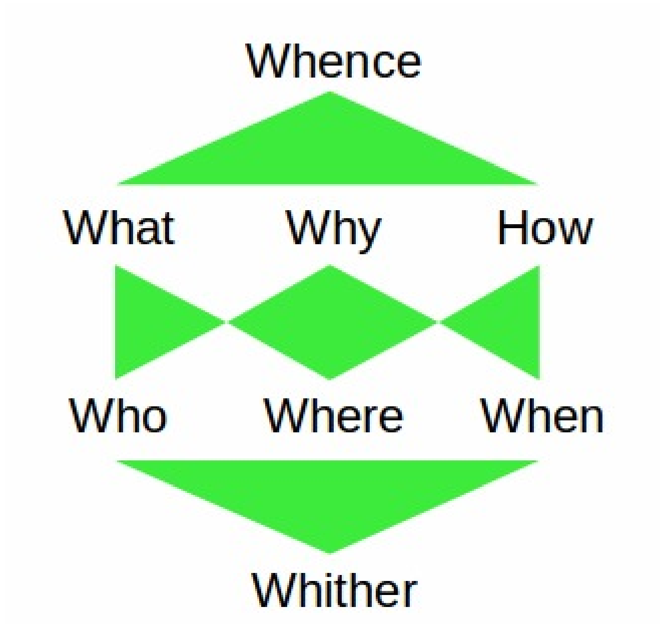


Figure 2: The basic questions (Baclawski et al, 2020b)

Whence. The first question is concerned with the origin or cause of a disaster. This is more subtle than it might seem. For example, it seems obvious that since the COVID-19 disease is caused by the SARS-CoV-2 virus, the COVID-19 pandemic was caused by this virus. However, that misrepresents the full lifecycle situation. At its initial stages, a pandemic begins as a local health emergency. The emergency can then progress to a local epidemic, and only when it spreads uncontrollably does it emerge as an epidemic or pandemic. The same is true for disasters in general; a risky situation may emerge as an emergency, becoming a disaster only when it can no longer be managed using available resources and plans. The inadequacy of available resources and the subsequent need for outside assistance that is more properly a necessary ingredient or cause of a disaster. The lack of available resources, in turn, is generally the result of an information failure due to poor communication, insufficient adequate knowledge, lack of access to relevant information, or other information failures (West. 2022). Accordingly, information is fundamental to understanding the cause of a disaster as well as how best to respond to it. Resources such as ontologies can play an important role in structuring information relevant to a disaster so that it can be correctly searched for and employed as required by the FAIR principles.

What. This dimension is concerned with the specific details of the disruption. From an ontological perspective, this is the domain of the disaster. The biomedical domain is especially important because of the ongoing COVID-19 pandemic as well as pandemics in general that have wide-ranging impacts on virtually everyone as discussed in Section 3. There are other aspects of health that can also have significant impact on the well-being of people, including nutrition and trauma (West, 2022; Fox, 2022; Dougherty, 2022). The environmental domain is another important source of disasters that have the potential for global impact. Climate change is a global emergency that has the potential to be a major disaster on many fronts; indeed, climate change is already having disastrous effects. Other environmental disasters include wildfires, floods (both of which are related to climate change), earthquakes, and volcanic eruptions. See Section 4. Monitoring the environment makes use of many types of sensors. Satellites are critically important for environmental sensing and are increasingly important for many essential services such as internet communication and navigation as discussed in Section 5. Large constellations of satellites have now been deployed and are continuing to be deployed that have their own vulnerabilities and potential for disasters. Outer space beyond the immediate vicinity of Earth is yet another source for potential disasters, affecting communications from space weather-driven solar flares as well as losses from potential asteroid and comet impacts (Hull, 2022).

Why. An explanation is the answer to the question "Why?" as well as the answers to follow-up questions such as a request for technical details. Accordingly, explanations generally occur within the context of a process, which could be a dialog between a person and a system or could be an agent-to-agent communication process between two systems (Baclawski et al., 2020a). Explanations and justifications are important during all stages of a disaster. Prior to a disruptive event, planning requires the allocation of resources, and explanations are necessary to make a convincing case. When an emergency is developing into a potential disaster and after the emergency has resulted in a disaster, explanations are needed for raising awareness to prevent the disaster or to recover from it. The words, phrases and metaphors used for the explanations will determine the narrative, and if poorly chosen can hinder responses. For example, if the cause of a pandemic is perceived as being an infectious disease, then people will use a "war" metaphor in which the infectious agent is regarded as the "enemy" that must be "fought" and "defeated". In fact, a pandemic is better regarded as being the result of issues such as human behavior and information failures, which are better described using very different terminology and metaphors.

How. By definition, "how" is concerned with the way something is done or happens. A complex event happens in a progression of stages called its lifecycle. The lifecycle of a disaster can be divided into stages: inactivity, onset, occurrence, recovery. The occurrence stage, such as in a wildfire, is generally referred to as "the disaster". The onset progresses through various levels of severity leading up to the point where it is clear that a disaster is in progress. The occurrence stage can have more than one "wave" as the severity waxes and wanes. In practice, the division between the various stages of a disaster will only be known in retrospect and will differ from one region to another. Disaster management also has a lifecycle that is divided into anywhere from three to five stages or phases, depending on the particular management framework. The stages overlap one another, and different sources list the stages in different orders. The most commonly mentioned stages are: prevention, mitigation, preparedness, response, and recovery. The UNDRR defines all of these terms (UNDRR, 2022). *Prevention* consists of activities and measures to avoid existing and new disaster risks. *Mitigation* is the lessening or minimizing of the adverse impacts of a hazardous event. *Preparedness* consists of the knowledge and capacities developed by governments, response and recovery organizations, communities and individuals to effectively anticipate, respond to and recover from the impacts of likely, imminent or current disasters. *Response* consists of actions taken directly before, 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. *Recovery* is the restoring or improving of livelihoods and health, as well as economic, physical, social, cultural and environmental assets, systems and activities, of a disaster-affected community or society, aligning with the principles of sustainable development and “build back better”, to avoid or reduce future disaster risk.

Another important management activity is hazard monitoring. The purpose of hazard monitoring is to achieve a state of readiness based on answering the basic question words for the hazard, such as: When, why and how may a hazard occur? Who would be affected? What are the warning signs? How do we minimize risk?

Who and **Where**. Disasters have a geographic extent where they occur, and the individuals who are affected are usually the ones living there. While the popularity of international travel has blurred the distinction between who and where, they are still closely related as disaster dimensions. The extent may range from a single individual to the entire world. A disaster for an individual may be an illness or trauma (Dougherty, 2022). An accident could involve just a few individuals. Local disasters can affect a city or a small region, such as epidemics, floods, wildfires and earthquakes (Fox, 2022; Jones and Moe, 2022; Berg-Cross and Sharma, 2022). Responses to disasters are generally at the national level even when a disaster is global. Global disasters include pandemics (Section 3), climate change (Section 4), and space disasters (Section 5). In all cases, geographic and geospatial information is critical in dealing with disasters.

When. The temporal span of a disaster has more than one aspect. The length of time can range from an hour or less to several millennia, and the onset of the disruption can be sudden or gradual. Yet another aspect of when is the phase of the lifecycle of a disaster. Pandemics generally develop relatively suddenly but can last for only a few years or for thousands of years. There are three major ongoing pandemics, where a major pandemic is one that has around one million or more fatalities per year. COVID-19 lasted two years before most nations achieved some degree of control. The HIV pandemic has lasted forty years so far. The Tuberculosis pandemic has lasted at least 6000 years (Baclawski, 2022). By contrast, the onset of climate change has been very gradual, and the impact will last for centuries. Other environmental disasters, such as floods and wildfires can be very sudden but also are relatively brief. Space related disasters, such as solar flares are very sudden but brief, while asteroid impacts are now highly predictable, so they no longer have a sudden onset. In general, the timeliness of sensing events and sharing the what and where of disasters is critical.

Whither. After a disaster has ended, the prudent course of action is to take steps to ensure that one is prepared so that similar emergencies do not escalate to become disasters. Unfortunately, it is common for governments to ignore the problem once the disruption is over and public interest has waned. The metaphor that determines the narrative of a disaster, whether explicitly or implicitly, will affect public attitudes. For example, the “war” metaphor for a pandemic that is ending would encourage people to return to “pre-war” behaviors now that the “enemy” has been “defeated”. A more appropriate response would be to begin preparing for the next emergency (which may be seasonal) by permanently changing behaviors and by building a better information infrastructure. An example of a good response to a disaster is the UK Digital Twin project (West, 2022), and there are many examples of projects that are developing proactive interventions to prevent disasters for public health (Lieberman, 2022; Churchyard, 2022; Gil, 2022), the environment (Section 4), and space (Section 5).

Risk. Disasters and risks are fundamentally related notions. Risk assessments are necessary for planning purposes to prevent disasters, for monitoring and mitigating the effects of a disaster, and for recovering from a disaster. Generally, cost-benefit analyses based on risk assessments are the basis for choosing the most effective means of dealing with disasters at every stage. In addition to overall risk assessments, it is also important to inform individuals about the risks associated with their behaviors. However, there are many interpretations of risk, and miscommunication can occur if different interpretations are

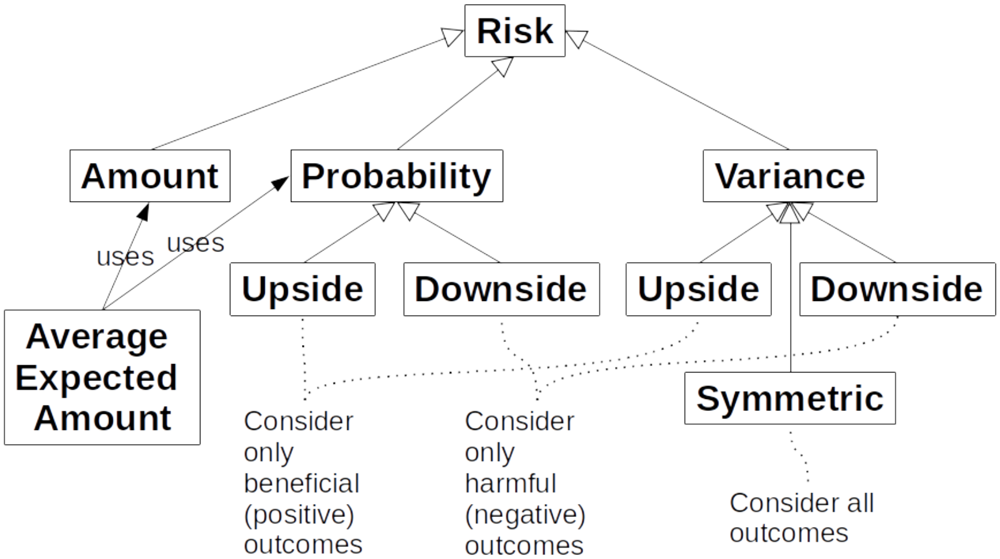


Figure 3: Taxonomy of Risk (Baclawski, 2022)

conflated. The taxonomy of kinds of risk is shown in Figure 3 (Baclawski, 2022).

Severity. The number of individuals who have been injured or died as a direct result of a disaster as well as the cost due to the destruction of infrastructure and property are important dimensions of a disaster; however, these are complex statistics. They vary over time and can be difficult to measure. Some jurisdictions may be reluctant to report cases or may have differing criteria for their reports. For some disasters, such as hurricanes, it is even possible for estimated net fatalities to be negative. This happens because the fatality rate during the disaster can exceed the average mortality rate for the affected region. In addition, most disasters also have their own domain-specific measures like wind-speed for hurricanes, depths for floods and snowstorms and extent for wildfires.

Supply Chains. Although the term "chain" suggests a linear sequence of activities, a supply chain is often a complex network of organizations, people, activities, information, and resources. Responding to a disaster usually requires supply chains for products and services, and a disaster can disrupt supply chains (Gil, 2022; Lieberman, 2022; Churchyard, 2022). For example, the COVID-19 pandemic required the creation of supply chains to provide vaccines, and the pandemic supposedly disrupted many supply chains. While there is evidence that the COVID-19 pandemic was one of the causes for supply chain disruptions, it is possible for supply chain disruptions to occur without any proximate cause because the supply chains can be dynamically unstable. This is known as the "bullwhip effect" (Section III, Baclawski et al, 2019).

Because a disaster is both affected by and affects supply chains, the disaster should be modeled as one of the components of the network. A further complication is that monitoring a supply chain (or any phenomenon) can affect the supply chain. This is known as the observer effect (Baclawski, 2018). To avoid observer bias, one should include monitoring processes as components in the network. The result of combining multiple supply chains, the disaster itself, as well as the monitors, in a network would require one to build and analyze a large, complex network. An important issue with complex networks is the need for interoperation and harmonization among components. Ontologies can help planners to model, analyze and monitor complex supply chains that affect and are affected by a disaster.

FAIR and **TRUST**. The degree to which information and semantic technologies relevant to a disaster conform to the FAIR and TRUST principles is an important dimension. When FAIR principles are not followed, disaster-related decision making can be very time-consuming because so much effort is required to acquire and to process the information that is necessary for a decision (Gil, 2022; Lieberman, 2022; Churchyard, 2022). Unfortunately, a recent survey of disaster management ontologies found that FAIR principles are seldom followed (Mazimwe, Hammouda, and Gidudu, 2021). The average Findability level was only 1.8%, the average Accessibility level was only 5.8%, and only 4.3% of the retrieved ontologies detail explicit mapping/correspondences between ontologies. Examples of disaster management projects that are based on ontologies conforming to the FAIR principles are described in Section 6.

3. Health Disasters

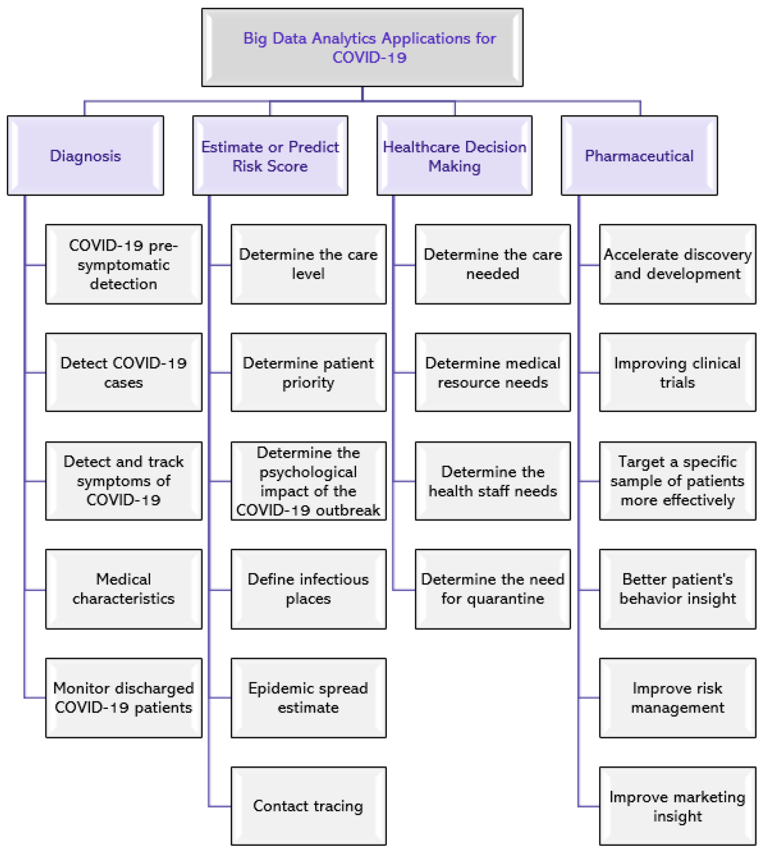
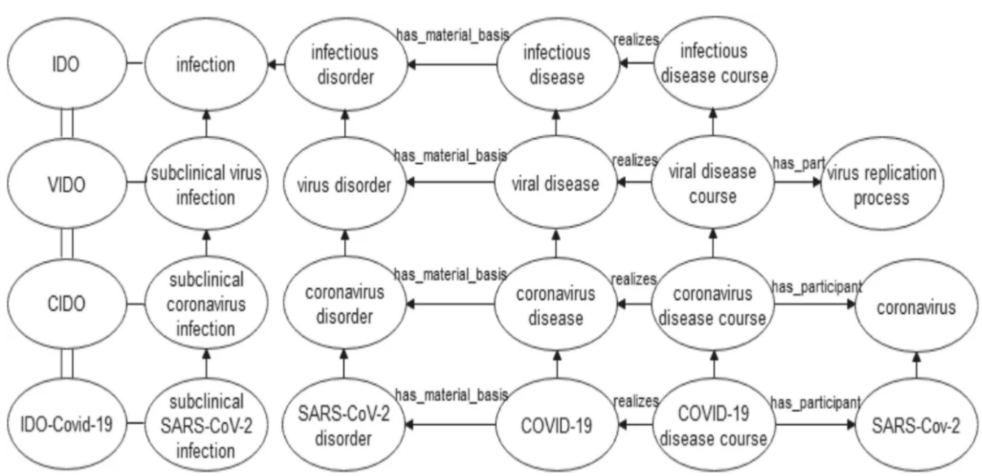


Figure 4: Taxonomy of COVID-19 Analytic Techniques
(derived from DeBellis and Dutta, 2021)

Health-related disasters span various landscape dimensions. For example, different diseases can affect different groups of people (i.e., who and where), and health emergencies can be short-term or long-term (i.e, when). In most cases, the onset of a health-related disaster will be relatively sudden. Health disasters significantly affect and are affected by supply chains. A substantial range of data resources and information generally be needed for situational understanding of health-related disasters. The COVID-19 pandemic caused a large number of human fatalities as well as considerable havoc in the economic, social, societal, and health systems around the world. Responding to the pandemic was a major challenge. One aid to response was the varied use of an unprecedented amount of big data derived from public health surveillance, including vast amounts of real-time monitoring of outbreaks, news reports, and organizational briefings. Some of the scope of the domain is shown in Figure 4. Much of this data was represented and stored using traditional data approaches, and websites offered a large, static representation of COVID-19 data. A limiting factor is that much of such data is largely unstructured (e.g., text, audio, video, image, newspaper, and blogs). This creates a major analysis and data integration problem. The data integration task gets simplified by the use of semantic technologies and the incorporation of knowledge organization systems (e.g., taxonomy, vocabulary and ontology) as background knowledge. Such resources fall along the semantic spectrum from controlled vocabularies to facilitate communication and understanding to linked data or structuring of data into easily queried knowledge graphs. Together these help meet the requirement for rapid data gathering and storage, but also results in COVID-19 data being stored across distributed geographies and often siloed databases, Such data siloing hinders translational and comparative research as well as slowing prognostic public health research needed in a time of a pandemic. For all these reasons, semantic technologies can help meet the challenge by supporting meaning-based data sharing across multiple disciplines and varied data systems.

Of particular interest is the use of formal, possibly openly available ontologies with well-specified syntax including a common space reachable by means of identifiers. One example of this is the adaptation of the Infectious Disease Ontology (IDO) made up of an aligned suite of interoperable ontology modules. These include ChEBI for chemical entities, Human Phenotype Ontology for human host phenotypes, and the more general Disease Ontology. Together these were designed to provide broad coverage across various aspects of the infectious disease domain. The IDO design was flexible to allow building new pathogen-specific ontologies in a simple way in order to allow novel disease data to be easily analyzed. This may take place in part by comparison to other pathogens, diseases and treatments. Using this knowledge an IDO implementation could help identify drug candidates that could be repurposed for an effective and safe COVID-19 treatment. Over 90 chemicals, drugs and antibodies against human coronavirus diseases were identified early on by mapping anti-coronavirus drugs to ontology IDs from ChEBI and drug data using semantic similarity analysis (Liu, et al. 2020).To do this for COVID-19 some parts of the core IDO model were enhanced by introducing the termed concept acellular which is a term that covers viruses along with other acellular entities that are part of the study of virology. This term allowed one to distinguish infectious agents (i.e., organisms with an infectious disposition) from infectious structures (i.e., acellular structures that have an infectious disposition).



Relationships among IDO, VIDO, CIDO, and IDO-Covid-19 from Patel, Archana, et al. 2021.

Figure 5: Mapping relationships among biomedical ontologies

Three new IDO extensions were developed. The IDO Virus Ontology (VIDO) extended IDO to deal with viral infections (Babcock et al, 2021). The Coronavirus Infectious Disease Ontology (CIDO) extended

VIDO for coronaviruses (He et al, 2022). Finally, CIDO was extended for COVID-19 cases and patient information with the CODO ontology, also called the IDO-Covid-19 ontology (Dutta, 2020; DeBellis, 2022; Dutta, 2022; DeBellis and Dutta, 2021). Relationships between these ontologies are summarized in Figure 5 which makes an essential point that modular ontologies may be aligned and work together using common concepts, such as exposure to COVID-19 and vital signs relevant to COVID-19, to cover portions of a domain of interest as needed and enabling broad querying among all the modules (Dutta and DeBellis, 2020). The work also illustrates the incremental way that modular ontologies may be matured (Berg-Cross, 2021c).

We have described some of the work on COVID-19 to help ensure FAIR principles as well as to promote understanding. Among other things, this work shows the effectiveness of modular ontologies working together, expanding and harmonizing to support other technologies such as knowledge graphs.

4. Environment Disasters

Improving environment disaster management and recovery techniques is a priority given their impacts and given trends such as increased floods, droughts and the impact of climate change. One impediment to achieving improvements is the many definitions of environmental terms. There are, for example, many definitions of wildfires and floods.

As is true of other disasters. environmental disasters need rapid, flexible, but deep situational awareness, and have big data and analytic challenges arising from data heterogeneity and complexity, isolation and lack of conformity to FAIR principles. The situational awareness driver to reduce ambiguity and improve predictions is to mix historical data (e.g., prior cholera outbreaks that may have affected regional vulnerabilities before a hurricane makes landfall) with real-time data. One challenge is to effectively capture the status information and structure in a way that effectively improves situational awareness using diverse types of information from diverse sources as soon as it becomes available. There have been ontologies developed for disasters such as floods (Sinha and Dutta, 2020). Most of these ontologies are task ontologies that are formal, modular and use the Web Ontology Language (OWL) for their representation. The most used and reused are the Semantic Web for Earth and Environmental Terminology (SWEET) ontology, the contextual design patterns of the Semantic Sensor Network (SSN) ontology, and ontologies for Time and Space. In general, the domain of flooding remains only lightly formalized.

As with the previously described COVID-19 work, knowledge graphs help handle some of the data silo problems by acting like a default common data model. Knowledge graphs, like ontologies, emphasize structuring relationships along with attributes. For more about knowledge graphs and their connections with ontologies see (Baclawski et al, 2020b).

Until recently, knowledge graphs were not very successful in the realm of environmental data and environmental intelligence. This was in part because spatial data requires special treatment and because of the difficulty of usefully lifting environmental data to a knowledge graph using formal semantics.

Fortunately, for the past 50 years the Earth science community has been establishing its infrastructure not only for current space-based image data required for monitoring the disasters but also for changes in the environment over the years (Sharma, 2022b). Semantics, metadata, sensors and platforms as well as repositories enable search and discovery tools, and communities are increasingly being formed to address timeliness and relevance of data for disaster management support. Harmonization of data and metadata, and use of diverse platforms from NASA, NOAA, ESA and other agencies is being increasingly sought and some ontologies addressing overlap areas are being developed (Sharma, 2022a; NASA, 2018). Agencies (e.g., UNDRR, FEMA) and communities (e.g., the Earth Science Information Partners (ESIP)) play increasing roles in monitoring and mitigation.

5. Aerospace and Maritime Disasters

As with health-related and environmental disasters, aerospace and maritime disasters can be characterized by the basic questions and the risk, severity and supply chain dimensions. The diagram in Figure 6 classifies disasters for aerial, maritime and outer space situations. The common thread is a distinction between human-associated hazards or activity, and natural phenomena that may potentially result in disasters. Note that the various hazards overlap with one another.

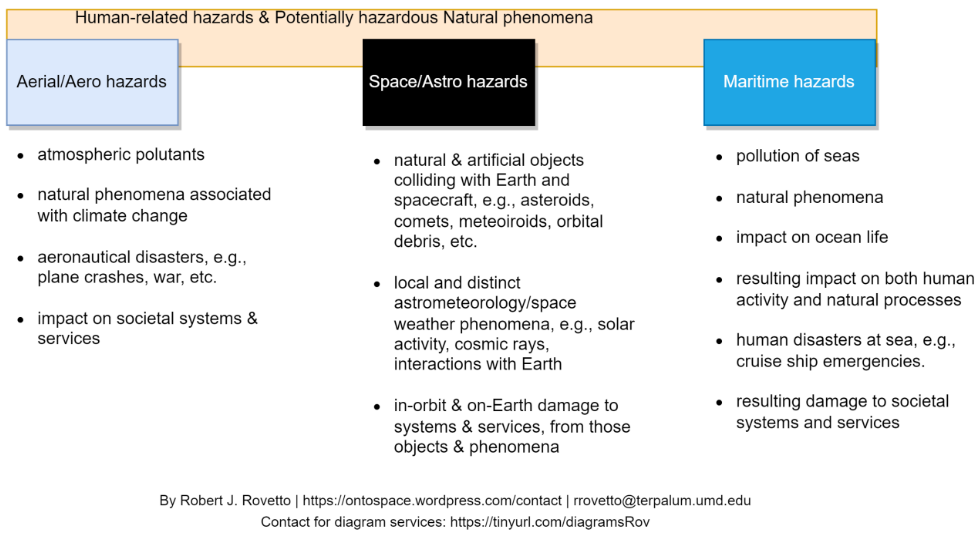


Figure 6: Classification of Aeronautical, Maritime, and Space Hazards (Rovetto, 2022)

Aeronautical and atmospheric hazards and disasters include artificial pollutants impacting the atmosphere and affecting the health of living creatures, natural phenomena possibly associated with climate change, airplane crashes, as well as human conflict activities such as war, crime, terrorism, etc. Disasters in this context may have harmful impacts on systems and services in societies, which overlaps with arguably any sort of potential disaster and context. For each, there is associated research, and investigative, activities that have collected various sorts of data (EPA, 2022).

Maritime hazards include artificial pollution of the seas and debris (NOAA, 2022), which can harm both human and non-human life (Avakian, 2022), thereby impacting natural processes and ecosystems; natural phenomena, whether associated with human activity or not; human emergencies at sea, such as cruise or cargo ship disasters; as well as any resultant damage to systems and services in societies. Like the aeronautical context, both data-centric research is conducted for changes in marine ecosystems, and data is collected for investigations into human disasters at sea.

Space hazards can come from both artificial and natural phenomena but are different in some respects from aeronautical and maritime hazards. The main kinds of space hazards are meteoroids, debris (NASA, 2022a), and solar flares. Smaller meteoroids are difficult to track although the technology is improving. The impact of a meteorite is literally its impact with the Earth. Space debris near Earth is now being tracked and can potentially be mitigated by preventing its creation through appropriate spacecraft design and debris removal measures. Like meteorites, space debris will impact the Earth, but can also impact spacecraft (NASA, 2016), which could harm astronauts as well as the financially expensive technological systems and the services they provide, with a significant impact on society. For example, loss of artificial satellites due to debris may result in damage to Global Positioning Systems, negatively impacting navigation on Earth. Similarly, so for the loss of communications services, internet services, observational services (scientific, military, etc.). A collision between orbital debris and other satellites would produce more debris which could cascade to render near Earth space activities impossible for decades, a phenomenon known as the Kessler syndrome (Hull, 2022). Extreme space weather, especially solar flares, is another kind of space hazard (ESA, 2022). The potential impact is on space-based and terrestrial communication and power systems (NOAA, 2023).

Given the active and diverse areas of big data research and given the need for data collection when investigating disasters such as those described above, knowledge organization systems (such as NASA, 2022b), including ontologies, could play a useful role. A space domain reference ontology is presented in Section 6.

6. Project Examples

In this section we summarize some of the projects that have been developing and using ontologies for disaster monitoring and response management.

VIDO, **CIDO** and **CODO**. VIDO extends the IDO ontology to add virus-specific entities and provides concrete information about the domain of virus disease. In particular, VIDO specialized the IDO concepts by addition of the term "virus" to create a subclass. Using what was known of the viruses the logical relations and textual information about the classes were ontologized. For example, as shown in Figure 5, IDO's Infectious Disease became Viral Disease. The latest version of VIDO was released in August 2020 (Babcock et al, 2021).

The CIDO ontology further specialized VIDO with coronavirus disease concepts. CIDO is a community-based, open source ontology that is interoperable with other existing Open Biological and Biomedical Ontology (OBO) Foundry ontologies. CIDO has imported terms from over 30 OBO Foundry ontologies, including all SARS-CoV-2 protein terms from the Protein Ontology, COVID-19-related phenotype terms from the Human Phenotype Ontology, and over 100 COVID-19 terms for vaccines from the Vaccine Ontology. CIDO has been used in various applications such as term standardization, inference, natural language processing (NLP), clinical data integration and drug repurposing for COVID-19 treatment (He et al, 2022).

The community based CODO ontology published on Bioportal has 4000 plus terms and was designed to capture particular data about the COVID-19 pandemic. The idea was to support the collection of epidemiological data starting with the representation of the novel corona viruses and variants along with phenotypes, anti-coronavirus drugs and medical devices (e.g., ventilators). An example of the part of the CODO ontology connected to a patient is shown in Figure 7 (Dutta, 2022).

The CODO ontology, available on the CODO Github (Dutta, 2020), was designed by analyzing disparate COVID-19 data sources such as datasets on cases, patients, relations (e.g., family, co-workers), and on the COVID-19 Data Repository at Johns Hopkins University. Geographic locations and date-time information was also available. CODO leveraged literature and services information, and its coverage includes contact tracing, diagnosis, disease measures, comorbidity, treatments and drugs, vaccination, cases and resource descriptions, tests, and preventive measures, along with responses and relevant contextual influences such as weather situations. To adapt to COVID-19 challenges a health facility concept had to be a sub-type as, for example, a COVID-19 dedicated facility which is further sub-categorized into COVID-19 care center, dedicated COVID-19 health center, and dedicated COVID-19 hospital. To facil-

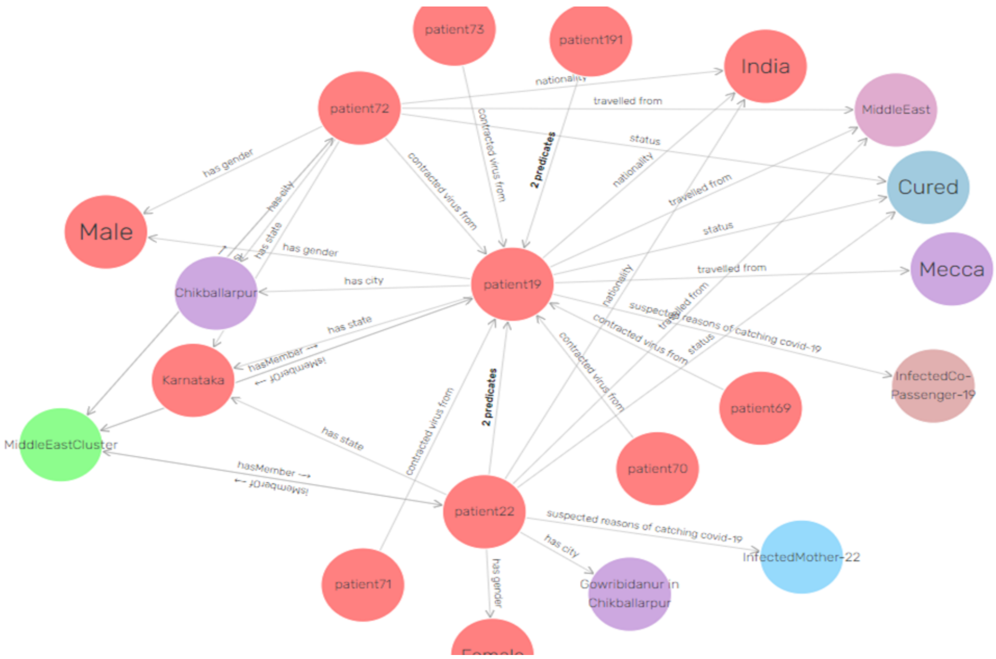


Figure 7: The part of CODO connected to a particular patient (Dutta, 2022)

itate its use by data and service providers, CODO was published using FAIR principles. The ontology has been used by several projects. For example, it has been used as a metadata enhancer to annotate COVID-19 literature, and for COVID-19 risk detection system which can help with COVID-19 contact tracing (Lin et al, 2021).

The value of the CODO ontology was demonstrated by using it to build knowledge graph using an agile approach in just a few months. The resulting knowledge graph had approximately 5M triples and allowed tracking cases with information about traveling companions. Taken as a whole the experience demonstrates some common principles that apply to the process of scaling up from an ontology model to a knowledge graph with real-world data and how resources get expanding and harmonizing to support other semantic resources like knowledge graphs (DeBellis and Dutta. 2021). Knowledge graphs, as discussed in "Ontology Summit 2020 Communiqué: Knowledge Graphs," are a novel paradigm for the representation, retrieval, and integration of data from highly heterogeneous sources. Within just a few years, knowledge graphs and their supporting technologies have become a core component of modern search engines, intelligent personal assistants, business intelligence, and so on (Baclawski et al, 2020b).

OGC Pilot. This Open Geospatial Consortium (OGC) Disaster Pilot 2021 (D21) uses a health spatial ontology for disaster response management. The goal of D21 is to develop standards-based services to support rapid decision making through the full lifecycle of disaster management for multiple hazards. D21 includes details for impacted entities, such as the affected individuals, vulnerable individuals (e.g., chronically ill and disabled persons), and the transportation infrastructure, both land and air. The objective is to ensure that the supply chains can adequately supply the pilot study area even when there is a disaster. For example, vaccines must be available to inhibit the spread of a disease, trauma treatment may be needed due to sudden floods. It is also necessary to prevent individuals from being victimized, losing personal effects, spreading other pathogens, etc. The pilot is a multi-layered thematic data approach and a conceptual model that is implemented using an ontology conforming to the FAIR principles (Churchyard, 2022; Lieberman, 2022).

D21 was applied during a flood disaster in the Peru - Rimac River Basin. The medical supply needs map uses a detailed workflow of the required and available supplies and includes a geospatial mapping of provider and supplier facilities and available inventory. D21 was also applied to a hospitals and medical supplies scenario in New Orleans, Louisiana. Future work and applications of the team at HSR.Health (Healthsolutionsresearch.org) are planned to include more studies of other disasters where response management depends on supply chains (OGC, 2021; 2022; Lieberman & Voidrot, 2021).

Smart Cities. The Smart Cities Working Group Report is based on foundational, citywide ontologies to address public health emergency service levels. The ontologies can be updated by one agency but can be read by multiple agencies. Entities have been defined and a dozen patterns have been developed that address concepts such as person, government and vaccination. Correlation matrices among patterns, and pattern-based disaster-related use cases have been developed. Other techniques that have been employed include micro theories and knowledge graphs (Fox, 2022).

Unfortunately, legacy systems can create disaster data silos across the departments/divisions/areas dealing with disasters. A first step to breaking down the silos is the creation of data standards, but sharing also requires harmonization without which a standard may become a hindrance because it is not trusted (Berg-Cross, 2021a, 2021b).

KnowWhere Graph. The KnowWhere Graph (KWG) is a spacial knowledge graph system that can quickly answer questions such as "What is here?", "What happened here before?", "Who knows more?", "How does it compare to other regions or previous events?". Situational awareness is enhanced by continually adding content and by using tools such as Environmental Systems Research Institute, Inc. (ESRI) GeoEnrichment. To overcome some shortcomings of knowledge graphs, they are combined with GeoEnrichment to form the KWG. Examples of applications include the Farm to Table Supply Chain and Sustainability Project. The KWG has reduced uncertainty for pandemic risk analyses. The KWG is currently a knowledge graph with over 10 billion edges. Examples of future challenges include spatiotemporally explicit knowledge graph embeddings that are invariant under syntactic changes (Janowicz, 2022).

A particular feature of the KWG effort is the process by which data becomes augmented using a range of auxiliary data and information adapted as needed to a geospatial study area. A simple example is mapping demographic data to the various ways that regions are represented. geoenrichment tools can significantly reduce the costs involved in acquiring, entering, and cleaning geo-data (Vockner and Mittlböck, 2014). However, until very recently, pre-knowledge graph approaches for geoenrichment were expensive, only used pre-defined categories of information to access data and were not effective in supporting the data integration or interoperability requirements of the FAIR principles (Janowicz et al., 2022). The KWG project supports a FAIR approach with data-driven decision-making and data analytics that address previous weaknesses of AI-based technologies, together with an open, cross-domain knowledge graph.

MINT. The Model Interventions (MINT) project is modeling complex human-nature systems for disaster preparedness and response. The natural disasters being studied are floods, food insecurity and drought. The goal is to use multiple interoperable models and AI to reduce the time required for making decisions for interventions from years to weeks. The impacts of many types of potential interventions can be modeled, such as reducing the fertilizer price or recharging the aquifers to ensure food security. Interventions are to indicate results, costs, risks, and baselines in this framework. Future work will incorporate uncertainties in models and sensitivity analyses of variables (Gil, 2022).

PLACARD and **weAdapt**. The PLAtform for Climate Adaptation and Risk reDuction (PLAC-

ARD) project seeks to support the coordination of climate change adaptation and disaster risk reduction communities (Barrott, Bharwani and Brandon, 2020). PLACARD is an EU Horizon 2020 (H2020) project that is working to change the basic organizational information and knowledge management (IKM) practices to accelerate action on climate change and to reduce impacts. The weAdapt project grew out of the PLACARD experience (Bojovic, Giupponi and Karali, 2017). Previous efforts to classify, categorize and structure climate-relevant knowledge as needed have not achieved FAIR data organization in the face of dynamic data acquisitions and have failed to leverage all information available or to reach intended audiences in a useful way. As a result, it has not been possible to easily and rapidly find, reuse and share relevant information (Barrott and Bharwani, 2022). When information can be found, it is often difficult or impossible to understand it, and thus it cannot be used (Zuccaro and Martucci, 2020). WeAdapt aims to provide FAIR data and understanding by developing some high level knowledge management structures such as standard topic areas and taxonomies but also practices and standards (Pulquério, 2017).

I-ADOPT. The InteroperAble Description of Observable Property Terminologies (I-ADOPT) is another project concerned with developing FAIR environmental information, but worked at a lower level than weAdapt, on vocabularies and might be seen as a complementary effort that could be leveraged by weAdapt. I-ADOPT is a community effort to develop a harmonizing framework to address the I in FAIR for discussing and representing climate topics. I-ADOPT started by gathering a series of use cases from the environmental science community. These were compiled and analyzed using a catalog of existing vocabularies and conceptual models. Using the results, the I-ADOPT community determined at a high level the minimal viable set of components and relationships needed to describe the variables and parameters of the various communities within and across environmental science domains. It was expected that annotation of current observable property standards using the FAIR vocabulary components of the I-ADOPT framework would aid in increasing interoperability across the wide variety of data standards within the environmental science domain (Magagna et al, 2022; Magagna and Schindler, 2022).

In particular, I-ADOPT represents the high level concepts of WHAT has been observed independently of WHERE, HOW and WHEN the data acquisition took place. Environmental examples include identifying wind speed (vs. speed of wind), soil color (vs. color of soils), concentration of atomic nitrogen in Earth's atmosphere (vs. nitrogen concentration). Of conceptual importance, the I-ADOPT Ontology builds on the high level framework by using a design pattern that adds the concept of matrix and its relations to entities, properties and constraints. The overall benefits of the I-ADOPT vocabulary include:

1. Supporting interoperability between existing terminologies
2. Enabling semantically precise and FAIR descriptions of variables
3. Decomposing descriptions into atomic components and linking those to existing vocabularies making these descriptions of observed variables machine-actionable
4. Providing abstract reusable semantic descriptions for concrete observations
5. Enabling mappings between variable descriptions across terminologies
6. Requiring no change to existing structures
7. Adding rich (human-readable and machine-actionable) descriptions with qualified references
8. Boosting Findability and Reusability of data

Satellite Teams. One of the most important services of near-Earth artificial satellites is for environmental sensing. There are well over 100 active government-sponsored Earth observation satellites, as well as around 40 active commercial Earth observation satellites. Within this large collection, there are constellations of satellites that cooperate to improve their observations by fusing their data. A prominent example is the A-train, currently consisting of three satellites: OCO-2, GCOM-W1 and Aura. The collective observations of A-train satellites are being used to build high-definition three-dimensional images of Earth's atmosphere and surface. Achieving such cooperation requires data harmonization so that the observations of the satellites can be fused to form common observations. Common data formats and available metadata are important for this process (Sharma, 2022b).

OSEDO. The Orbital Space Environment Domain Reference Ontology (OSEDO) suite is a set of ontologies and other semantic resources to support astronomical and astronautical data, research, science, activity and interdisciplinary activities (O'Neil and Rovetto, 2021; Rovetto, n.d.; Rovetto, 2016). The suite includes the Orbital Debris Ontology (Rovetto, 2015), Space Situational Awareness ontology (Rovetto and Kelso, 2016), Astronomical Environment ontologies, and the Astrometeorology/Space Weather Ontology, among others. Example applications in the suite include interactive 3D orbital systems. These ontologies serve as conceptual models, sources for terminology, and formal representations of the target topic areas. They aim to provide metadata to annotate data and documents associated with relevant topics, as well as definitions and formal semantics. Some of the activities supported by OSEDO include conceptual analysis, concept clarification, developing and offering vocabularies, modeling for various stakeholders, exploring terminology synchronization and semantic harmonization for the respective disciplines and stakeholders, and multidisciplinary collaboration and innovation (NASA, 2019). Future services will include ontology-assisted space debris and collision avoidance management. Within the discipline itself, removing harmful space debris is an active area of research that will make the orbital space environment safer for the global community (Rovetto, 2022).

7. Summary and Conclusion

The main findings in this article are:

1. Due to framing, terminology and metaphors can have unanticipated, negative effects on disaster response. It is important for disaster relief agencies to be careful to choose the terminology and metaphors and to control the narrative in outlets such as social media as well as to ensure the proper use of relevant information (Stickles, 2019).

2. The root causes from whence a disaster arises are often misunderstood or misrepresented. The root causes of the COVID-19 pandemic were information and behavioral failures, not the disease, which was the immediate, proximate cause.

3. Explanations can be a useful tool for disaster management, but they must be in the form of an interactive dialog rather than simple flat answers (Baclawski et al., 2020a).

4. There are many interpretations of risk, with the main split being between risk as a probability and risk as a variance. Clarifying the intended interpretation would help prevent misunderstanding. Ideally, it would be best to use full probability distributions, or at least both the probability and the variance.

5. Work is still needed to make semantic resources and knowledge organization systems compliant with FAIR and TRUST principles.

6. We have observed that there are cross-disaster linkages among kinds of disasters; for example, environmental disasters impacted pandemic patients, its spread and supply chain routes required to care for the patients. The landscape dimension framework developed in Section 2 was intended to help identify cross-disaster linkages and to find opportunities for reusing ontologies and other information resources, but more work needs to be done to realize this potential.

With regard to health disasters, work still needs to be done to incorporate heterogeneous data concepts; for example, “long COVID” for the COVID-19 pandemic and “close contact” for different diseases and variants. Moreover, incorporating heterogeneous data concepts should be done in a way that provides deeper harmonization between not only the data, but also the metadata as found in glossaries, e.g., (Penn, 2022) and other semantic technologies. As in many knowledge engineering efforts, access to the best suite of domain experts is a limiting factor, especially during emergencies.

While there is much we now know about developing knowledge graphs for environmental disasters, there is much more to learn as we blend the role of classical knowledge representations with the machine learning (ML) approach of knowledge embeddings. A hybrid approach seems like an important part of future work as more reasoning is enabled as part of a knowledge graph. Key research questions include how to incorporate spatiotemporal and commonsense reasoning, how to learn and support geographic knowledge graph summaries that are meaningful to users, how to quantify and represent regional differences, and how to detect and mitigate bias in geographic knowledge graphs.

Acknowledgments

Certain commercial software systems are identified in this paper. Such identification does not imply recommendation or endorsement by the National Institute of Standards and Technology (NIST) or by the organizations of the authors or the endorsers of this article; nor does it imply that the products identified are necessarily the best available for the purpose. Further, any opinions, findings, conclusions or recommendations expressed in this material are those of the authors and do not necessarily reflect the views of NIST or any other supporting U.S. or European governments or corporate organizations.

We wish to acknowledge the support of the ontology community, especially the invited speakers and participants who contributed to the Ontology Summit 2022, which was the primary basis for this article. There were many invited speakers, some of whom gave presentations at more than one session. The complete list of sessions, speakers, and links to presentation slides and video recordings is available at (Ontology Summit, 2022).

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