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Toward the Use of an Upper Ontology for U.S. Government and U.S. Military Domains: An Evaluation

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Abstract

Momentum is gaining to develop a Semantic Web to allow people and machines to share the meaning (semantics) of data and ultimately of applications. Key to the vision of a Semantic Web is the ability to capture data and application semantics in ontologies and map these ontologies together via related concepts. One approach for mapping disparate ontologies is to use a standard upper ontology. In determining how Semantic Web technologies might be applied to United States (U.S.) Government domains, we consider whether the use of standard upper ontologies makes sense in these environments. This paper attempts to examine current candidate standard upper ontologies and assess their applicability for a U.S. Government or U.S. Military domain. We evaluate the state of the art and applicability of upper ontologies through the lens of potential application in these domains. The evaluation includes consideration of the ontology purpose, ontological content decisions, licensing restrictions, structural differences, and maturity. We conclude with some recommendations and predictions.

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1 Introduction

Commercial and government organizations are moving toward the use of Web technologies, leading to unprecedented levels of data exchange. However, exchanging data does not mean that the data is understood. There still exists a strong need to help people and machines to understand the meaning, or semantics, of the data and ultimately applications. Momentum is gaining to develop a Semantic Web to allow people and machines to share these data and application semantics. Key to the vision of a Semantic Web is the ability to capture data semantics in ontologies and link these ontologies to interconnect related concepts. One approach touted for linking ontologies is to use a standard upper ontology. There are several efforts to develop standard upper ontologies to facilitate mutual understanding. There are however differing opinions on the viability of an upper ontology standard. For example, Colomb [12] states that it "is extremely doubtful that these universal ontologies can be used as the basis for ontologies supporting interoperating information systems because information systems are largely concerned with institutional facts, which are enormously variable. Institutional facts depend heavily on context and background". Proponents of the approach believe that such context and background can be encoded within a neutral upper ontology, and differences of language and knowledge separated from issues of ontology. A more extensive discussion of this debate can be found at [75]

As we examine how Semantic Web technologies could be applied to United States (U.S.) Government domains, we question whether the use of standard upper ontologies makes sense in these environments. The objective of this effort is to examine current candidate standard upper ontologies and assess their applicability in a U.S. Government or U.S. Military domain. Other examinations and comparisons of upper ontologies exist [6][20]. We evaluate the state of the art and potential applicability of upper ontologies from the point of view of using an upper ontology in a U.S. Government application. Our evaluation includes consideration of the purpose for which the ontology was built, ontology licensing restrictions, structural differences and maturity. We also discuss the impact of ontological choices, although this is not part of our evaluation.

2 Background

2.1 What is an Upper Ontology?

Ontologies may exist at many levels of abstraction. We group ontologies into three broad categories of upper, mid-level and domain ontologies. In this section we define what we mean by an upper ontology and characterize the differences between these three levels. Figure 1 is a graphical depiction of these notional levels along with some sample concepts that may be found at each level.

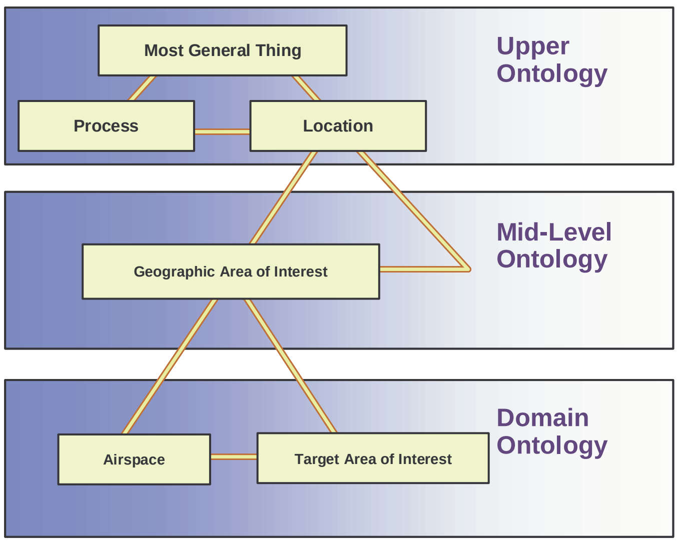

Figure 1. Ontology Categories

2.1.1 Upper Ontology Definition

An upper ontology, as defined by [53], is a high-level, domain-independent ontology, providing a framework by which disparate systems may utilize a common knowledge base and from which more domain-specific ontologies may be derived. The concepts expressed in such an ontology are intended to be basic and universal concepts to ensure generality and expressivity for a wide area of domains. An upper ontology is often characterized as representing common sense concepts, i.e. those that are basic for human understanding of the world [50]. Thus, an upper ontology is limited to concepts that are meta, generic, abstract and philosophical [65]. Standard upper ontologies are also sometimes referred to as foundational ontologies [52] or universal ontologies [12].

2.1.2 Upper Ontology versus Mid-level Ontology

A mid-level ontology serves as a bridge between abstract concepts defined in the upper ontology and low-level domain specific concepts specified in a domain ontology. While ontologies may be mapped to one another at any level, the mid-level and upper ontologies are intended to provide a mechanism to make this mapping of concepts across domains easier. Mid-level ontologies may provide more concrete representations of abstract concepts found in the upper ontology. This ontology category also encompasses the set of ontologies that represent commonly used concepts, such as Time and Location. These commonly used ontologies are sometimes referred to as utility ontologies.

2.1.3 Upper Ontology versus Domain Ontology

A domain ontology specifies concepts particular to a domain of interest and represents those concepts and their relationships from a domain specific perspective. While the same concept may exist in multiple domains, the representations may widely vary due to the differing domain contexts and assumptions. Domain ontologies may be composed by importing mid-level ontologies. They may also extend concepts defined in mid-level or upper ontologies. Reusing well established ontologies in the development of a domain ontology allows one to take advantage of the semantic richness of the relevant concepts and logic already built into the reused ontology. The intended use of upper ontologies is for key concepts expressed in a domain ontology to be derived from, or mapped to, concepts in an upper-level ontology. Mid-level ontologies may be used in the mapping as well. In this way ontologies may provide a web of meaning with semantic decomposition of concepts. Using common mid-level and upper ontologies is intended to ease the process of integrating or mapping domain ontologies.

2.2 Why Do We Care About Upper Ontology?

2.2.1 How Upper Ontologies May Help

Today's World Wide Web (WWW) is geared toward presenting information to humans. The Semantic Web is an evolution of the WWW that is intended to capture the meaning of data (i.e., data semantics) precisely enough that a software application can interpret them. A key element of the Semantic Web is the use of ontologies to define concepts and their relationships. With ontologies supplying the context of data, information retrieval and search engines can exploit this contextual information to perform semantic searches based on the meaning of the concept, rather than syntactic searches of a given text string. In this way, one could discriminate between horses and cars which both have the same label of "mustang." Rich semantics captured in ontologies also provide the ability to combine simple facts together to infer new facts, and to deduce new generic knowledge in the form of proven theorems that is only implicit in the ontologies. With data and applications mapped to ontologies, inference engines could be used to improve the discovery and understanding of data as well as the discovery and composition of applications like Web services. Furthermore, ontologies may be used to represent the semantics of applications and services directly, much as UML object and conceptual models do today for specific systems and enterprises, though these do so incompletely, inconsistently, and unsoundly, without explicit use by the applications of these models at either system-generation time or run-time. Upper ontologies are intended to define foundational concepts used in both mid-level and domain ontologies. In theory, the mapping between domain ontologies becomes easier if the ontologies to be mapped are derived from a standard upper ontology.

Two approaches exist for the use of upper ontologies: top-down and bottom-up. In a top-down approach one uses the upper ontology as the foundation for deriving concepts in the domain ontology. In this way, the domain ontology designer takes advantage of the knowledge and experience already built into the upper ontology. Furthermore, use of the upper ontology provides a theoretical framework on which to build. In a bottom-up approach, the ontology designer maps a new or existing domain ontology to the upper ontology. This approach also capitalizes on the knowledge built into the upper ontology but one would expect the mapping to be more challenging, as inconsistencies may exist between the domain and upper ontology. Some upper ontologies utilize a combination of these two approaches.

2.2.2 A Software Engineer Analogy

Let's use a software engineering analogy to describe the value of using standard upper and mid-level ontologies. Mid-level ontologies can be seen as analogous to software libraries. Early high level programming languages evolved to contain software libraries of commonly used functions. High quality software libraries allowed programmers to reuse the knowledge and experience built into the software library and freed them to concentrate on domain specific issues. As software libraries evolved, programming tasks became easier. Programmers do not need to understand the detailed implementation of libraries in order to use them. Similarly, mid-level ontologies can evolve to act as ontological utilities. With the existence of such ontologies, ontology designers can compose their domain ontologies using these utility ontologies and inherit the concepts and inferencing capabilities provided by them. Just as software libraries make programming tasks easier, so too would the availability of high quality, commonly used utility ontologies make ontology development easier. Further, concepts in the utility ontology could be mapped to concepts in an upper ontology without the need for users of the utility ontology to be aware of these mappings.

Because it is early in the Semantic Web evolution (OWL became a World Wide Web Consortium recommendation in Feb'04) few utility ontologies exist. However, they are emerging, as evidenced by the DARPA funded effort to create a standard time ontology [14].

3 Major Representation and Ontological Choices

Two important dimensions that must be considered when evaluating an upper ontology are: 1) the expressivity of the knowledge representation language in which the upper ontology is encoded, and 2) the ontological choices, assumptions, and commitments that a given upper ontology makes. Although the latter is clearly the more important dimension (since it directly affects domain ontology semantic possibilities), the knowledge representation language the ontology is represented in may indeed limit the full expression of the ontology syntactically.

3.1 Knowledge Representation Language

A given ontology is syntactically expressed in a particular logical or knowledge representation language. Although the choice of knowledge representation language is secondary to the actual ontological content, it is still important because it determines whether in fact the upper ontology can be utilized completely or just partially.

Typically, upper ontologies require expressiveness at the level of First Order Logic (FOL), but occasionally require more, i.e., second-order or higher. Second-order is required if the upper ontology quantifies over predicates (or relations or properties), though limited finite quantification over predicates (in the form of a list of predicates) can be supported in a first-order language, as KIF/Common Logic demonstrates [13]. Furthermore, an upper ontology may require a modal extension of FOL, depending on how modalities such as necessity/possibility and potential modalities such as temporal/spatial operators are expressed in the ontology. In general, modalities (necessity, belief, obligation, time, etc.) can be expressed either in the (meta level) logic/KR language or in the (object level) ontology, but in either case, ways to assert and refer to modal assertions will differ. These differences may be important to the expressions a domain ontology wants to make. Table 1 [14] displays the levels of representation necessary for an ontology. The top level is the logic/KR language level. This level determines what can be expressed at the ontology concept level, the second level. The ontology concept level is the level that characterizes the generic descriptions of the ontology, i.e., the ontology proper, which might be either the organizing structure for the ontology instance level, the intensional level which describes the properties that will hold specific individuals (the extension) at the ontology instance level, or itself a quantificational domain (if the logic/KR language is second-order) and hence instantiating higher-level descriptions – depending on one's particular perspective within the ontology community and toward the formalization.

Table 1. Ontology Levels

Level	Example Constructs
Knowledge Representation (KR) Language (Ontology Language): Meta Level to the Ontology Concept Level	Class, Relation, Instance, Function, Attribute, Property
Ontology Concept (OC) Level: Object Level to the KR Language, Meta Level to the Instance Level	Person, Location, Event, Medicine, Tractor, Tank, Food, F-16, EPA-SuperFund-Site-AmeliorationProcedure, etc.
Ontology Instance (OI) Level: Object Level to the Ontology Concept Level	Pfc. Andrew Q. Public, Harriet Beecher Stowe, Person243904, Location190, F-16C/D-Block-50/52-General Electric-F110-GE-100/129-SerNum28924195402, 68th-Street-Dump/Industrial-Enterprises-RosedaleMarylandEPA-ID-MDD980918387-AmeliorationProcedure503, etc.

If the logic/KR language in which a given upper ontology is encoded is less expressive than the logic/language in which the upper ontology is expressed, semantic information loss will result. The resulting encoding of the upper ontology will contain only a subset of the original expression of the ontology. For example, if the original upper ontology is expressed in KIF/Common Logic [13] and then encoded in OWL [61], only a portion will be retained in OWL, which, being a description logic-based ontology language, tries to maximize machine tractable reasoning by minimally, but definitely, limiting expressivity. OWL Full, the most expressive "dialect" of OWL, may in fact be nearly equivalent in expressivity to FOL, but remains ultimately less expressive.

Finally, it should be noted that KR languages that are either not sufficiently formalized so that there is a clear notion of the formal semantics of the language, or are sufficiently formalized, but offer only indirect expression of upper ontology axioms, then portions of the upper ontology cannot be used by interpreting software. Portions of the upper ontology can only be annotated and interpreted solely by human beings.

3.2 Ontological Choices

Among the criteria it is useful to consider when evaluating upper ontologies are the ontological choices a given ontology makes. The WonderWeb Ontology Library Final Report [40] (see also [6]), for example, describes a number of such ontological choices: descriptive vs. revisionary, multiplicative vs. reductionist, universals vs. particulars vs. sets, endurants vs. perdurants, and more. Other choices include 3-dimensional (3D) vs. 4-

dimensional (4D) [29], distinct notions of “part” and “whole”, different notions about what constitutes a property (and attribute), how change should be represented, distinctions about granularity, vagueness, etc. Many of these choices are intricately linked, so, for example, discussions on endurants and perdurants invoke 3D and 4D views, and crucially elucidate the notion of persistence through time and change. In addition, multiplicative ontologies, because they tolerate a greater range of modeling complexity (model whatever is called for by reality), generally enable multiple objects with different identity criteria to co-occur/co-locate in the same spacetime [40]. In the following, we discuss some of these choices.

3.2.1 Descriptive vs. Revisionary

Descriptive and *revisionary* ontologies [67], [49] are based on ontological stances or attitudes towards the effort of modeling ontologies, i.e., how one conceptualizes the world and what an ontological engineering product is or should be. A *descriptive* ontology tries to capture the more commonsensical and social notions based on natural language usage and human cognition, emphasizing the agent who conceives and deemphasizing scientific and philosophical considerations. A *revisionary* (sometimes called *prescriptive*) ontology, on the other hand, does emphasize (or even, strictly adheres to) the scientific and philosophical perspectives, choosing to base its constructs and modeling decisions on scientific theories and a philosophical stance that tries to capture the world as it really is (it *prescribes* the world), and not necessarily as a given historical agent conceives it to be. A revisionary ontology therefore says that its modeling constructs are about real things in the world as it is.

In practical terms, all of the constructs in a *revisionary* ontology will be space-time objects, i.e., necessarily having temporal properties; in a *descriptive* ontology, that will not be the case. In the latter, *entities* (sometimes called *endurants,* but perhaps better called *continuants*) such as “hammer” and “tank” that have only incidental temporal properties and *events* (processes, actions, activities, etc., sometimes called *perdurants*, but perhaps better called *occurrents*) such as “attacking” and “cashing a check” that have explicit temporal properties, are modeled with or without those temporal properties, respectively. Often in natural language there are two correlated forms/usages that express the distinction: the nominal and the verbal. A nominal (noun) “attack” is expressed as in “The attack on the enemy began at 600 hours.” A verbal (verb) “attacked” is expressed as in “We attacked the enemy at 600 hours.”

3.2.2 Multiplicative vs. Reductionist

A multiplicative upper ontology is expressively profligate in that concepts can include anything that reality seems to require, and so any distinction that seems useful to make can be made in the ontology. Contrarily, a reductionist ontology reduces the number of concepts to the fewest primitives sufficient to derive the rest of complex reality.

In the WonderWeb Foundational Library, the Descriptive Ontology for Linguistic and Cognitive Engineering (DOLCE) and the Basic Formal Ontology (BFO) are multiplicative and descriptive, whereas the Object-Centered High-Level Reference Ontology (OCHRE) is reductionist and revisionist. SUMO could be said to be both multiplicative in that it aims to cover at a general level any concept that reality requires, and reductionist in that it attempts to be minimal rather than profligate.

We note that many of these dichotomous ontology choices (*descriptive* vs. *revisionary*, *multiplicative* vs. *reductionist*, etc.) really have behind them a set of assumptions about how to view the world (e.g., strict realism with no notion of a different possibility) and what an engineering model of the world or parts of the world can achieve. Therefore, many of the ontology choices will tend to co-occur: e.g., *revisionist* and *reductionist* will generally go together.

3.2.3 Universals, Particulars, Sets, Possible Worlds

The distinction between *universals* (forms, ideas) and *particulars* (individuals) brings up a range of philosophical argument that we cannot address here. For our purposes, universals (whether based on realism, conceptualism, or nominalism) are general entities. Universals are often characterized as natural classes that abstract or generalize over similar particular things. Person, Location, Process, etc., are examples of universals, and would be represented at the Concept level in Table 1.

If you take a *realist* stance, universals are "entities of a general kind that exist independently of us and of our ways of thinking and speaking about the world" [28]. A *conceptualist* views universals as existing in human minds and primarily functioning as concepts that generalize and classify things. *Nominalists* view universals as largely a notion of our human language, the mode of expression of our thoughts. In an extreme view of realism, Platonism, universals independently exist (it's usually considered unproblematic that particulars exist in reality), and so in our discussion of upper ontologies here, universals would exist in a quantificational domain distinct from that of particulars. This could be the case, for example, if universals were represented at the Ontology Concept level, but the Knowledge Language level of Table 1 permitted second-order quantification, i.e., quantification over concepts (properties, predicates, classes, relations, etc.), rather than just over particulars (individuals, instances) at the Ontology Instance level.

A further distinction can be made: some instances (particulars or individuals) can themselves be considered universals [16]. The Semantic Web ontology language OWL in fact allows for this [61].

Particulars, or individuals or instances, are specific entities and taken to be instantiations of universals. Particulars exemplify properties (which are usually understood as universals), meaning they possess specific values such as Sam Jones being the father of Bill Jones, this apple in my hand being red, and that ball being on that table at 11 am EST, on April 19, 2004, in my house in Fairfax, Virginia, USA. Particulars are represented at the Instance level in Table 1. Instances of classes (concepts), *facts* (specific instantiated relations/properties, e.g., Sam's fatherhood-ness to Bill, my apple's redness), and *events* (a fact that occurs at a specific time, a specific perdurant) [54] are typically taken to be particulars.

Sets are mathematical objects that are sometimes, but not always used to abstractly characterize the different ontological categories, i.e., the logical apparatus used to define and order the logico-mathematical notions of ontology. Model-theoretical semanticists use set theory, but formal ontologists object; see, e.g., [62], where *mereotopology* (discussed below) is argued to provide a better foundation for ontology. Nonetheless, a set does not typically constitute a separate ontological category in its own right – except insofar as it is used as a human artifact. So, for example, SUMO [68] defines a *set* as an ontological entity in its upper ontology because it does represent an entity that it used by other components of the SUMO upper ontology and potentially other lower, domain ontologies which use SUMO and make reference to sets directly, as ontological objects. A set in the first sense, i.e., as a defining mathematical notion, would typically be expressed at the meta-level, i.e., the Language level in Table 1, and thus is not itself an object for ontological modeling.

It is perhaps a bit confusing or disconcerting to find that the object *set* really exists at two levels, i.e., at the modeling content level (Concept level in Table 1) and also at its meta-level (Language Level). The confusion devolves at least partially on the distinction between *use/mention* [69], [70], i.e., natural language typically allows one to both use a word and to mention it. So in this sense, 'set' is both an ontological object at the Ontology-Concept modeling level, and the meta-level object at the Language level which helps to define the entire Ontology-Concept level below it.

An additional consideration – which we will not discuss in any detail here – is the notion of *possible worlds*, which is a way of formally characterizing the distinction between *descriptions* (intensions) and *individuals which possess the properties described by the descriptions* (extensions). In a sense, the Cyc context and *microtheory*-based systematic manner of segregating assertions into theories, two of which taken together and compared may contradict each other, can be considered an implementation of the notion of possible worlds. *Possible worlds semantics* is usually a notion that also involves modal logic.

3.2.4 Endurants and Perdurants

The distinction between *endurants* and *perdurants* is sometimes conflated with two different distinctions: 1) the distinction between *3D* and *4D* ontological objects, and 2) the distinction between *continuant* and *occurrent*, respectively. However, these conflations are problematic [29], [58], [16]. According to the usual definitions [4], an *endurant* is an entity which exists in full in every instant at which it exists at all; a *perdurant* "unfolds itself over time in successive temporal parts or phases." Both endurants and perdurants are taken to be *concrete particulars*, i.e., instances.[40] Obviously, the notion of identity- and essence-defining properties intersect with changeability. A perdurant is typically taken to be a *spacetime worm*, i.e., an object that persists (perdures) through spacetime by way of having different temporal parts at what would be different times (temporal non-locality), but a view of *instantaneous stages* is possible too [58]. An endurant goes through time (endures), with identity/essence-defining properties that perhaps depend on occurrent objects but are not essentially constituted by those occurrent objects. The crucial distinction between these constructs is that of the nature of the identifying essential properties of the object and its change or non-change, usually defined with respect to time. Related to the distinction is the notion of *temporal parts*, i.e, whether or not a given object has temporal parts and the nature of those parts. But it is not just that distinction that defines 3D and 4D views, since some 3D perspectives permit instantaneous objects to be the temporal parts of themselves [58]. For our purposes here, however, we will equate endurantism with the 3D view, and perdurantism with the 4D view.

A *partonomic* hierarchy, for example, is usually defined in terms of a special *partonomic* relation, the part-of relation. *Mereology* is the analysis of the part-of relation and the set of axioms that seem to constitute our notion of what a part is. In modern ontological axiomizations, mereology is combined with *topology* (connectedness among objects) to be *mereotopology* [59], [9] since *parthood* really does seem to require either point "touching", overlap, or transitivity of those (i.e., the 'southern edge of London' is part of London or connected to those regions which are part of southern London). Here we begin to get into notions of granularity and vagueness, and so we'll end our discussion.

3.3 Ontological Choices: Conclusion

This discussion has tried to highlight issues that are important for differentiating prospective upper ontologies. Many of the upper ontologies that exist today, and nearly all of those that we discuss in our evaluation, address these issues – because they must. They must because, even with relatively superficial analyses of the distinctions that are important for modeling domains, these upper ontologies in general are sophisticated in their view of what constitutes modeling the world and the way it behaves, and what that really means.

Table 2. Ontological Choices Summary

	Choice	Details
1	Descriptive	**Viewpoint:** Distinguishes between things (spatial objects) and events (temporal objects) **Example:** Distinguishes car from car repair. Car is a class of object abstracted away from time. Car repair or car repairing is a class of object necessarily having a temporal property, e.g., having a start and end time (even if those times are not known or are vague). **Implications on Upper Ontology:** Ontology constructs can be added if there are natural language or cognitive (human or social) reasons for adding them. Each should correspond to something that seems to be required based on what is known

	Choice	Details
		or believed about natural language, human cognition, and social/cultural phenomena. **Implications on Domain Ontology:** Objects (entities, relations, instances, etc.) in the domain may stand in for (be *about*) anything that humans conceive to be important or useful in the world. They do not have to be things that exist intrinsically in the world, i.e., devoid of human or social conceptualizing.
1	Revisionary	**Viewpoint:** Everything extends in space and time **Example:** Both car and car repair are spatial-temporal objects (thing-events). **Implications on Upper Ontology:** Ontology constructs cannot be added arbitrarily. Each must correspond to something that really exists in the world, divorced from any given human conceptualization of the world. **Implications on Domain Ontology:** Objects in the domain have to be things that exist intrinsically in the world, i.e., devoid of human or social conceptualizing.
2	Multiplicative	**Viewpoint:** Ontology concepts can include anything that reality seems to require, so a profligate or very expressive stance **Example:** A vase and the clay it is composed of are separate objects, co-located in some space and co-occurring in some time. Before the vase is created and after it is broken, there is only clay: the vase does not exist. A person and his/her body are distinct objects. A person ceases to be a person at death or when some essential part is replaced, though the body may remain. For example, should a person receive a brain transplant, the person is essentially changed; this is not true if the person receives a heart transplant. Personality and character are essential to a person and are mostly located in that person's brain **Implications on Upper Ontology:** A *constitution* relation is specified, that says that one object (a vase) is constituted of another or other objects (clay). This is not the *part-of* relation, since neither the vase nor the clay is part of the other; each exists simultaneously. **Implications on Domain Ontology:** Once the vase is broken, you can say that the vase does not exist anymore [60]. A soldier instance ceases to be a soldier when he/she is killed.
2	Reductionist	**Viewpoint:** Ontology concepts are reduced to a minimum, to include only the fewest number of primitives sufficient to derive the rest of complex reality. Each space-time location contains at most one object **Example:** A vase and the clay it is composed of are one and the same object. There are just multiple views of that same object. Before the vase is created and after it is broken, there is just the same vase-clay object: only the view of that same object changes. **Implications on Upper Ontology:** No *constitution* relation is specified. There can only be a vase-clay object, and two views will have to be created that describe the

	Choice	Details
		two different ways of viewing the object **Implications on Domain Ontology:** Once the vase-clay is broken, you can say that the clay doesn't have a vase shape anymore [60]. A soldier person-body instance does not cease to be a soldier person-body when the body is killed.
3	Universals	**Viewpoint:** Entities that can be instantiated. Are properties defined at the universal or generic level, with the same property being instantiated by distinct instances that use this property? Or are properties specifically tied to and defined by instances themselves? Sometimes universals are considered real; sometimes they are considered categorizing objects only. **Example:** The color 'red'. If it is a universal property, then different apples will have the exact same color, i.e., 'red'. If there is no universal property 'red', then two particular apples have distinct particular colors, no matter how similar those colors are. **Implications on Upper Ontology:** If universals exist in a particular upper ontology, they probably exist as a means to classify the instances (particulars), and are not themselves classified according to meta-properties. Generally, nearly every upper ontology, as does nearly every ontology per se, has universals in the form of classes that can be instantiated. Some ontology languages, such as OWL, allow classes to be instances too, in which case an upper ontology that used that construct would be distinct from an upper ontology that allowed only universals to have instantiations. For the purposes of this paper, we will assume that all upper ontologies have both universals and particulars. **Implications on Domain Ontology:** If an upper ontology includes classes as instances, then a domain ontology could model a universal as both a class and an instance, Example: An elephant is a class of mammal. But an elephant could also be an instance of species.
3	Particulars	**Viewpoint:** Entities that cannot be instantiated. **Example:** The USS Enterprise. **Implications on Upper Ontology: See the above discussion on universals.** **Implications on Domain Ontology: See the above discussion on universals.**
4	Endurants (3D)	**Viewpoint:** Entities that are wholly and completely present at each of several different times in their existence. **Example:** A book **Implications on Upper Ontology:** First, we note that both endurants and perdurants persist through time. It is just the nature of that persistence that is different in the two views. If an upper ontology allows only endurants, it is difficult to see how change in the properties of entities, especially change in the parts of an object, can be modeled –

	Choice	Details
		at least directly. A book ages, the paper becomes yellowed, pages become dog-eared, the typescript blurred. Yet the book at time 1 and the book at time 2 are taken to be the identically same book, if they are endurants. Yet, if they are identically the same, how can they have different properties? Book 1 and Book 2 have to be associated with distinct time intervals, and it is those entity-time interval relations that have to be talked about. **Implications on Domain Ontology:** A domain ontology that has only endurants has to consider how the change in an object is to be modeled. A given soldier with both arms and that same soldier without his right arm would be the same soldier. The spatial parts of that soldier will have to be modeled with respect to some temporal interval. So a given property that can change (having both arms) will be relative to a time interval.
4	Perdurants (4D)	**Viewpoint:** Entities that happen in time, they extend in time by accumulating different temporal parts, so at any given time, only their temporal parts are present. **Example:** A book. Reading a book **Implications on Upper Ontology:** "Reading a book", i.e., events or processes (occurrents) obviously require persistence through time, and have temporal parts, i.e., part of "reading a book" is first, "opening the book cover", then "reading the first page", then each page until the last page is completed, then "closing the book cover". However, in a perdurant view, even objects such as "a book" (a continuant) is a perdurant, because that book has distinct temporal parts at different times, i.e., at time 1, the book is new; at time 2, the book is old, having yellowed and dog-eared pages, and blurred text. For a perdurant, all properties are asserted timelessly. Change is modeled by the assertion of a property to one specific temporal part of an object. **Implications on Domain Ontology:** The perdurant view of occurrents is unproblematic, because we understand that events and processes have temporal parts. However, the perdurant view of continuants (entities) causes some confusion. The soldier of yesterday (with both arms) and the soldier of today (with one arm) are the same entity, but they are just different temporal parts of that soldier. So an instance is really seen to be an aggregate of its temporal parts.

4 Upper Ontology Initiatives

There are a number of ongoing initiatives to define a standard upper ontology. Two initiatives focused on in this paper are the IEEE Standard Upper Ontology Working Group (SUO WG) [65] and WonderWeb [76]. IEEE SUO WG is a standards effort operated under the IEEE Standards Association and sponsored by the IEEE Computer Society Standards Activities Board. Its goal is to specify an upper ontology that will enable computers to use it for applications such as data interoperability, information search and retrieval, automated inferencing, and natural language processing. IEEE SUO WG is considering three candidate upper ontologies, namely Suggested Upper Merged Ontology (SUMO), Upper Cyc Ontology (UCO) and Information Flow Framework (IFF).

WonderWeb is a project consortium of universities and Industry, working in cooperation with the DARPA DAML program and W3C. WonderWeb aims to define a library of foundational ontologies that cover a wide range of application domains. This library is intended to be used as a basis for the development of more detailed domain ontologies. Currently three modules, DOLCE, OCHRE, and BFO exist. In this paper, our focus is on DOLCE.

This section provides further details on these upper ontologies and mentions other upper ontologies.

4.1 SUMO

SUMO was initially developed by Ian Niles and Adam Pease at Teknowledge Corporation and is currently maintained by Adam Pease at Articulate Software. It is one of three starter documents under consideration by the IEEE SUO WG. SUMO was developed to facilitate data interoperability, information search and retrieval, automated inference, and natural language processing [45]. SUMO contains both cognitively specific categories as well as elements of realism [20]. The origin of SUMO was the merging of different existing upper ontologies,but the sources were starting points and the current version bears limited resemblance to any of the individual initial contributions. Ontologies that were merged included: John Sowa's upper level ontology, Russell and Norvig's upper level ontology, James Allen's temporal axioms, Casati and Varzi's formal theory of holes, Barry Smith's ontology of boundaries, Nicola Guarino's formal mereotopology and various formal representations of plans and processes including Core Plan Representation (CPR) and Process Specification Language (PSL) [46]. SUMO is written in Standard Upper Ontology Knowledge Interchange Format (SUO-KIF), which is a variation and simplification of the KIF format. SUMO is distributed under a free license from the IEEE. The SUMO-based domain ontologies are distributed as open source under GNU GPL.

At present, SUMO consists of 1,000 concepts, including 4,000 assertions over 800 rules [45]. The structure of SUMO is illustrated in Figure 2. SUMO is modular and is divided into 11 separable modules with an indicated dependency structure. The mid- and domain-level ontologies are also separate modules. The topmost concept in SUMO is "Entity". This is further split into physical and abstract entities. Physical entities are further divided into objects and processes [20]. Other general topics include: structural concepts (instance, subclass), general types of objects and processes, abstractions including set theory, attributes, and relations, numbers and measures, temporal concepts such as duration and parts and wholes [45].

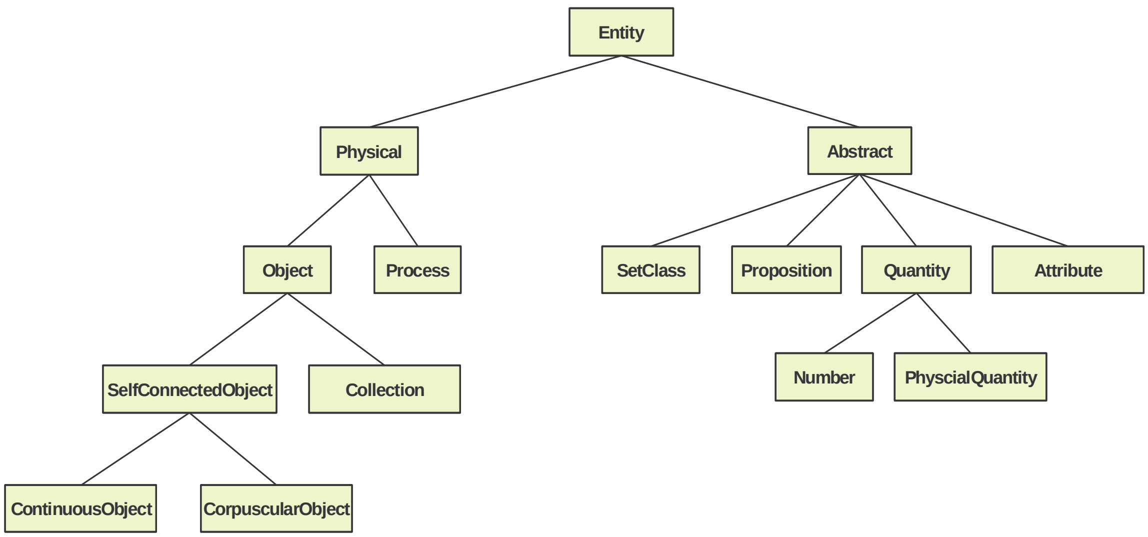

Figure 2. A subset of top level categories in SUMO [47]

In SUMO, concrete entities are represented by Physicals, while abstract entities are represented as Abstracts. Given its development philosophy, SUMO is clearly multiplicative in nature. SUMO does not classify universals, and thus takes a particulars view.

In addition to the SUMO core upper ontology, SUMO is also associated to lower level ontologies, including a Mid-level Ontology (MILO) and a set of domain ontologies, available at [81]. Domain ontologies relevant to this study include ontologies for the military, government, terrorism, and weapons of mass destruction. Together, these ontologies now total some 20,000 terms and 60,000 axioms. SUMO and MILO have also been linked by hand to all 100,000 synsets in WordNet 1.6 [80]. SUMO is being actively extended. The ontologies of Viruses and Engineering, for example, have been developed by groups that were not among the core SUMO developers.

4.2 Upper Cyc Ontology

The Upper Cyc Ontology (Upper Cyc) was initially developed at the Microelectronics and Computer Technology Corporation (MCC) beginning in 1984, under the leadership of Douglas Lenat, founder of Cycorp, Inc. Cycorp is continuing development of Upper Cyc. It was built as a commonsense knowledge base to support natural language processing, thus attempts to capture naïve concepts of the real world [6]. Upper Cyc is primarily represented in CycL, which closely resembles KIF in that it follows similar naming conventions [20]. The Cyc Ontology is proprietary and a part of the Cyc Knowledge Base, which may be licensed through Cycorp Inc. for commercial use. A subset of the Cyc Knowledge Base, OpenCyc, is also available under the GNU Library or Lesser Public License [52]. Under this license, the modules of OpenCyc, called microtheories, and any changes or additions to these modules, must remain public. However, anyone is free to create new proprietary microtheories that refer to, but do not copy, OpenCyc content. Another caveat is that unlike Cyc itself, OpenCyc currently does not have any rules, which are important in defining the meaning of the terms.

The Cyc Ontology currently consists of over 100,000 atomic terms, with 5000 concepts and 50,000 axioms. It is modular, in the sense that it is divided into microtheories. Each microtheory contains a set of assertions and assumptions shared by all the assertions in the particular microtheory. One microtheory may inherit and extend another microtheory. The highest entity in the Cyc Ontology is “Thing”, which is further partitioned into Individual, PartiallyIntangible and MathematicalOrComputationalThing. All instances of MathematicalOfComputationalThing are abstract entities that do not have temporal or spatial properties. Individual defines the set of individuals that are not a set or collection. However, individuals may have parts. This structure is illustrated in Figure 3.

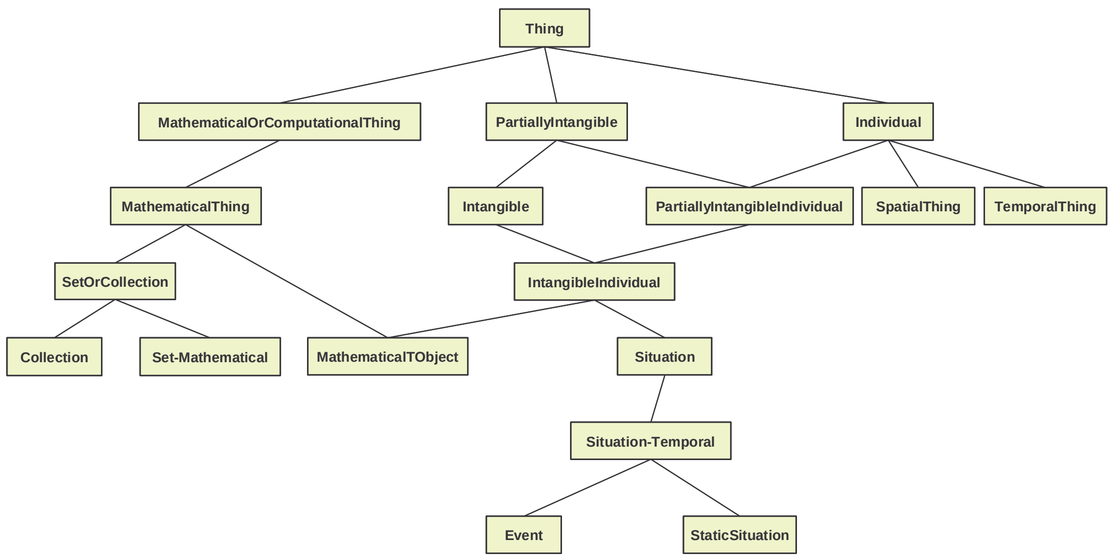

Figure 3. A subset of top level categories in Upper Cyc Ontology [34]

The Upper Cyc Ontology takes a multiplicative view, but weaker than DOLCE. Upper Cyc adopts a 3D view, thus classifies both Endurant, as SomethingExisting, as well as Perdurant, as SituationTemporal. Upper Cyc admits both particulars and universals. Abstract entities in Upper Cyc are classified as SetOrCollection, while Individuals, TemporalThing, SpatialThing are concrete entities.

4.3 Information Flow Framework

The Standard Upper Ontology IFF was authored by Bob Kent and is currently being developed under the IEEE SUO Working Group. IFF provides a framework for sharing ontologies, manipulating ontologies as objects, relating ontologies through morphisms, partitioning ontologies, composing ontologies via fusions, noting dependencies between ontologies, and declaring the use of other ontologies [37]. It takes the building block approach to ontology construction and management, using category theory and Information Flow Theory [37] to support ontology modularity.

Since IFF is primarily a meta-ontology, to be used for ontology-ontology integration, and is still in early stages of development, it has no apparent representation that may be immediately applicable to this paper's focus on upper ontologies. Therefore, IFF will not be evaluated and discussed in the remainder of this paper.

4.4 DOLCE

DOLCE is being developed by researchers associated with the Laboratory for Applied Ontology under the WonderWeb project [20]. It is proposed as the first module within a library of foundational ontologies, serving as a reference module for the library. DOLCE itself is a single ontology and is not divided into modules. Its intended use is to compare and make explicit relationships and assumptions underlying future modules of this library. A variant of the full form of DOLCE is currently available in KIF. A simplified version of DOLCE, which does not consider modality, temporal indexing, and relation composition, is available in the Web Ontology Language (OWL). DOLCE is free, with no apparent licensing restrictions [20].

DOLCE is based on principles specified in the OntoClean methodology [26]. Among other distinctions, the most fundamental division in DOLCE is between perdurants, entities that unfold in time, and endurants, entities that are present all at once in time. Endurants are further specified as those that have spatiotemporal properties, PhysicalEndurant, and those that do not, NonphysicalEndurant. Perdurants are further divided into events and states, classified according to their temporal characteristics. A subset of the structure of DOLCE is illustrated in Figure 4.

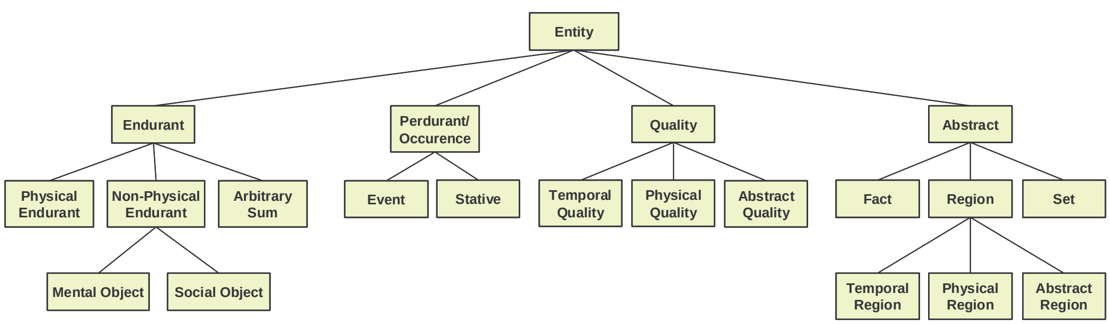

Figure 4. A subset of top level categories in DOLCE [41]

As illustrated in Figure 4, DOLCE represents both Endurant and Perdurant, thus takes a 3D view. It does not classify universals, and thus is an ontology of Particulars. Abstract entities are represented by Abstract Qualities or Abstract. Endurant, Perdurant, Temporal

Qualities, Physcial Qualities are concrete entities. DOLCE adopts a descriptive and multiplicative approach and thus accepts co-localized entities.

4.5 Other Upper Ontologies

Other upper ontologies not part of SUO WG or Wonder Web, but deserve a mention, include: Basic Formal Ontology (BFO) [3], General Ontology Language [22], Sowa's Top level ontology [64], Penman Upper Model [4], Object-Centered High Level Reference Ontology (OCHRE) [57], and Bunge-Wand-Weber (BWW) [78].

5 Ontological Choices: Military and Government Perspective

In recent years there have been a growing number of military and government applications using ontologies. In general, military applications outpace other government applications, but this state of affairs is changing with the advent of eGov [48]. Recently, the Defense Advanced Research Projects Agency (DARPA) has focused two ontology-related programs, High Performance Knowledge Bases (HPKB) [11] and Rapid Knowledge Formation (RKF) [55], on problems relevant to the military: geopolitical crisis management, biological weapons acquisition [55], automated target recognition [38], so-called “battlespace management” problems [36] including understanding and planning issues such as situation awareness (what is the current situation?), course of action analysis and critiquing (what should be done, given the current situation?), and strategic “center of gravity” determination (“those characteristics, capabilities, or localities from which a military force derives its freedom of action, physical strength, or will to fight” [17]; derived from [10]; see [71]). In addition, data fusion, related to situation awareness, has had a strong focus [72], [42], [7]. Data fusion is “the process of combining data [from multiple sources] to refine state estimates and predictions” [66]. Finally, coalition interoperability has been addressed [8].

As discussed above, there are many ontological choices that an upper ontology makes. With respect to military and government applications, we will focus on a specific application domain, where ontologies have been developed recently to address a specific problem: *situation awareness*, as in [39], [42], [7], and especially [43], and try to gauge these ontological choices. Although there have been some studies that try to gauge the kind of modeling effort required to map lower-level military domains to an established upper ontology, these are indeed few [1], and probably not consequential for our evaluation.

The situation awareness model of [43] crucially uses the Joint Directors of Laboratories (JDL) data fusion levels [66] of Table 3, and focuses on level two, *situation assessment* (highlighted in bold in the table), which is what situation awareness is called in the data fusion community. Levels 2 and 3 are entities and networks of relations among entities gleaned from Levels 0 and 1, where sensors of various types obtain information about objects (hypothesized entities). The ontology developed to address situation awareness requires a notion of change over time for objects on the battlefield. One example involves tanks and their movement across a terrain and their relationships to other, enemy tanks that are approaching them. These objects possess a number of properties that change over time, which is how the change in those objects are determined. [43] describes a number of modeling decisions that needed to be made, to capture this notion of change in properties of objects, as derived from dynamic sensor (sensing or perception-registering and reporting devices such as radar, satellite, and other visual or sound-detecting devices) data.

Table 3. JDL Five Levels of Data Fusion

Fusion Level	Association Process	Estimation	Entity Estimation
L.0 Sub-Object Assessment L.1 Object Assessment	Assignment	Detection Attribution	Single Physical Object
L.2 Situation Assessment L.3 Impact Assessment	Aggregation	Relation Plan Interaction	Aggregation Effect (Situation given Plans)
L.4 Process Refinement	Planning	(Control)	(Action)

The situation assessment ontology developed in [43] requires objects to evolve over time (Figure 5). *Attributes* are characteristics of objects and possess specific *property values* that are updated whenever there is a new *event notice*, which contains information about real world events observed by a specific sensor at a specific time. Note that property values here are close to so-called (non-repeatable) atomic *property instances* or *tropes* in the terminology of [57] and OCHRE, one of the WonderWeb foundational ontologies [40], and seem to indicate the 4D (perdurant) *stage* theory of [58].

Alternative models of [43] that were evaluated but found wanting included a so-called *snapshot* class for any object of a situation, having a time property with a unique timestamp value assigned to the object, for an aggregation of *attribute values* and *relations* (i.e., those true at the given time for the object), each considered separately. This model came in two varieties: one based on temporal instants (points) and one based on temporal intervals. The final alternative considered the *attribute* and the *relation* as both utilizing a common *property value*, which itself is associated with a specific *time interval*. As noted, however, in the final design, the notion of time interval was eliminated, in favor of an *event notice*, itself taking place in time. Hence, the event onset itself (reported by the sensor) delineates the time for the change in property value, signified by an event notice.

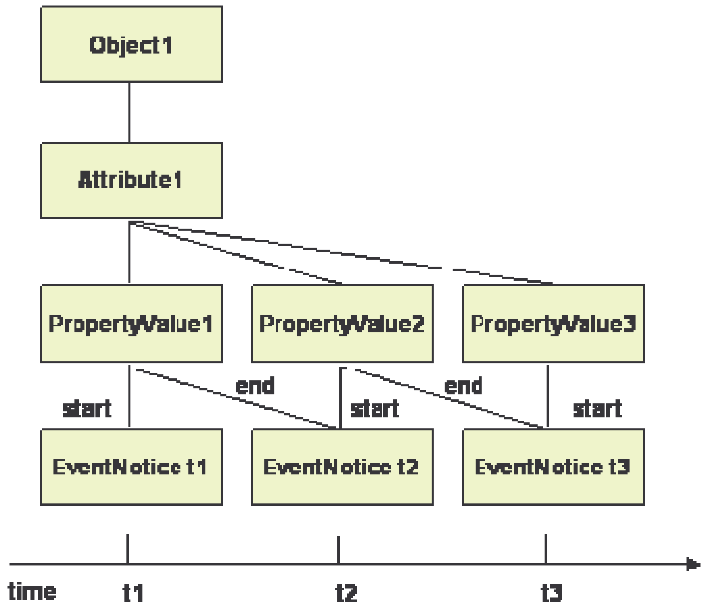

Figure 5. PropertyValues Delineated by EventNotices [43]

Although our analysis is preliminary, and so possible conclusions are incomplete, the above discussion of the ontological modeling alternatives for the military case of situation awareness seems to indicate that a 4D (perdurant) upper ontology would be useful for at least some fairly complicated domain ontologies. Because the upper ontologies such as SUMO, Cyc, DOLCE, and OCHRE all support some notion of perdurant, it is not clear to us that this apparent domain ontology requirement can't be provided by any one of the upper ontologies, and hence that *perdurantism* constitutes a distinguishing criterion we can use to adjudicate among the upper ontologies.

6 Upper Ontology Evaluation

Our evaluation examines three upper ontologies, SUMO, Upper Cyc, and DOLCE, from a U.S. Government or U.S. Military (hereafter referred to as Government) perspective. We begin this section by defining our evaluation criteria and providing our opinion on their preferred values based upon our collective experience in this domain. The criteria and assumptions are discussed priority order, followed by our ontology evaluation. Our evaluation includes a discussion of the purpose for which the ontology was built, which has implications on its applicability, and an assessment, using the evaluation criteria.

6.1 Assessment Criteria

6.1.1 Licensing

An open license is crucial in a Government domain. While in the commercial sector, proprietary formats may be acceptable and necessary to maintain competitive edge, the Government requires open standards to facilitate interoperability and information sharing across Government organizations, as well as with coalition partners. This has direct implications on the acceptable licensing for upper ontologies.

Upper ontologies may be made available for use and extension freely with no restrictions, freely under certain licensing terms, or licensed for some associated cost. Furthermore, there may exist certain conditions, based on the intended use of the upper ontology that may limit use of the upper ontology. For example, the commercial sector may follow a different license agreement than the academic or Federal Government sector. Licenses may apply certain restrictions if the upper ontology is used as is, and other restrictions when the upper ontology is being modified or extended. Finally, upper ontology providers may dictate certain terms and licenses for ontologies that are built on top of or make use of their upper ontology. These terms and conditions are considered in assessing the openness of the upper ontology candidates.

6.1.2 Structure

Another important consideration in choosing the right upper ontology is structure. Structure should allow extensibility and flexibility. All the subject ontologies are intended to be used as libraries, where developers may contribute modules, associating their module with a given upper ontology. However, most upper ontologies are being developed as independent efforts, with limited prospects for interoperating with other upper ontologies. We evaluate structure based on the current structural state of the upper ontology as well as future prospects for extensibility. We assume that modularity facilitates extensibility, and is therefore the preferred approach in Government domains.

6.1.3 Maturity

A third basic requirement for upper ontology use is maturity. A technology applied in a Government domain should be sufficiently mature that it provides a certain level of reliability. This is especially important where immaturity could have severe consequences, as is the case in a military environment. Maturity is not as important in other sectors, such as academia, where cutting edge technology is actually the norm and drives research forward.

Maturity, however, is a qualitative measure. In order to evaluate the upper ontologies, we need to associate quantitative measurements that may serve as good indicators of maturity. For the purposes of this evaluation, we define indicators of maturity as date of origin, development state, and level of adoption.

6.1.4 Miscellaneous

Other considerations that are important from a Government perspective, but are not evaluated, include granularity and security. While concepts of time and space are generally important, fine granularity is required for Government applications. Due to the nature of military applications, precision of time and location are essential and the lack of precision can result in drastic consequences. Likewise, security is an essential component of any technology. The ability to adequately express policy at varying levels of granularity is vital. Further experimentation is required to make an assessment of how well the candidate upper ontologies meet these requirements.

6.2 Candidate standard upper ontology assessments

6.2.1 SUMO

SUMO, initially developed in 2001, appears to have encouraging adoption prospects. It has been mapped to a number of domain ontologies, including government, financial, transportation, and geography. There also appears to be extensive documentation [45] and support provided by the developers of SUMO. Furthermore, SUMO has been mapped to other upper level ontologies and WordNet, a lexical database. SUMO appears to be relatively mature, i.e. it is not actively being developed, but rather is in maintenance mode. SUMO is relatively small as it is intended to be a lightweight ontology that a single person can easily understand. Although size in terms of number of concepts or axioms is not as important as are other aspects, it is noted that SUMO is intermediate in size between the smaller DOLCE and the larger Upper Cyc.

SUMO was intended to be used for enabling data interoperability, information search and retrieval, automated inference, and natural language processing. There is some indication that it is being applied as intended. Currently, SUMO has been applied to problems, such as information extraction, document retrieval, and semantic interoperability [33]. From a Government perspective, semantic interoperability is a key function.

One unique aspect of SUMO is that its developers have also released a mid-level ontology, MILO [68], which is closely integrated with SUMO but has more concrete concepts. Furthermore, as mentioned earlier, a number of domain ontologies exist for SUMO. This coupling of an upper and mid-level ontology and potentially reusable domain ontologies should make it easier for domain ontology developers to adopt SUMO. To further enhance the practicality of SUMO, it has an associated open source ontology management and inference system [79], providing a capability to create, test, modify, and inference on ontologies associated with SUMO.

SUMO has an open license and provides no restrictions on ontology products that may reference SUMO. The licensing terms facilitate open use and sharing across Government organizations. Such an approach to openness, as adopted by SUMO as well as its associated ontology management system, is very promising.

6.2.2 Upper Cyc Ontology

Relatively speaking, the Upper Cyc Ontology is the largest and oldest ontology, originating in 1984 and containing over 6,000 concepts with over 60,000 assertions. However, the publicly available OpenCyc is much smaller and newer. From an adoption perspective, there are a few cited examples that show use of Upper Cyc within the Government. For example, two DARPA projects, High Performance Knowledge Base [73] and Rapid Knowledge Formation [31], have applied the Cyc Knowledge Base.

The Cyc Knowledge Base is intended to be a repository of common sense knowledge which has implications on the structure and contents of Upper Cyc. Upper Cyc appears to contain both elements of realism as well as cognitively specific concepts. While it may support data integration, it appears to be primarily aimed at supporting Artificial Intelligence applications, including speech understanding, auto-routing, summarizing, and annotating [52].

Upper Cyc has licensing limitations. While there does exist a version of the Cyc Knowledge Base that has open license terms based on the GNU license (OpenCyc), portions of the Cyc Knowledge Base are proprietary and have an associated cost. Furthermore, OpenCyc has limitations, such as it does not contain rules.

Structurally, Upper Cyc is flexible in that it, and its associated Cyc Knowledge Base, is divided into microtheories which can be extended. However, while a single microtheory should follow a common set of assumptions, there may be contradictions between microtheories.

The Upper Cyc Ontology seems to be quite tightly coupled with the Cyc Knowledge Base, making it harder to use the Upper Cyc Ontology as a standalone upper ontology or within the framework of an ontology library. A consequence of this coupling is tighter restrictions being placed on the use of Upper Cyc. It is unclear what implications this has on the use of Upper Cyc in the context of the military. Further investigation of what is available in each form of the upper ontology is necessary to assess how this impacts usability by the military.

6.2.3 DOLCE

DOLCE is not intended to be a single standard upper ontology, as is the case with SUMO and Upper Cyc. Instead, it serves as the topmost reference ontology of a library of foundational ontologies. Therefore, the context in which DOLCE is modular is quite different than that of SUMO and Upper Cyc. While SUMO and Upper Cyc are themselves modularized, DOLCE is intended as a single module within a larger set of foundational ontologies. This provides strong prospects for interoperability with other foundational ontologies. Furthermore, DOLCE is developed based on the principles outlined by the OntoClean [26] methodology, giving it formal structure.

DOLCE is the first module of a library of foundational ontologies. While the approach taken by the developers of DOLCE appears promising for long-term applicability and extensibility, it raises the question of how useful DOLCE is in the short term, since the library is not fully developed. Besides DOLCE, two other modules exist within the foundational ontology library, OCHRE and BFO. Further investigation is needed to assess the use of this library for Government purposes.

Finally, as with SUMO and Upper Cyc, DOLCE appears to be quite open and freely available to the public. There is no associated license with DOLCE, thus providing no restrictions to the use and extension of DOLCE.

A summary of our evaluation is provided in Table 4.

Table 4. Evaluation Summary

	SUMO	Upper Cyc	DOLCE
Licensing (open license)	Free to use with no licensing terms or conditions. Domain ontologies use GNU License.	Subset free to use (Open Cyc), most portions proprietary.	Free to use with no licensing terms or conditions.
Structure (modular)	Modularity explicit	Divided into microtheories – facilitates modular design.	Intended use within a modular library of foundational ontologies, but not currently divided into modules.
Maturity (evidence of use)	Currently in maintenance mode. Has been mapped to MILO and used to develop domain ontologies.	Continuing development and maintenance. Cyc KB has incorporated a number of domain ontologies.	One of three modules in the WonderWeb foundational ontology library. Currently, DOLCE has been mapped to OCHRE.

7 Conclusions

Evaluating key upper ontology initiatives led us to five conclusions. First, to be valuable to the Government, a standard upper ontology must have an open license. Openness is critical in these domains where trends are toward greater sharing and sharing partners may be dynamic, especially when one considers current coalition military operations. We found that two of the three ontologies we evaluated met this criterion.

Our second conclusion is that it is difficult to use an upper ontology as intended today. By ‘as intended’ we refer to mapping a domain ontology to an upper ontology to reuse or refine concepts that exist in the upper ontology. There is no agreed upon standard upper ontology and few proven implementations. Further, the differing theoretical approaches taken by the candidate standard upper ontologies we examined are evidence that there is no consensus on which approach is better. In fact, there may never be a single correct answer. Rather, which theoretical approach is best may be situational. Also, as we saw in section 3, ontological choices are made in the development of upper ontologies that have implications for their use in domain ontologies. These implications are not clear and there is little guidance available within the ontologies to help a domain ontology designer discern the impact of using a particular upper ontology concept within their domain. In fact, we contend that even experienced knowledge engineers would find it difficult to use upper ontologies because this is a new paradigm for knowledge engineering. Tools and methodologies to provide guidance to domain ontology designers would be very helpful, even if the guidance was captured as annotations within the upper ontology.

Our third conclusion is that upper ontology approaches are maturing. As discussed in section 5, some ontologies are relatively mature, while others are early in the development lifecycle. There is growing interest in the potential use of upper ontologies in the Semantic Web. Two initiatives, IEEE SUO [65] and WonderWeb [76], have objectives that include developing foundational ontologies for use in a wide range of applications. We also see a trend toward making these upper ontologies easier to use. For example, the Mid-level ontology (MILO) was developed as a bridge between the abstract contents of SUMO and domain ontology details.

Our fourth conclusion is that, at a minimum, ontology developers should consider upper ontologies as they design their mid-level and domain ontologies. As IEEE SUO and WonderWeb progress toward upper ontology standards, one should consider upper ontologies as they design their mid-level and domain ontologies. Because upper ontologies are evolving, the “best” one today may not remain the “best” in the future. However, upper ontologies do provide a theoretical foundation and give clues on concepts people may wish to consider in their ontology development, even if they don’t actually map their domain concepts to an upper ontology.

While there is an analysis cost in selecting an upper ontology as theoretical framework, there is a greater cost in not doing so, especially when one is dealing with relatively abstract concepts. Considering the contents of an upper ontology as one designs a domain ontology allows one to build upon the knowledge and experience already captured in an upper ontology. Upper ontologies are built by experts with backgrounds in formal ontology and formal semantics who have spent much time analyzing and then elaborating concepts that make upper level distinctions. Therefore, in general, one would expect that the upper ontology embodies greater expertise regarding the general concepts it contains than exists in a typical domain ontology. Also, modeling a domain ontology after an upper ontology by leveraging or extending concepts already defined in it would reduce the potential for duplication of effort in the domain ontology and would increase the likelihood of a semantically richer domain ontology. Where inter-ontology mapping is desired, use of a common upper ontology could simplify the mapping process. One fear is that without the use of a standard upper ontology, we could create conceptual stovepipes at the semantic level.

Which upper ontology is best to use as even a conceptual model is situational and may change over time as upper ontologies mature and experience is gained with their use. However, the risk of a suboptimal selection is mitigated by the fact that future upper ontologies are likely to be founded on current candidate standard upper ontologies.

Although there is no single best upper ontology, our current bias is to use DOLCE as a conceptual framework for mid-level and domain ontologies. This is not only because DOLCE is modular and has an open license, since both SUMO and OpenCyc are modular and open. But DOLCE is in general better informed by formal ontological analysis and formal semantics and builds on ontological engineering practices begun in Cyc and continued in SUMO. Finally, we see the approach of developing a library of foundational ontologies in which independent ontology developers could contribute their modules within such a common library as promising.

Our final conclusion is that utility ontologies would be valuable in a Government domain. There are many concepts common across military domains (time, location, mission, etc.). If utility ontologies were created and posted in a publicly accessible location, this could save ontology designers time and money and could lead to an emerging "best of breed" library of utility of ontologies. (See our software engineering analogy in section 2.2.2.) Utility ontologies could be especially important in Government domains where the growing culture of information sharing makes flexible data interoperability between applications key.

8 Predictions

This evaluation led us to four predictions relevant to upper ontologies. Our predictions are summarized in this section.

First, we predict that ontological modularity will become even more important over the next five years. Any complicated information modeling effort will require concept decomposition. This in effect creates "upper" concepts that can be abstracted into an upper model. These upper models could be abstracted further until they map to mid-level ontologies or super-domain ontologies. The mid-level ontologies may be mapped to an upper ontology but this mapping may in fact be transparent to the mid-level ontology user. These upper models or super-domain ontologies could then be used across a set of related domains. For example, one could have a mid-level ontology that captures key concepts common across a large domain such as military command and control. Using a common definition of these key concepts could help evolve the mid-level ontology toward "utility" status as described in our software engineering analogy (see section 2.2.2). Figure 6 depicts a notional ontological layering.

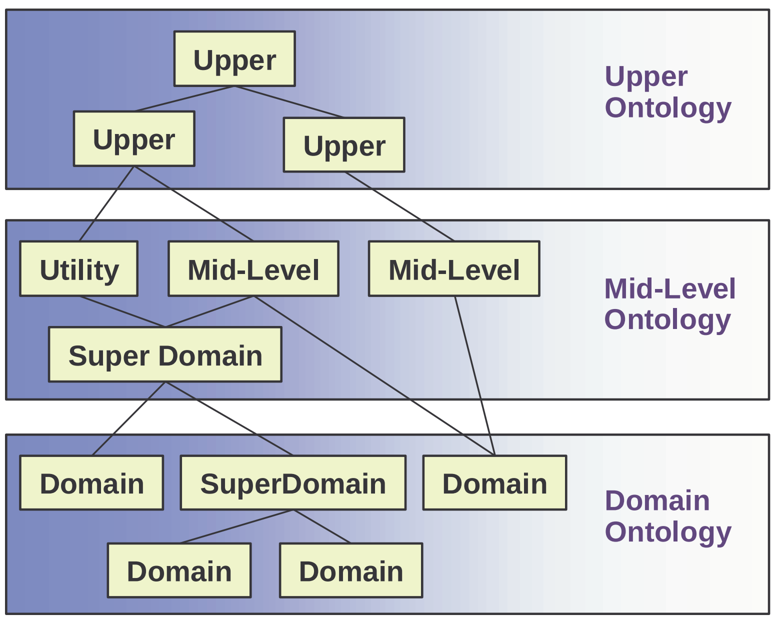

Figure 6. Notional Layering

Our second prediction is that over the next five years there will be more development of super-domain or mid-level ontologies for distinct large domains. Sample domains include the U.S. Military (command and control, operations, intelligence, logistics, etc.), biology (processes, experiments, functions, etc.), and finance. This prediction is clearly related to the previous one.

Our third prediction is that over time there will be more support for use of utility ontologies through the development of a more automated ontology infrastructure. This infrastructure will ease the process of registering, discovering, and reusing ontologies, as well as mapping between them. We hope ontology best practices will also be easily accessible to make it easier for ontology designers and application developers to make sound choices in the use of ontologies.

Finally, we predict that the formal analysis occurring at the upper ontology level will migrate down to lower level ontologies. This analysis migration should lead to spreading improvement in areas such as ontology completeness and consistency.

9 Future Direction

This paper describes a preliminary evaluation of candidate standard upper ontologies from the perspective of use in the Government. A logical next step is to take a more scientific approach and perform a more formal evaluation. Resources permitting, we would like to design an experiment to more formally evaluate candidate upper ontologies using ontologies from a Government domain.

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