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Toward a Representation of Semantic Change in Linked Data

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Abstract: In this article, we introduce a new framework, the Intensional–Ontological Model (IOM), for representing meaning, and especially for representing semantic change, in linguistic linked data resources. This framework, which makes use of previous work in the literature on lexical semantics and ontologies, is intended to help clarify what we mean when we model semantic change and to assist in elaborating different ontology patterns for doing so. In this work, we assume a simple architecture, one which is at the basis of the well-known OntoLex-Lemon vocabulary and which consists of one or more lexicons linked to an ontology. Our model, which is based on this architecture and informed by previous work on word senses and ontologies, is intended to provide a clear interpretation for the modelling of both onomasiological and semiasological changes, in both static and dynamic versions. This article describes how the IOM framework represents word meaning as the relationship between a word and an ontological concepts in the 'static' case, demonstrating that the IOM is compatible with OntoLex-Lemon (while at the same time providing a greater level of detail as to the meaning of the 'sense' and 'reference' relationships). It then goes on to detail how the IOM can help us understand how to model semantic shifts in linked data lexical resources with a focus on conceptual change and the addition of temporal information to semantic shift data.

Keywords: linked data; semantic shift; ontologies; lexical semantics

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1. Introduction

The study of meaning change is an active area of research within historical linguistics. However, words (and linguistic expressions more generally) can change in their meanings over time through different kinds of semantic shift without this necessarily implying that there has been a corresponding change in the concepts being referred to. For instance, the word *mouse* has come, through a process of metaphorical shift, to refer to a kind of rodent as well as an input device for a computer with a similar shape to this rodent. But although this is an example of a modification in the meaning of a word, it cannot really be considered a kind of conceptual change since it does not imply any fundamental alteration in the concept of mouse qua rodent. Changes in scientific or technical concepts, on the other hand, usually *do* entail changes in how words are used.[1] In this type of change, either a new word is coined or borrowed from another language, or the meaning of some already existing word undergoes a process of specialisation in order to refer to the modified concept. In the latter cases, the semantic shift may only be detected by comparing a specialised corpus with a more balanced, wide-overage one. Take the case, for instance, of the Latin word *mater* 'mother', which acquired the technical meaning of 'placeholder of right, duties and assets', but this change was limited to Roman legal texts (Ribary and McGillivray 2020, p. 20). Or to cite another example, the word *tomato* refers to what is, from the taxonomical point of view, a fruit; nonetheless, the word is usually represented in word embeddings as being closer in similarity to vegetables such as *potato*, *onion*, and *carrot* than to other fruits such as *apple*, *grape*, or *strawberry*, reflecting a non-scientific understanding of the concepts in question.

Descriptions of both kinds of change, both semantic and lexico-conceptual—both of which we will refer to using the catch-all term of *semantic change* in what follows—tend to take many different types of information into consideration: information, that is, belonging to various different fields of enquiry and potentially involving different kinds of resources and materials—e.g., linguistic, historical, bibliographical, and geographical. In particular, these descriptions involve linguistic and conceptual or ontological information. Datasets describing semantic change would therefore seem ideal candidates for modelling as *linked data* and publication on the *Semantic Web*, since the Semantic Web is particularly suited for the integration of heterogeneous data in a standardised, highly interoperable way. Moreover, the Semantic Web has had a strong emphasis on ontological resources since its beginnings, as well as a more recent focus on the provision of lexical data (witness the recent popularity of OntoLex-Lemon; further details on the use of linked data models for linguistic data can be found in Khan et al. 2022). The integration of heterogeneous datasets in the Semantic Web takes place at different levels, but in the first place it should occur at a semantic level, that is, on the basis of the meaning of the data itself. Ideally, this requires data modellers to make the meaning of their data as explicit and as *machine actionable* as possible. Furthermore, in order to ensure the maximum of interoperability to their data, users are encouraged, as far as possible, to model and publish data using pre-existing standards, resources (such as vocabularies and ontologies), and technologies: starting from the modelling language itself,[2] namely, the Resource Description Framework (RDF).

Given the arguable suitability then, of the linked data paradigm for the modelling and publication/dissemination of semantic change data,[3] it is essential to have some guidance on how to carry out these tasks in a way that sufficiently respects the meaning of such data and that fully leverages the technological affordances offered by linked data in the Semantic Web. In order to keep to the spirit of the Semantic Web, we should also aim to work in a modular fashion and with specialised datasets that can be re-used for different tasks or use cases, resources such as (in our case) lexicons and ontologies. Unfortunately, there does not seem to exist much in the way of such guidance at the time of writing this article. In response, the present article proposes a Semantic Web-native framework for modelling semantic change using resources such as lexicons and ontologies (among others) that is well motivated from the theoretical point of view (and is in fact grounded in classic views of lexical semantics as well as more recent corpus-based ones) and that is intended to help clarify the meaning of different modelling decisions.

Our framework, the **Intensional–Ontology Model** (IOM), assumes a very basic core 'conceptual' architecture for modelling semantic change that consists of two types of resources:[4] lexicons and ontologies, where broadly speaking, the ontology describes the semantics of the elements in the lexicon. Note that this is also the set up behind the popular OntoLex-Lemon model for lexical resources in RDF, which we will describe in Section 3.1. To this core set-up, we can of course add other kinds of resources such as linguistic corpora (to link lexical entries to their attestations or examples of use), but we will keep to this basic architecture in this article. We will refer to resources that implement this architecture as *lexico-ontological* resources. Such resources allow us to formulate questions regarding semantic change using linked data-based resources such as the following.

> Given a lexico-ontological resource with a lexicon(s) to provide a linguistic description of words (and other linguistic phenomena) and an ontological (ideally language independent) description of concepts, how can we show (i) how *the meanings of words change over time with reference to concepts in an ontology* and, in the other direction, (ii) how can *we trace the different lexemes used to refer to the same (ontological) concept over time*?

Before we introduce the IOM in Section 3, it will be useful to discuss a number of theoretical preliminaries in Section 2. In particular, in that section, we present two different views on what a word sense is: first as an intension, in Section 2.2, and then as a description of use, in Section 2.3. The IOM attempts to reconcile these two views together by making use of a well-known definition of what an ontology is, as detailed in Section 2.4. In Section 3.1, we introduce the OntoLex-Lemon model, which the IOM is influenced by and which it is compatible with (as we shall show). After describing the IOM we use it in Section 4 to describe the special case of conceptual change where it alters the meaning of a given sense, since this raises a lot of interesting issues. Next, in Section 5, we look at different strategies for how to add temporal information to semantic shift data.

Before moving on, we should clarify the scope of this paper. Our intention in the present work is not to provide a comprehensive guide to modelling semantic change phenomena in linked data on the basis of existing vocabularies and ontologies (with a view ultimately to publishing such data and making them more widely available and interoperable with other relevant datasets), since we doubt that we could do the subject justice in a single article. However, as we will argue below, and particularly in Section 3.1, existing Semantic Web vocabularies and ontologies already offer substantial provision for describing a large variety of linguistic phenomena related to language change, as well as representing dynamic linguistic data more generally (see Section 5). What has not been developed as much up until now is a detailed, theoretically well-motivated discussion of *which aspects of word meaning* should be described at the level of word senses, and which at the level of the ontology (in the lexico-ontological architecture that frames our discussion and, which thanks to its use in OntoLex-Lemon, has become a standard for representing lexical semantics in linked data), and how all of this might be impacted by the necessity to model changes at both the sense and the ontological level of word meaning (broadly understood). This is what we propose to accomplish in this article. We will motivate one approach to modelling meaning in a lexico-ontological resource using a description of the senses of a lexicon and an ontology in a way that aligns and is compatible with (but which goes well beyond) the most widely used vocabulary/ontology for doing so in the Semantic Web, namely, OntoLex-Lemon.[5] In addition, we look at extensions of OntoLex-Lemon for representing sense shift data (proposed in previous work) on the basis of our account of the modelling of word meaning, since one of the main focuses of this article is the representation of semantic change. Our original contribution is to clarify the interpretation of such data in a way that will guide user decisions on how to structure their ontologies and which kinds of concepts to include in them, with the goal of representing semantic change. For instance, we recommend the inclusion of non-existent elements in the ontology, in cases such as those of the whale example in Section 4, something that has an important impact on how we view ontologies and their role in modelling meaning. As a preliminary to all this however, we will have to clarify what we mean by the terms *sense* and *ontology*—and this is what we will do in the next section.

2. Preliminaries

2.1. Two Important Scenarios

In order to motivate our approach to modelling meaning in lexico-ontological resources (on the basis of which we will subsequently develop an approach to modelling semantic change), we will look, in the current section, at two practical scenarios. These describe two important use cases for any such lexico-ontological resource consisting of a lexicon $\mathcal{L}$ for a language *lan* and an ontology $\mathcal{O}$:

1. In the first scenario, we would like to model (or, from the point of view of a user of the resource, to query) how a concept, c in $\mathcal{O}$, is referred to in $\mathcal{L}$. To make the scenario even simpler, we assume that there exist a series of words, or more broadly lexemes, in $\mathcal{L}$ that are w_1,w_2,..., all of which refer to this concept.[6]
   For instance, the ontological concept Mammal might be associated with the words *mammal* and, possibly, *mammalia* in an English language lexicon. We call this scenario the ***onomasiological*** case.
2. In the second scenario, we would like to be able to associate a lexeme w in $\mathcal{L}$ with (and again from the user's point of view, to be able to retrieve it) all of the different concepts $c_1, c_2, \ldots$ in $\mathcal{O}$ that it can be used to refer to. We call this the ***semasiological*** scenario. For instance, the word 'mouse' is associated with both a kind of rodent and a kind of computer input device.

Both scenarios require us to associate lexical entries together with ontological concepts in some kind of referential relation. How in this case, then, should we understand this relation between an entry w and a concept c? One simple way would be to see c as *directly* standing for the *extension* of w, that is, the set of things to which w refers to in the world. For example, according to this point of view, the extension of the word *whale* is the set of whales in the world, and this latter set is represented by an ontological concept Whale. However, this turns out to be a very simplistic way of modelling word meaning (using ontological concepts) since, among other things, it neglects that part of word meaning that relates to the *use* of linguistic expressions to mean things. Moreover, it also fails to take into consideration both the *intensional* aspect of senses, i.e., the conceptual content of a word's meaning (for more details, see Section 2.2), as well as the *intensional* aspect of ontological concepts (for more details, see Section 2.4). In fact, it turns out that what we are missing here are intermediate entities that link a word and its extension indirectly and that also allow us to provide a more detailed description of word meaning.

This necessity for an intermediary is easy to see in the case of expressions that refer to titles or roles that are obsolete in the contemporary world, such as *Holy Roman Emperor*, *Bey*,[7] or *King of France*. If we view each of these expressions as referring to sets of things in the world, that is, in terms of their extensions, then (at the time of writing) all of them refer to the same thing, that is, *nothing*, namely, each term has the empty set as its extension. However, this fact clearly does not exhaust the meanings of the expressions themselves,[8] and, in a very rough approximation, we call the part of word meaning that is not captured by the extension of a word the *sense* of the latter.

It is notable that each of the expressions mentioned above picked out different sets of things in the world—that is, has had different extensions—throughout the period in which it was part of the English lexicon, without, that is, necessarily undergoing corresponding changes in its definition: the definition of each expression is arguably, more or less, the same as it was 200 or 300 years ago. This definition, we would argue, only *indirectly* refers to the extension of each expression by helping to pick it out and is, in fact, part of the description of the sense of the expression. In the next two sections, we look at two different perspectives on what these *senses* are; this will provide the background and motivation for our modelling of the *meaning* of word meaning in the following (as ultimately inspired by the two scenarios above).

2.2. Senses as Intensions

The term *sense* is used to refer to a number of different aspects of word meaning. In the current subsection and the next, we will hone in on two of the most important of these (that is, important for our purposes) and see how we can reconcile them via our framework later in the article. Some of these aspects of *sense* are closely related to how a word is used (as we shall see in the next section, Section 2.3); in other cases, however, the term *sense* has been treated as synonymous with what linguists/philosophers of language call the *intension* of a word or expression, where this latter term is taken to refer to that part of an expression's meaning that, abstracted away from particular concrete examples, serves to map a series of contextual/circumstantial variables to an extension in some *reference domain* (Speaks 2019). More formal definitions of the concept of intension often make use of a possible worlds' semantic framework. See, for instance, the *the epistemic intensions* proposed by Chalmers in Chalmers (2002), which can be described as mappings from a 'maximal' *state of affairs*[9] to a subset of a relevant domain, that is, the *extension* of the given state of affairs. On this view of senses, then, the intension of the predicate 'is blue' in English would correspond to a function that, given a sufficiently detailed (formal) description of a possible world, would return the set of all blue objects in that world. Broadly speaking, we can describe an *intension* as that part of the meaning of a linguistic expression that, given certain relevant facts, helps to narrow down or determine its extension, that is, which classes, properties, individuals, etc., it refers to at any moment in time—in much the same way that a traditional (Aristotelian) dictionary definition does. Take, for instance, the following definition for the word *aardvark*:

> A South-African quadruped (Orycterdpus capensts Cuv.), about the size of the badger, belonging to the insectivorous division of the Edentata, where it occupies an intermediate position between the Armadillos and Ant-eaters.[10]

In this definition, the meaning of *aardvark* is explained in terms of a series of properties representing (some of) the *most salient* typical features of aardvarks (where they are found, how many legs they have, etc.) and that serve to distinguish individuals of this particular class from individuals of other classes. Since the population of aardvarks varies over time (especially given the impact of human beings in its environment), the set of individuals that this definition pertains to at any one moment (namely, its extension) changes, even if the definition continues to be the same throughout. We will refer to this part of word meaning as *sense as intension*. We choose to focus on it both because it is an important part of what are called the classical semantic theories of meaning in the influential tradition of Fregean semantics (Speaks 2019), but also because of its compatibility with the theoretical description of ontologies given by Guarino et al. (2009) and described below in Section 2.4. In this latter, respect senses as intensions suggest one natural way in which ontologies can be used to describe meaning in lexico-ontological resources. To summarise then, we view *senses as intensions* as that part of word meaning that helps to fix the extension of a word, the set of things that it refers to, in a given context. In formal work on semantics, this is often represented as a function from a set of possible worlds to the subset of a domain; however, this function plays much the same role as a traditional Aristotelian definition in a dictionary.

2.3. Senses and Language Use

As well as being viewed as intensions (and frequently described using modal logic-based formalisms such as in the tradition of Montague Semantics (Janssen and Zimmermann 2021)), word senses are also often described in terms of regularities in the use of words in concrete situations of language production (where these are based on native speaker intuitions or on the statistical analysis of a balanced, large scale electronic corpus). For instance, Kilgarriff (1997), in a highly influential work within the corpus-based tradition of lexical semantics, describes senses as 'abstractions from clusters of corpus citations' with the latter (the clusters and not the word senses themselves) being regarded as 'the basic objects in the ontology'. This definition reflects a certain skepticism of previous theoretical approaches,[11] the latter of which, according to the author, fail to properly address the (supposed) instability of the traditional concept of the word sense. More generally, however, the corpus tradition in linguistics has (arguably) demonstrated the practical usefulness of such approaches in accounts of word meaning. The utility of the corpora-based approach has been further demonstrated by the recent popularity, in Natural Language Processing, of word embeddings, i.e., automatically derived, vectorial representations of word usage in a sufficiently large corpus—with the latter turning out to be surprisingly effective as machine-actionable representations of word meaning.[12] In this short description of what we might term the usage or corpora-based view of word senses, we have not even touched upon the centrality of corpus attestations in describing word meaning in historical and scholarly dictionaries such as the Oxford English Dictionary. The foregoing should be sufficient, however, to hig ight the importance of a use-based perspective on word senses as opposed to, or rather in addition to, what we might call the intensional perspective.

We can summarise these last few sections as follows. We have identified two different perspectives on what a word sense might be.[13] The first of these relates to the role of a sense (as intension) in determining, given sufficient information and/or context, what things in the world a word refers to. The second is concerned with describing actual language use with respect to the kinds of information that can be automatically derived from large language corpora. In many, if not most, cases, we are interested in capturing both aspects of word meaning; so, from the point of view of knowledge representation, we will want to model both. Moreover, given the particular perspective we adopted in this study, we would like to be able to reconcile both perspectives and to integrate both of them into one, single Semantic Web-based framework with the aim of eventually combining together different kinds of machine-actionable descriptions of word meaning.

Having examined the description of word meaning in a lexicon, we will now move on to the ontological part of a lexico-ontological resource and look at how the concepts in an ontology should be understood.

2.4. What Is an Ontology?

Let us focus on the role that ontologies play (in our proposal) in modelling meaning in lexico-ontological resources. In order to do this, we need to expand upon what we intend by ontologies in the first place. In this we follow the account given in Guarino et al. (2009), which fleshes out the standard definition of an ontology as a 'formal, explicit specification of a shared conceptualisation' and lends it a detailed mathematical interpretation. The authors of that work define an ontology as a logical theory in a first-order logical language $\mathcal{L}$ (with vocabulary $\mathcal{V}$) with respect to an *ontological commitment* $\mathcal{K}$, the latter of which serves to approximate the set of intended models of $\mathcal{L}$. In order to unwrap this definition somewhat, and in particular to explain what we mean by an ontological commitment, we will need the additional notion of a *conceptualisation* defined as an *intensional* relational structure $\langle \mathcal{D}, \mathcal{W}, \mathcal{R} \rangle$, which (in contrast to *extensional* first-order relational structures) consists of a domain $\mathcal{D}$, a set of possible worlds $\mathcal{W}$, *and* a set of intensions (also known as intensional relations) $\mathcal{R}$. An ontological commitment $\mathcal{K}$ with respect to a first-order language $\mathcal{L}$ with a vocabulary $\mathcal{V}$, then, is a tuple consisting of a conceptualisation (as defined above) and an interpretation for each symbol in $\mathcal{V}$, which maps each such symbol either to an element of $\mathcal{D}$ or an intension in $\mathcal{R}$.

To put it in less formal language: conceptualisations serve to determine the *meaning* of a vocabulary item, rather than (directly) assigning a set of individuals or a tuple (an extension) to that item in a given model. Indeed, given any sufficiently descriptive (formal) representation, a conceptualisation will enable us to pick out the sets of things (the extensions) described by concepts such as Animal or knows. The authors of Guarino et al. (2009) define an intended model $\mathcal{L}$ *according to* a conceptualisation as a first-order (extensional) model that corresponds (in a precisely defined way) to the value of the conceptualisation in some possible world. An ontology from this point of view, then, constitutes a logical theory whose models are approximations to the intensional structure given in a ontological commitment; in other words, an ontology serves to describe some domain or domains of interest at an *intensional* rather than an extensional level. This fits in well with our view of senses as intensions (unsurprisingly so, given that all of the ideas that we have cited ultimately derive from common work at the intersection of mathematical logic, philosophy, and linguistics).

To summarise, a well-known formal treatment of the standard definition of an ontology as a shared conceptualisation in a formal language, and which sees conceptualisations as descriptions of a domain at an intensional rather than (directly) at an extensional level, fits the view of senses as intensions that we described in Section 2.2; this would seem to confirm that this aspect of word meaning would be best described using an ontology. We will further explore this theme in the next section.

3. Introducing the Intensional–Ontological Meaning Model

Taking inspiration from the work described above in this present section we introduce the *Intensional–Ontological Meaning* (IOM) model, which is our framework for the modelling of word meaning using linked data lexico-ontological resources. This framework describes a linguistically grounded way of using an ontology, $\mathcal{O}$, to model the meaning of entries in a lexicon, $\mathcal{L}$, in some language *lan* (note that it can be easily extended to the case of multilingual resources, describing more than one language). The model directly responds to the requirements brought up by the two (static) scenarios described above, and can be easily extended to the dynamic versions of these scenarios, as laid out below. Note that since IOM is based on RDF, we have limited ourselves in what follows to working exclusively with unary and binary relationships (see the discussion in Section 3.2.1).

Word Meaning in IOM

Given an entry $w \in \mathcal{L}$, a lexical sense $s \in \mathcal{S} \subseteq \mathcal{L}$ (where $\mathcal{S}$ is the subset of $\mathcal{L}$ containing lexical senses) and the ontology vocabulary item $o \in \mathcal{O}$, we can relate w, s, and o together using the relations $sense \subseteq \mathcal{L} \times \mathcal{S}$ and $intens \subseteq \mathcal{S} \times \mathcal{O}$, i.e., $sense(l, s)$ and $intens(s, o)$ as follows:

- The lexical sense s is used to describe commonalities and tendencies in the use of w (those that are part of the description of the semantics of that word when it refers to the language-independent concept o) in situations of actual language production; this part of the description of l is dependent on a particular language;
- The ontology vocabulary item o is used to describe the 'intensional' part of w's meaning (that part of the meaning of w corresponding to s that it shares with words in other languages that it can be translated into), where this 'intensional' meaning is 'extra-linguistic', in the limited sense that the same item can be used to describe the meaning of different linguistic entities and in different languages (i.e., o represents the sense as intension of an entry as mentioned above).

Note that in the IOM model, the ontological item, o, plays the role of the language-independent concept in the post-Lovejovian sense of Kuukkanen (2008), amongst others. This becomes clearer below when we look at what it means to model the process of meaning change using IOM. The lexical sense s, on the other hand, pertains to that part of word meaning that is dependent on a particular language as manifested, for instance, in corpus data. The lexical sense can be seen as a 'linguistic' outer layer of the meaning of a word, and the ontology item can be seen as its intensional kernel, with the latter allowing for the identification of an extension in terms of a set of entities.[14] Both a word's lexical senses (sense as use description) and its senses as intensions can change significantly over time and this is the topic of Section 4. Before that, we look at the OntoLex-Lemon vocabulary.

3.1. The Ontolex-Lemon Model and IOM

OntoLex-Lemon is by far the most well-known and most widely used model/vocabulary for publishing lexical resources as linked data (McCrae et al. 2017). Although it is currently used as a general purpose vocabulary for creating lexicons in RDF, OntoLex-Lemon was originally intended for the narrower task of grounding ontologies with linguistic information; it is therefore ideally suited to the creation of lexico-ontological resources. Ontolex-Lemon follows the so-called *sense by reference paradigm* (McCrae et al. 2011), which entails that 'the meaning of a lexical entry is specified by pointing to the ontological concept that captures or represents its meaning'.[15] The definitions of core classes like LexicalEntry and LexicalSense and properties like sense and reference are compatible with the IOM model. In particular, the class LexicalSense is defined in the Ontolex-Lemon W3C Community Report[16] as representing

> the lexical meaning of a lexical entry when interpreted as referring to the corresponding ontology element. A lexical sense thus represents a reification of a pair of a uniquely determined lexical entry and a uniquely determined ontology entity it refers to. A link between a lexical entry and an ontology entity via a Lexical Sense object implies that the lexical entry can be used to refer to the ontology entity in question.

In addition, the property sense is defined in the W3C Community Report as '[relating] a lexical entry to one of its lexical senses' and reference is defined as '[relating] a lexical sense to an ontological predicate that represents the denotation of the corresponding lexical entry'. That is, lexical senses in IOM correspond to OntoLex-Lemon lexical senses; the IOM $sense \subseteq \mathcal{L} \times \mathcal{S}$ relation corresponds to the OntoLex-lemon sense property, and the IOM $intens \subseteq \mathcal{S} \times \mathcal{O}$ relation corresponds to the OntoLex-Lemon reference property.

Although IOM is compatible with OntoLex-Lemon, the description of the IOM model given above makes use of additional theoretical assumptions that are not (so far) present in accounts of the semantics of OntoLex-Lemon, or rather, they are left somewhat underspecified. These extra assumptions are important for the extensions of IOM that we will propose and that are intended to describe semantic change (Section 4). It might be argued that in aligning the elements of IOM with those of OntoLex-Lemon, we are taking too great an advantage of the theoretical underspecification existing with respect to the definitions of the latter.[17] While there is a lot to be said for proposing a new RDF vocabulary for IOM (as an alternative or competitor for OntoLex-Lemon), in doing so we would inevitably lose out on the kind of interoperabilty that is one of the main advantages of linked data.

Other relevant OntoLex-Lemon classes/properties, in addition to those described above, include denotes, which is used to connect a lexical entry with the various ontology entities (individuals, classes, or properties) that describe its meaning, thereby bypassing LexicalSense; it is equivalent to the property chain sense o reference. Furthermore, the Usage class can be utilised to add further text descriptions of the usage of a sense. Listing 1 and Figure 1 below give an encoding in RDF (using both the Manchester OWL syntax and in a diagrammatic form, respectively) of an example OntoLex-Lemon lexico-ontological resource. In the example, we have $lex1$ and an ontology $\mathcal{O}$. $lex1$ is a lexical entry with a sense $sense1$, which in turn refers to an ontology item c_1; it also has a sense $sense2$, which refers to the ontology item c_2, where c_1 and c_2 are both distinct.

Listing 1. An OntoLex-Lemon example.

```
Individual: lex1
    Types: ontolex:LexicalEntry
    Facts: ontolex:sense sense1,
           ontolex:sense sense2
Individual: sense1
    Types: ontolex:LexicalSense
    Facts: ontolex:isSenseOf lex1,
           ontolex:reference o:c1
Individual: sense2
    Types: ontolex:LexicalSense
    Facts: ontolex:isSenseOf lex1,
           ontolex:reference o:c2
```

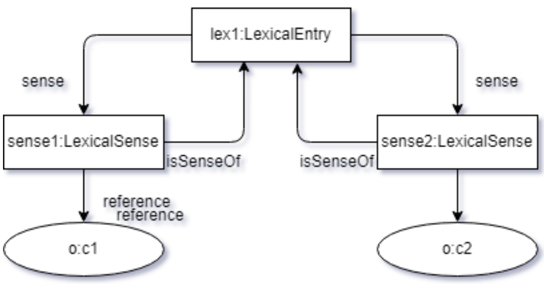

Figure 1. Ontolex-Lemon example.

Relationships between senses themselves are covered by the OntoLex-Lemon Variation and Translation (vartrans) module.[18] In particular, this module contains the object property senseRel, which is intended to relate together 'two lexical senses that stand in some sense relation'. OntoLex-Lemon also allows for the *reification*[19] of this generic relationship between different senses with the LexicoSemanticRelation class. By associating together two senses, i.e., individuals of the type Lexical Sense, using the source and target properties, we can thereby define any kind of (lexico-semantic) relationship between them in order to specify, e.g., whether one sense is the generalisation or narrowing of another or whether one is derived from it. Again, this is compatible with our IOM model, as long as we ensure that the sense relationships describe language-specific relationships between senses as used, and we use the ontology part of a lexico-ontological resource to describe extra-linguistic aspects of the relationship between these two meanings, i.e., those pertaining to the things they refer to. The ranking or ordering of senses (as in dictionaries, which we can use to assert the pre-dominance of certain senses) can be modelled in OntoLex-Lemon in a generic way using the LexicographicComponent class of the lexicographic module of OntoLex-Lemon.[20] We discuss previous approaches to specifying temporal precedence between senses below in Section 3.2. Work on the Frequency, Attestation and Corpus Information module for OntoLex-Lemon is currently underway within the W3C group of the Ontology Lexicon Group (Chiarcos et al. 2020); the module is currently in its final draft[21] and is due to be published this year (we therefore foresee at most only very minor changes to the following description). This module, when published, will allow for the encoding of corpus-related information into lexicons, as well as making special provision for modelling (information relating to) word embeddings (using the Embedding class and the embedding relation). Attestations of the sense of a word will, in conformity with the other parts of OntoLex-Lemon, pertain to OntoLex-Lemon Lexical Sense elements. The FrAC model allows for the association of a sense with a location in a corpus (using the locus property). Dating information associated with the metadata for the corpus can then be used to help locate a sense in time, as was proposed by Khan and Bowers (2020). None of the latest developments in the FrAC module are incompatible with IOM, and we can easily extend IOM with the corresponding classes and properties. More broadly speaking, the purpose of this whole discussion has been to show that the OntoLex-Lemon model is compatible with the IOM in its treatment of word meaning.[22] We will therefore use it as a basis for the serialisation of examples into RDF below.[23]

3.2. Previous Work in Semantic/Conceptual Change in RDF

3.2.1. The Limitations of RDF

There are a number of (well-known) advantages to publishing resources as linked data.[24] At the same time, however, linked data is not without some rather significant limitations. One of the most important of these relates to the fact that in order to ensure that datasets are as interoperable as possible, linked data best practises recommend the use of a common underlying formal language, RDF, which limits users to unary and binary predicates to describe data. Indeed, RDF datasets essentially consist of a series of subject–predicate–object triples, which, taken together, describe the content (or meaning) of the data:

$$(s_0, p_0, o_0), (s_1, p_1, o_1), \ldots, (s_n, p_n, o_n).$$

So, we are effectively limited to making statements that can be expressed in the forms $C(x)$ and $R(y,z)$, where C is a unary relation, R is a binary relation, and x, y, z are variables belonging to a set of individuals. RDF doesn't allow us to (directly) add a temporal parameter to the relationship between a word and its senses and include three-place relations in our data such as $Sense(w, s, t)$. There are several strategies to get around this limitation (we will see a four-dimensionalist one in Section 5.1).

3.2.2. Semantic Change, Etymologies, and Beyond

Moving on to work on semantic change, there have been some recent attempts at automatically detecting semantic change both in large corpora (see Tahmasebi et al. 2018) and in Semantic Web ontologies and vocabularies. In the latter category, we can mention Wang et al. (2011), who referenced both intensional and extensional changes, although the modifier 'intensional' there is understood somewhat differently from the current work. Fokkens et al. (2016), influenced by Wang et al. (2011), propose an RDF modelling of concept drift that is based on *lemon*, the predecessor of OntoLex-Lemon, with the addition of contexts to RDF graphs in order to model temporal information. However, their article does not go into much detail as to their more general approach to handling conceptual changes in RDF. Proposals for the use of OntoLex-Lemon to model semantic change, and diachronic data more generally, have largely taken place in the context of the modelling of etymologies as linked data. Previous work in this line includes Moran and Bruemmer (2013) and Chiarcos et al. (2016). In the latter, the authors defined an extension of *lemon* (the predecessor of OntoLex-Lemon) with two new properties: etymological cognate and the transitive derivedFrom. However, a more extensive modelling strategy for modelling semantic change in etymologies using OntoLex-Lemon was given by Khan (2018). In this case, a vocabulary was defined, *lemonEty*, (a version of which can be found on github[25]), which provides classes and properties for specifying an etymological link (EtyLink) between two elements of an OntoLex-Lemon lexicon, one of which is the source (which we specify by etySource), and the other is the target of the etymological link (etyTarget). We can therefore use EtyLink to define etymological relationships between two senses, potentially subtyping this link for the kind of etymological relationship involved, e.g., in the case where one sense is derived from another through a metaphorical or metonynmic semantic shift. Once again, this is compatible with the IOM approach. The *lemonEty* vocabulary was used in the Linking Latin Project (LiLa)[26] to encode etymologies from De Vaan's *Etymological Dictionary of Latin and the Other Italic Languages* (Mambrini and Passarotti 2020) and to link them to the LiLa knowledge base. In the work of Khan (2020), the approach taken by Khan (2018) is further extended using a four-dimensionalist strategy (see Section 5.1 for an explanation of what such a strategy entails). Khan (2020) shows how both quantitative temporal information (containing dates or specific centuries, years, or millennia) along with qualitative temporal information (descriptions containing intervals more vaguely defined, e.g., the period during which Old English was spoken) can be used to define and even to reason about the relationships of temporal precedence between senses in a lexico-ontological resource as well as when senses overlap or coexist, using so called Allen relations. In addition, the approach described by Khan (2020) also allows us to represent temporal part-hood relations between senses since we associate them directly with their histories. We present more details about four-dimensionalism and describe an approach for associating temporal information to senses in Section 5.

In Section 4.1 we encode a number of sense shift examples into RDF using OntoLex-Lemon using the class SemanticShift and the properties senseShiftsTo, shiftSource, and shiftTarget from Khan (2020). They are defined as follows:

- SemanticShift represents instances of semantic shift f relating together two instances of LexicalSense, s_0 and s_1, where the former is the source of the shift, and the latter is the target;
- shiftSource is an object property that has as its domain the class SemanticShift and its range LexicalSense and relates together an instance of the semantic shift with its source, i.e., $shiftSource(f, s_0)$;
- The object property shiftTarget has as its domain the class SemanticShift and its range LexicalSense and relates together an instance of the semantic shift with its target, i.e., $shiftTarget(f, s_0)$;
- The object property senseShiftsTo has LexicalSense as its domain and range and holds between two senses to represent that the latter derives from the former due to some kind of etymological process. The property senseShiftsTo is equivalent to the following property chain:

  shiftSource o shiftTarget .

Note that the current work focuses on RDF as a format and takes its expressive limitations as a formalism into consideration in the proposal of an approach for representing dynamic data. However, recently, promising work has been carried out on the use of other knowledge-based graph technologies, such as GraphBRAIN in representing and reasoning about semantic change (McGillivray et al. 2023). This latter approach has its own advantages in terms of more efficient reasoning capabilities, but lacks the high levels of interoperabilty that are offered by RDF.

4. Using IOM to Model Semantic Change in Case of Conceptual Evolution

In the current section, we will show how to extend the basic account of word meaning in the IOM in order to model how a *concept* evolves in ways that changes the meaning of terms in a lexicon. This is a use case that raises a lot of interesting questions which is why we focus on it here. Broadly speaking, such cases can be modelled as follows within the IOM framework:

i By making the lexicon *dynamic* while keeping the ontology static[27] **(ontology as static pivot)**;

ii By making *both* the lexicon and the ontology *dynamic* **(dynamic ontology)**.

To see what these strategies might look like in practice, we will take the example of the taxonomic classification of whales. As is well known, despite being mammals whales were originally classed as a species of fish, due to their appearance and aquatic habitat—and were even regarded as such by Linnaeus himself (although he subsequently changed his mind[28]). Thanks to the rapid growth of zoology as a scientific field during the 19th century, however, the English word *whale*—which had started off 'referring' to a kind of fish—began to 'refer' to a kind of mammal. Granted that, at first, this shift was limited to the scientific literature; however, it soon became part of general knowledge.

Given a lexico-ontological resource and given approach (ii) above (the dynamic ontology approach), we could model this example with two so-called snapshot lexico-ontologies.[29] The first of these would represent a pre-19th century state of taxonomical knowledge in which the lexicon would contain, say, words from English in the early modern period and a corresponding ontology representing an early modern understanding of concepts such as Fish, Mammal, and Whale. The second lexico-ontology snapshot, on the other hand, would represent contemporary usage with a lexico-ontology in which the ontology part encompasses an up-to-date taxonomy of relevant kinds of flora and fauna. These two different lexico-ontological snapshots could then be related together with an ontology evolution/change approach such as that described by Kauppinen and Hyvönen (2007). This solution is attractive because it allows us to model the way the meaning of the word *whale* has changed, but at the same time, it also enables us to describe the way in which relevant concepts such as Whale and Fish have changed as well. Figure 2 shows a diagrammatic representation of this use case. Here, we have two lexico-ontological resources: LO_1, representing a description of the pre-modern meaning of the word *whale*, and LO_2, representing a description of the contemporary meaning of the word.

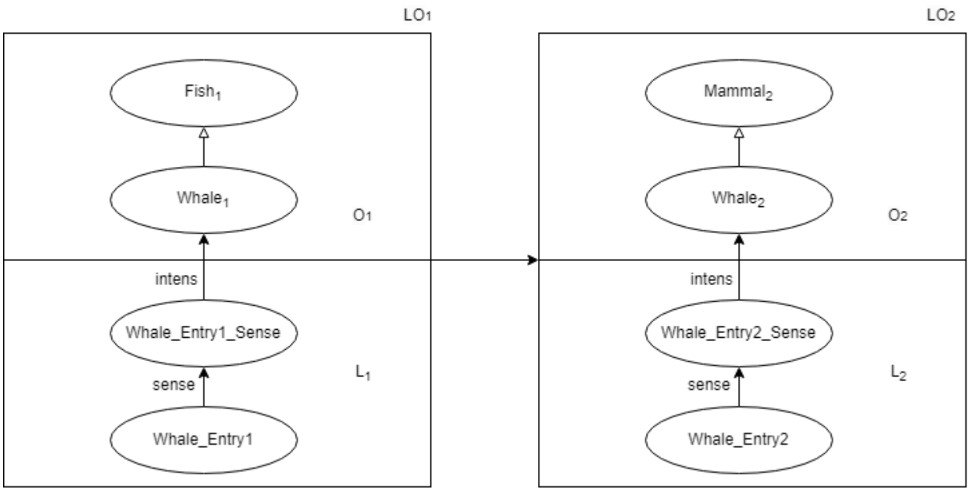

Figure 2. The snapshot approach.

Approach (i), on the other hand, the ontology-as-static-pivot approach, suggests a less prolix and less granular solution in which changes in the intensions of words (that is, senses as intensions) are described using a (static) *core* ontology that represents a fixed inventory of concepts (we call this *a pivot ontology* in the following), with the possibility of defining additional ontology concepts with the role of representing senses as intensions. Taking advantage of ontological modularity, we can specify these additional concepts as belonging to another ontological module separate from our core ontology, with this latter core ontology taking on the status of a repository of fixed, fundamental concepts. This modular approach allows us to reason with ontological concepts corresponding to senses as intensions as well as to model cases where different languages refer to the same concept, and at the same time to maintain a separation between the purely linguistic and the language-independent aspects of word meaning. Returning to our whale example, using this approach we could represent the pre-modern meaning of the word *whale* with a sense which points, by means of the OntoLex-Lemon property reference (or some other similar property), to the concept Fish, and the modern meaning with a sense which points, again via reference to the concept Whale (a subclass of the concept Mammal): with the concepts Fish and Mammal described using a modern day (zoologically accurate) taxonomy.

Staying with approach (i) in its modular form, we might even decide to create an ontological concept that encapsulates the (sense as) intension of the pre-19th century sense of the word *whale* (we could call it Whale-as-Fish but the name of the concept does not matter, whereas its interrelations with other concepts do). This concept describes such animals as having a particular internal structure and other characteristics more usually associated with mammals while still being classified as a fish. Here, the relevant characteristics would be described using concepts and terms conceived according to contemporary (and not pre-19th century) scientific knowledge. In the case of *whale*, this means that the intension of the non-contemporary sense would have a corresponding extension that was the empty set (since, according to current scientific knowledge, a sufficiently detailed version of the pre-19th century definition holds no single individual). However, since we use the ontology as a means of describing the intension of a word sense (and not the *extension*, at least according to the description given in Section 2.4), we do not need to directly link the sense in question to the empty set, although this could be part of the ABox of the ontology.

We represent our whale example in diagrammatic form in Figure 3; our architecture consists of two lexicons (one pre-modern and one modern) and one ontology with two modules (a core pivot component, O_P, and a module dedicated to describing the intensions of words, O_S). That is, our lexico-ontological resource contains one single shared ontology between two lexicons, each of which represents two contiguous stages in the history of a word. Below we present an RDF listing of the same example using the OntoLex-Lemon vocabulary.

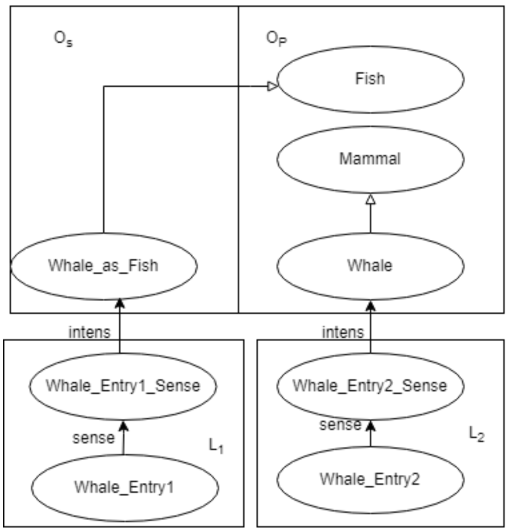

Figure 3. The pivot approach.

We can make the following observations here. The first is that although the ontology part of our lexico-ontological resource is indeed less prolix in in approach (i) than in the previous approach—since we do not need separate concepts corresponding to different stages in the evolution of the concept of Fish and Mammal in each of the separate lexico-ontological resources—we have introduced a spurious concept into that ontology, Whale-as-Fish, which we would not find in any (self-respecting) contemporary zoologically accurate taxonomy. This concept moreover, fails to correspond to anything in the world—even if, in fairness, it is not included in the 'core' module of this ontological resource, O_P, the part that is supposed to reflect (a contemporary view of) reality. We can respond to this as follows. First of all, the ontology, taken as a whole, is intended as part of a description of the semantics of the words in the lexicon and not as a description of the world per se (although part of the ontology, O_P, in our case is so intended). Moreover, the idea that ontologies[30] are simply objective descriptions of the world, or rather inventories of what *exists in the universe*, does not accord with the standard definition of them as shared conceptualisations of one or more domains, or with the formal elaboration of that definition given by Guarino et al. (2009). It is thus legitimate, from this point of view, to include concepts in an ontology that serve only to provide a formal description of the intensions of a word —especially since such concepts are often language independent, e.g., *baleine* and *Wal* also referred to kinds of fish at more or less the same period in which *whale* did. Given a lexico-ontological resource, the kind of resource that models like OntoLex-Lemon assume, it is hard to see where else to add this information. It might be that we need a more sophisticated conceptual architecture in order to model word meanings using ontologies, but a more complicated architecture (with different kinds of relationships between different ontologies and/or other kinds of semantic artifacts) would struggle to find the level of consensus among users as OntoLex-Lemon has (Listing 2).

Listing 2. Ontolex-Lemon example in Turtle.

```
## Op ontology
Op:Whale rdfs:subClassOf Op:Mammal .
Op:Whale rdf:type owl:NamedIndividual .

## Os ontology
Op:Whale_as_Fish rdfs:subClassOf Op:Fish .
Os:Whale_as_Fish rdf:type owl:NamedIndividual .

## L1 lexicon
L1:Whale_Entry1 rdf:type ontolex:LexicalEntry ;
    ontolex:sense L1:Whale_Entry1_Sense .
L1:Whale_Entry1_Sense rdf:type ontolex:LexicalSense ;
    ontolex:reference Os:Whale_as_Fish .

## L2 lexicon
L2:Whale_Entry2 rdf:type ontolex:LexicalEntry ;
    ontolex:sense L2:Whale_Entry1_Sense .
L2:Whale_Entry2_Sense rdf:type ontolex:LexicalSense ;
    ontolex:reference Op:Whale .
```

At the end of the day, either one of these two approaches to modelling meaning, (i) or (ii), may be more or less appropriate depending on the particular use case and/or the particular research questions concerned. The dynamic ontology approach, (ii), is probably more suited to fine-grained studies on conceptual changes within a cluster of related concepts in a given semantic field as well as more generally in scenarios in which we are interested in focusing both on the details of conceptual change (allowing us to provide a much more detailed account of this process itself) and how this affects language. On the other hand, a study that focuses largely on the linguistic aspect is likely to be more efficiently modelled using the ontology-as-static-pivot approach, especially since in this approach, we are not obliged to simultaneously model how ontological concepts or senses have evolved. Approach (i) would suit the kind of model of conceptual change proposed by Kuukkanen (2008), in which concepts have cores ('something that all instantiations must satisfy in order to be the "same concept"') and margins ('all the rest of the beliefs that an instantiation [of a concept] might have'). The definition of both core and margin could make use of a fixed pivot ontology. Take, for instance, Kuukkanen's example of 'element', where the core sense of the term can be described as follows: 'if X is an element, then it is a material and indecomposable body'. Assume, for instance, that our pivot ontology includes an ontological concept ElementCore, which is the intersection (say) of two other concepts in our ontology, MaterialBody and IndecomposableBody (corresponding to the descriptions in the definition of 'element'). Then, each appropriate sense of 'element' can be described using a number of different subclasses of ElementCore, which add to the description of this intension with 'marginal' details.

In closing this discussion, it is important to note that the clarifications offered by the IOM model at the theoretical level can ultimately help us to work out the consequences of various different lexical/ontological design decisions in terms of the *meaning* of our data. We are better able to put our cards on the table, so to speak, and justify our conceptual modelling decisions in detail, even those that seem controversial at first—indeed, especially those that seem controversial at first. On the other hand, current documentation relating to OntoLex-Lemon leaves too many things underspecified with regard to these issues.

4.1. Latin Examples

To show how this approach can put into practice, and demonstrate how salient it can be even in use cases which seem to be fairly simple, we will look at the encoding in RDF of a small number of Latin lexical terms notable for having undergone sense shift during the onset and consequent spread of Christianity in the Roman world. These terms are listed in Table 1 along with a gloss of an original pre-Christian sense and a subsequent Christian era one; in certain instances, a note provides additional details on the sense shift in question. The examples themselves are taken from McGillivray et al. (2022) which presents a study on the manual annotation of these words and others in a Latin corpus. The changes in the meanings of the words listed in Table 1 are due either to the introduction of new concepts thanks to the influence of Christianity (see, e.g., *potestas*, *scriptura*, and *uirtus*) or shifts in already existing concepts as a result of other kinds of societal and cultural change (see, e.g., *ciuitas*, *cohors*, and *consul*). In this case, the various different ontological distinctions adopted during each time period are clearly relevant to the description of the semantics of the words themselves. We can adopt a pivot approach using one single ontology to describe all these meaning shifts, in case we do not want to explicitly model how the ontological concepts themselves changed or came into being. A dynamic alternative would be to use two different ontologies, a pre-Christian one and a Christian-era one, to track how the conceptual schemes assumed by the two consecutive historical periods changed.

Table 1. Latin sense shifts.

Lemma	First Sense	Second Sense	Note
ciuitas	citizenship	city	Metonymy. Second meaning became more common in Middle Ages.
cohors	cohort	imperial court	Generalisation, then narrowing.
consul	consul	municipal official	Not Christian.
dolus	deceit	pain	
dux	leader	duke	Narrowing. Early medieval period.
humanitas	humanity	benevolence	
imperator	general	emperor	
potestas	power	angel	Christian. Direct translation of the Greek.
scriptura	writing	Holy Scripture	Christian. Not used in reference to holy texts prior to Christianity. Influenced by Greek.
uirtus	manliness	Christian virtues	

In the following listing, we take a IOM pivot approach using the OntoLex-Lemon vocabulary, to which we add a number of relations and classes to model semantic shifts themselves, taken from Khan (2020), and described in detail in Section 3.2.2. These include the class SemanticShift; the properties senseShiftsTo, shiftSource and shiftTarget. Below, we present a listing of the first of these lexical entries, with senses linked to DBpedia[31] entries (our static ontology in this instance) (Listing 3).

Listing 3. Ontolex-Lemon example in turtle.

```
ex:entry_ciuitas rdf:type ontolex:LexicalEntry ;
    lexinfo:partOfSpeech <http://www.lexinfo.net/ontology/2.0/lexinfo#noun> ;
    ontolex:canonicalForm ex:lemma_ciuitas ;
    ontolex:sense ex:sense_ciuitas_1, ex:sense_ciuitas_2 .
ex:lemma_ciuitas rdf:type ontolex:Form ;
    ontolex:writtenRep "ciuitas"@la .
ex:sense_ciuitas_1 rdf:type ontolex:LexicalSense ;
    skos:definition "citizenship"@en ;
    ontolex:reference <https://dbpedia.org/resource/Citizenship> ;
    ex:senseShiftsTo ex:sense_ciuitas_2 .
ex:sense_ciuitas_2 rdf:type ontolex:LexicalSense ;
    skos:definition "city"@en .
ex:shift_ciuitas rdf:type ex:senseShift ;
    rdfs:comment "Second␣meaning␣became␣more␣common␣in␣Middle␣Ages" ;
    ex:shiftSource ex:sense_ciuitas_1 ;
    ex:shiftTarget ex:sense_ciuitas_2 .
```

Note that in the Appendix A to this article, we provide an encoding of all of the entries in the table. We can make a number of observations here. First of all, semantic shift data do not always necessarily include a lot of qualitative temporal information; in the use case above we are dealing with references to time periods that aren't defined in terms of fixed dates, that is quantitively, but rather *qualitatively*. In the next section, we will indeed look at how to work with explicit temporal information (and more generally, how to reason with qualitative time periods), but often, as in this case, this kind of information is not available. The second observation is that the pivot approach helps to explain and motivate the use of one static ontology in cases like the current one for describing the meanings of the words, even though concepts they referred to like Citizenship and City were also changing over time—and all of this in a straightforward example where we do not have to deal with, e.g., multiple etymologies and the interaction of different kinds of linguistic description. This use case therefore highlights the importance of clarifying the meaning of semantic shift data when modelling it as linked data.

5. Explicitly Representing Time in Conceptual Change

Let us go further then and look at how to add quantitative temporal information to semantic shift data within the IOM framework—taking advantage of the (relative) clarity offered by working within the framework as to what such data *means*. In the following, we will adopt approach (i) and assume a static pivot ontology since this will make everything simpler to work with. In other words we make the (simplifying) assumption that the concepts in our ontology (including senses as intensions) are static, and, therefore, do not change over time; whereas the lexical senses of a word (that is, senses as use descriptions) potentially do, and can therefore take on temporal parameters. This means that temporal information is only (directly) associated with the lexicon in a lexico-ontological resource. (In future work, we plan to look in more detail at how to work with dynamic ontologies.) With this in mind, let us revisit the two scenarios previously described in Section 2.1; this time, however, we will add temporal parameters:

1. In the dynamic version of Scenario 1, we wish to formally describe how a concept c in our ontology $\mathcal{O}$ is lexicalised over time using words in a lexicon $\mathcal{L}$ for the language *lan* (again, this can be easily extended to more than one language). So, for instance, this could be a concept like Element or Democracy (in our pivot ontology) that has different sub-concepts, $c_1,\ldots,c_n$ (with these representing Kuukkanen's core and margin, respectively). In this dynamic version, we add time as a parameter in order to allow us to enumerate, for a specific time period, t, all of the lexical entries, or rather the lexical senses, that referred to c during t.
2. In the dynamic version of the second scenario, given a specific word (or lexical sense) we wish to retrieve all pof the different concepts that it referred to over a given time period t (focusing on the concepts in a pivot ontology). Again, in this scenario, we could assume a fixed core concept c and look at how the marginal concepts changed.

Both scenarios require us to express the fact that a lexical entry l has a lexical sense s_1 during the interval t_1, and a lexical sense s_2 during the interval t_2. This means that the *sense* relation here is a *fluent*, or rather a *tensed relation*, a relation that can potentially hold at some times (or some time intervals) and not at others. Unfortunately, for the reasons mentioned in Section 3.2.1, we cannot simply add time as a parameter to RDF properties such as sense. There are a number of solutions, or rather design patterns, intended to overcome this expressive limitation and that allow us to remain within the expressive constraints of RDF; see Garbacz and Trypuz (2017) (we do not look at extensions to the RDF model that go beyond these constraints here since in our opinion none of these have yet achieved wide enough consensus). In the rest of this article, we will take a perdurantist approach and look at specifically perdurantist design patterns for representing tensed or temporally indexed relations using the IOM model and the static pivot approach to lexico-ontological resources, rather than an endurantist approach. We discuss this choice in more detail in Section 5.1.

5.1. Endurantism vs. Perdurantism

Before we discuss our proposal for explicitly representing time in semantic change data using the IOM model, it will be useful to briefly discuss two of the most well-known ways of modelling dynamic information in the fields of ontology engineering and conceptual modelling. These two approaches are based on a philosophically founded distinction with regard to how things exist in time, namely, the distinction between some entity either enduring or, instead, perduring through time (Effingham 2012). From the point of view of common sense, we regard 'concrete' entities such as persons, buildings, and planets as endurants, that is, as things that *endure* through time. In effect, this means that such entities retain a single identity through their lifetimes, and this identity is 'wholly present' at every moment of those respective lifetimes (even though certain so-called 'accidental' properties will change during that same interval). On the other hand, events such as barbecues, wars, and supernovae are viewed as entities that *perdure* through time or perdurants. Such perdurants are composed of temporal parts in much the same way as concrete, physical entities are composed of physical parts. Unlike endurants it is not the whole, but only a temporal part (or parts) of the whole that exists during any given interval of time.

Notwithstanding the intuitive appeal of the distinction between endurants and perdurants, there exist several ontology modelling approaches, so-called perdurantist approaches, that handle dynamic information by modelling entities that are normally considered endurants as perdurants—or, as has been famously described, by modelling everything as *four-dimensional space time worms*. An account of the philosophical merits of perdurantism, or four-dimensionalism as it is often known, including how it facilitates the modelling of vagueness (along with several other kinds of phenomena that have been brought to light over the last hundred years or so of fundamental research in physics), can be found in the work of Sider (1997). What is notable for our purposes here is the fact that perdurantism is becoming an increasingly popular way of approaching the modelling of dynamic data using linked data formalisms such as RDF and OWL. One major reason for this (aside from the philosophical advantages alluded to above) is that it helps to resolve the expressive limitations of RDF semantically rather than syntactically (Welty et al. 2006). In fact, a number of different perdurantist approaches have been suggested for representing dynamic data in RDF; we will look at three of these in the following in order to showcase our dynamic IOM approach within a standard RDF setting.

The first approach we will look at is the Welty–Fikes perdurantist pattern as introduced by Welty et al. (2006), probably the earliest and most influential such approach in the context of OWL ontology modelling. In this pattern, fluents/tensed binary relations hold between temporal parts of entities and not the entities themselves. That is if $R \subseteq D \times G \times T$ is a fluent that relates together elements from a domain D and a range G during a time interval taken from T, then, under this pattern, R can be remodelled as a binary relation R' between temporal parts of elements from D and G, respectively. This pattern has the advantage that we can continue to describe properties, such as functionality, symmetry, reflexivity, etc., using standard OWL constructs as well as standard off-the-shelf OWL reasoning tools. In terms of our running example, this means that we no longer use the OntoLex-Lemon property sense but must define a new property 4dsense that holds between two temporal parts or slices. In this case, we can use the 4dFluents ontology proposed, once again, in Welty et al. (2006).

The definition of 4dsense is as in Listing 4.

Listing 4. Definition of 4dsense.

```
ObjectProperty: 4dsense
Domain: 4dFluents:temporalPartOf only ontolex:LexicalEntry
Range: 4dFluents:temporalPartOf only ontolex:LexicalSense
```

The range is restricted to temporal parts of lexical entries, and the domain is restricted to temporal parts of lexical senses. We can then model the example mentioned above as in Listing 5.

Listing 5. Modelling of example.

```
Individual: lex1@t1
Types: 4dFluents:TemporalPart
Facts: 4dFluents:temporalPartOf lex1,
       4dsense sense1@t1

Individual: lex1@t2
Types: 4dFluents:TemporalPart
Facts: 4dFluents:temporalPartOf lex1,
       4dsense sense1@t2

Individual: sense1@t1
Types: 4dFluents:TemporalPart
Facts: 4dFluents:temporalPartOf sense1

Individual: sense2@t2
Types: 4dFluents:TemporalPart
Facts: 4dFluents:temporalPartOf sense2
```

This pattern has the disadvantage that it requires us to re-define all our fluent properties so that they now hold between suitable subclasses of the class of temporal parts. A further simplification to Welty/Fikes was proposed by Krieger (2010); this can be encapsulated by the slogan "what has been an entity becomes a time slice". That is, in the Krieger pattern, the fluent property $R \subseteq D \times G \times T$ has the signature $R \subseteq D \times G$, where the elements of classes D and G, which are redefined as subclasses of the class Perdurant, can have temporal parts that also belong to the classes D and G, respectively. We can then relate these elements with their subparts with the object property hasTimeSlice. In the Krieger pattern, a timeslice describes a specific bundle of properties of a perdurant that remains constant over a given time interval (See Listing 6).

Listing 6. Definitions.

```
Class: Perdurant
Class: TimeSlice

ObjectProperty: hasTimeSlice
Domain: Perdurant
Range: TimeSlice

ObjectProperty: timeSliceOf
Domain: TimeSlice
Range: Perdurant

ObjectProperty: hasTime
Domain: TimeSlice
Range: owl:Time
```

We can then represent our running example as in Figure 4 and Listing 7 (having specified that LexicalEntry and LexicalSense are both subclasses of Perdurant).

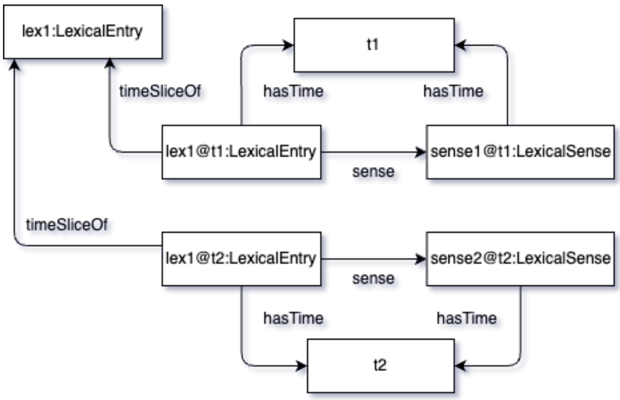

Figure 4. Running example.

Listing 7. Running example.

```
Class: ontolex:LexicalEntry
    SubClassOf: Perdurant
Class: ontolex:LexicalSense
    SubClassOf: Perdurant

Individual: lex1@t1
Types: ontolex:LexicalEntry
Facts: timeSliceOf lex1,
        ontolex:sense sense1@t1,
        hasTime t1

Individual: lex1@t2
Types: ontolex:LexicalEntry
Facts: timeSliceOf lex1,
        ontolex:sense sense1@t2,
        hasTime t2

Individual: sense1@t1
Types: ontolex:LexicalSense
Facts: timeSliceOf sense1,
        hasTime t1

Individual: sense2@t2
Types: ontolex:LexicalSense
Facts: timeSliceOf sense2,
        hasTime t2
```

We can simplify this even further by allowing perdurants to have temporal extents (rather than just timeslices). Lexical senses are dependent on their lexical entries in the sense that the former exist as long as the latter do; in fact, this is an assumption that is made in OntoLex-Lemon and that we follow, and it also implies that a sense cannot be shared between lexical entries (although in the case of perdurant lexical entries, we have to be careful, since two lexical entries in a temporal parthood relation will share senses). This allows us to simplify the example further by relating lex1 directly to sense1 and sense, see Figure 5.

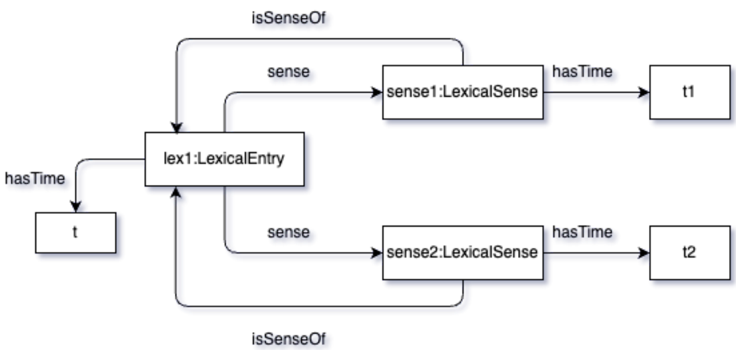

Figure 5. Simplified example.

This last strategy has been followed by Khan and Bowers (2020) for modelling dynamic linguistic data allowing for the easy addition of information about time periods and the definition different kinds of temporal relationships between senses. For instance, in the case of our Latin examples, following this approach we would define pre-Christian and Christian time periods and relating them to individual senses as perdurants.

Our intention in this section has been to describe some perdurantist strategies that, when taken together with the IOM model, allow for the detailed representation of the dynamic semasiological and onomasiological scenarios in Section 5. In this case, we modelled semantic changes in a lexico-ontological resource by modelling lexical senses in a lexicon as perdurants while keeping the ontology static.

6. Conclusions

In this article, we have proposed a new approach to modelling conceptual and semantic shift in linked data lexico-semantic resources using a new conceptual framework, the Intensional–Ontological Model (IOM). The IOM takes two different aspects of the meaning of a word into consideration, those pertaining to senses as intensions and those pertaining to senses as theoretical entities describing the usage of words. We also looked at how the IOM can help us to clearly describe different approaches to modelling conceptual and semantic changes. Finally, we showed how, by taking a perdurantist approach, we can use the IOM to model time to describe instances of semantic change.

In future work, we plan to publish a series of Ontology Design Patterns (ODPs) based on IOM to cover different lexico-semantic use cases. ODPs are intended to provide standard modelling solutions for recurrent problems in ontology design. The concept itself is based on previous work on pattern-based designs in software engineering, and the concept is intended to help make knowledge bases more reusable. ODPs can be classified into a number of types (Presutti et al. 2012). These include **logical ODPs**, namely, design patterns that deal with limitations in the expressivity of formal languages such as OWL; **architectural ODPs**, which are compositions of logical ODPs; **reasoning ODPs** that focus on automated inference; and, finally, **content ODPs**, which deal with domain-specific problems (a full list is provided by Presutti et al. 2012). Moreover, there exist specialised languages for ODPs too, notably OTTR (Skjæveland et al. 2018). Our intention in terms of further work is to produce content ODPs based on the IOM, both for static and dynamic cases, following both the pivot and dynamic ontology approaches, as well as those including explicit temporal information—and to implement these using OTTR. These patterns will also be incorporated into a series of guidelines and best practises, which we also plan on compiling for working with semantic shift data.

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Abbreviations

The following abbreviations are used in this manuscript:

IOM	Intensional–Ontological Meaning
ODP	Ontology Design Pattern
RDF	Resource Description Framework
SPARQL	SPARQL Protocol and RDF Query Language
OTTR	Reasonable Ontology Templates
OWL	Web Ontology Language

Appendix A

The following listing (Listing A1) presents a full encoding of the examples given in Table 1. Each row has been converted into an OntoLex-Lemon LexicalEntry, associated with a part of speech from the lexinfo vocabulary[32], a lemma form via the OntoLex-Lemon property canonicalForm, and with its two senses via sense. Each of these two senses are related together through an individual of the type senseShift and the properties shiftSource and shiftTarget; all of these vocabulary items are described above.

Listing A1. Full Ontolex example in turtle.

```
ex:entry_ciuitas rdf:type ontolex:LexicalEntry ;
    lexinfo:partOfSpeech <http://www.lexinfo.net/ontology/2.0/lexinfo#noun> ;
    ontolex:canonicalForm ex:lemma_ciuitas ;
    ontolex:sense ex:sense_ciuitas_1, ex:sense_ciuitas_2 .
ex:lemma_ciuitas rdf:type ontolex:Form ;
    ontolex:writtenRep "ciuitas"@la .
ex:sense_ciuitas_1 rdf:type ontolex:LexicalSense ;
    skos:definition "citizenship"@en ;
    ontolex:reference <https://dbpedia.org/resource/Citizenship> ;
    ex:senseShiftsTo ex:sense_ciuitas_2 .
ex:sense_ciuitas_2 rdf:type ontolex:LexicalSense ;
    skos:definition "city"@en .
ex:shift_ciuitas rdf:type ex:senseShift ;
    rdfs:comment "Second␣meaning␣became␣more␣common␣in␣Middle␣Ages" ;
    ex:shiftSource ex:sense_ciuitas_1 ;
    ex:shiftTarget ex:sense_ciuitas_2 .

ex:entry_cohors rdf:type ontolex:LexicalEntry ;
    lexinfo:partOfSpeech <http://www.lexinfo.net/ontology/2.0/lexinfo#noun> ;
    ontolex:canonicalForm ex:lemma_cohors ;
    ontolex:sense ex:sense_cohors_1, ex:sense_cohors_2 .
ex:lemma_cohors rdf:type ontolex:Form ;
    ontolex:writtenRep "cohors"@la .
ex:sense_cohors_1 rdf:type ontolex:LexicalSense ;
    skos:definition "cohort"@en ;
    ontolex:reference <https://dbpedia.org/ontology/cohort> ;
    ex:senseShiftsTo ex:sense_cohors_2 .
ex:sense_cohors_2 rdf:type ontolex:LexicalSense ;
    skos:definition "imperial␣court"@en .
ex:shift_cohors rdf:type ex:senseShift ;
    rdfs:comment "Generalisation,␣then␣Narrowing" ;
    ex:shiftSource ex:sense_cohors_1 ;
    ex:shiftTarget ex:sense_cohors_2 .

ex:entry_consul rdf:type ontolex:LexicalEntry ;
    lexinfo:partOfSpeech <http://www.lexinfo.net/ontology/2.0/lexinfo#noun> ;
    ontolex:canonicalForm ex:lemma_consul ;
    ontolex:sense ex:sense_consul_1, ex:sense_consul_2 .
ex:lemma_consul rdf:type ontolex:Form ;
    ontolex:writtenRep "consul"@la .
ex:sense_consul_1 rdf:type ontolex:LexicalSense ;
    skos:definition "consul"@en ;
    ontolex:reference <https://dbpedia.org/ontology/consul> ;
    ex:senseShiftsTo ex:sense_consul_2 .
ex:sense_consul_2 rdf:type ontolex:LexicalSense ;
    skos:definition "municipal␣official"@en .
ex:shift_consul rdf:type ex:senseShift ;
    ex:shiftSource ex:sense_consul_1 ;
    ex:shiftTarget ex:sense_consul_2 .

ex:entry_dolus rdf:type ontolex:LexicalEntry ;
    lexinfo:partOfSpeech <http://www.lexinfo.net/ontology/2.0/lexinfo#noun> ;
    ontolex:canonicalForm ex:lemma_dolus ;
```

```
    ontolex:sense ex:sense_dolus_1, ex:sense_dolus_2 .
ex:lemma_dolus rdf:type ontolex:Form ;
    ontolex:writtenRep "dolus"@la .
ex:sense_dolus_1 rdf:type ontolex:LexicalSense ;
    skos:definition "deceit"@en ;
    ontolex:reference <https://dbpedia.org/resource/Deception> ;
    ex:senseShiftsTo ex:sense_dolus_2 .
ex:sense_dolus_2 rdf:type ontolex:LexicalSense ;
    skos:definition "pain"@en .
ex:shift_dolus rdf:type ex:senseShift ;
    rdfs:comment "Not␣Christian.␣Similar␣change␣to␣iter..." ;
    ex:shiftSource ex:sense_dolus_1 ;
    ex:shiftTarget ex:sense_dolus_2 .

ex:entry_dux rdf:type ontolex:LexicalEntry ;
    lexinfo:partOfSpeech <http://www.lexinfo.net/ontology/2.0/lexinfo#noun> ;
    ontolex:canonicalForm ex:lemma_dux ;
    ontolex:sense ex:sense_dux_1, ex:sense_dux_2 .
ex:lemma_dux rdf:type ontolex:Form ;
    ontolex:writtenRep "dux"@la .
ex:sense_dux_1 rdf:type ontolex:LexicalSense ;
    skos:definition "leader"@en ;
    ontolex:reference <https://dbpedia.org/resource/Leadership> ;
    ex:senseShiftsTo ex:sense_dux_2 .
ex:sense_dux_2 rdf:type ontolex:LexicalSense ;
    skos:definition "duke"@en .
ex:shift_dux rdf:type ex:senseShift ;
    rdfs:comment "Early␣Medieval␣Period" ;
    ex:shiftSource ex:sense_dux_1 ;
    ex:shiftTarget ex:sense_dux_2 .

ex:entry_humanitas rdf:type ontolex:LexicalEntry ;
    lexinfo:partOfSpeech <http://www.lexinfo.net/ontology/2.0/lexinfo#noun> ;
    ontolex:canonicalForm ex:lemma_humanitas ;
    ontolex:sense ex:sense_humanitas_1, ex:sense_humanitas_2 .
ex:lemma_humanitas rdf:type ontolex:Form ;
    ontolex:writtenRep "humanitas"@la .
ex:sense_humanitas_1 rdf:type ontolex:LexicalSense ;
    skos:definition "humanity"@en ;
    ontolex:reference <https://dbpedia.org/resource/Human> ;
    ex:senseShiftsTo ex:sense_humanitas_2 .
ex:shift_humanitas rdf:type ex:senseShift ;
    ex:shiftSource ex:sense_humanitas_1 ;
    ex:shiftTarget ex:sense_humanitas_2 .
ex:sense_humanitas_2 rdf:type ontolex:LexicalSense ;
    skos:definition "benevolence"@en .


ex:entry_imperator rdf:type ontolex:LexicalEntry ;
    lexinfo:partOfSpeech <http://www.lexinfo.net/ontology/2.0/lexinfo#noun> ;
    ontolex:canonicalForm ex:lemma_imperator ;
    ontolex:sense ex:sense_imperator_1, ex:sense_imperator_2 .
ex:lemma_imperator rdf:type ontolex:Form ;
    ontolex:writtenRep "imperator"@la .
ex:sense_imperator_1 rdf:type ontolex:LexicalSense ;
    skos:definition "general"@en ;
    ontolex:reference <https://dbpedia.org/resource/General> ;
    ex:senseShiftsTo ex:sense_imperator_2 .
ex:sense_imperator_2 rdf:type ontolex:LexicalSense ;
    skos:definition "emperor"@en .
ex:shift_imperator rdf:type ex:senseShift ;
    ex:shiftSource ex:sense_imperator_1 ;
    ex:shiftTarget ex:sense_imperator_2 .


ex:entry_potestas rdf:type ontolex:LexicalEntry ;
    lexinfo:partOfSpeech <http://www.lexinfo.net/ontology/2.0/lexinfo#noun> ;
    ontolex:canonicalForm ex:lemma_potestas ;
    ontolex:sense ex:sense_potestas_1, ex:sense_potestas_2 .
ex:lemma_potestas rdf:type ontolex:Form ;
    ontolex:writtenRep "potestas"@la .
ex:sense_potestas_1 rdf:type ontolex:LexicalSense ;
    skos:definition "power␣"@en ;
    ontolex:reference <https://dbpedia.org/ontology/power> ;
    ex:senseShiftsTo ex:sense_potestas_2 .
ex:sense_potestas_2 rdf:type ontolex:LexicalSense ;
    skos:definition "angel"@en .
ex:shift_potestas rdf:type ex:senseShift ;
    rdfs:comment "Christian.␣Direct␣translation␣of␣the␣Greek." ;
    ex:shiftSource ex:sense_potestas_1 ;
    ex:shiftTarget ex:sense_potestas_2 .
```

```
ex:entry_scriptura rdf:type ontolex:LexicalEntry ;
    lexinfo:partOfSpeech <http://www.lexinfo.net/ontology/2.0/lexinfo#noun> ;
    ontolex:canonicalForm ex:lemma_scriptura ;
    ontolex:sense ex:sense_scriptura_1, ex:sense_scriptura_2 .
ex:lemma_scriptura rdf:type ontolex:Form ;
    ontolex:writtenRep "scriptura"@la .
ex:sense_scriptura_1 rdf:type ontolex:LexicalSense ;
    skos:definition "writing␣"@en ;
    ontolex:reference <https://dbpedia.org/resource/Writing> ;
    ex:senseShiftsTo ex:sense_scriptura_2 .
ex:sense_scriptura_2 rdf:type ontolex:LexicalSense ;
    skos:definition "Holy␣Scripture"@en .
ex:shift_scriptura rdf:type ex:senseShift ;
    rdfs:comment "Christian.␣Not␣used␣in␣reference␣to␣holy␣texts..." ;
    ex:shiftSource ex:sense_scriptura_1 ;
    ex:shiftTarget ex:sense_scriptura_2 .

ex:entry_uirtus rdf:type ontolex:LexicalEntry ;
    lexinfo:partOfSpeech <http://www.lexinfo.net/ontology/2.0/lexinfo#noun> ;
    ontolex:canonicalForm ex:lemma_uirtus ;
    ontolex:sense ex:sense_uirtus_1, ex:sense_uirtus_2 .

ex:lemma_uirtus rdf:type ontolex:Form ;
    ontolex:writtenRep "uirtus"@la .

ex:sense_uirtus_1 rdf:type ontolex:LexicalSense ;
    skos:definition "manliness␣"@en ;
    ontolex:reference <https://dbpedia.org/resource/Masculinity> ;
    ex:senseShiftsTo ex:sense_uirtus_2 .
ex:sense_uirtus_2 rdf:type ontolex:LexicalSense ;
    skos:definition "Christian␣virtues"@en .
ex:shift_uirtus rdf:type ex:senseShift ;
    ex:shiftSource ex:sense_uirtus_1 ;
    ex:shiftTarget ex:sense_uirtus_2 .
```

Notes

1. We would argue that conceptual changes always affect the lexicon in some way. In any case, in the present work, we take a lexico-centric view, and do not look at conceptual change in isolation from the lexicon.
2. See, in particular, the five-star linked data deployment scheme: https://5stardata.info/en/ (accessed on 16 May 2024).
3. Note that in the rest of the article, we will not be interested in purely theoretical descriptions of lexical semantics but will instead be concerned with digital resources (especially lexical resources and ontologies). This is despite the fact that in many cases, we are dealing with idealised descriptions of such resources—abstractions. We are especially interested in how such resources can help meet the information needs of scholars in different fields, but also of the general public. The decision to work with linked data and the Semantic Web limited the level of sophistication of the formal models we are concerned with.
4. In this article, we assume that these are linked data resources. However, although our focus here is on RDF, much of what we write here should apply to any formal knowledge representation approach to modelling language change on the basis of the assumptions set out in the previous section, for which we have a basic architecture consisting of the lexicon of a language and an ontology to work with (we do not abstract more than this). Even our recourse to perdurants can be justified independently of the need to overcome the limitations of RDF.
5. The latter can indeed be regarded as a de facto standard for the creation of lexicons in linked data.
6. The paradigmatic case here would be common nouns such as *mammal*, *whale*, *water*, and *bank*.
7. 'A Turkish governor of a province or district: also a title of rank' from Murray et al. (1888).
8. This was of course one of Gottlob Frege's great insights Zalta (2023).
9. These states of affairs are formal descriptions of possible worlds.
10. Definition from Murray et al. (1888).
11. This is evidenced rather infamously, of course, by the title of the article itself. Our view is that it is possible to appreciate, and indeed to incorporate, this usage-based approach in our work without having to go as far as Kilgarriff in challenging the validity of the notion of word sense itself.
12. The word embedding approach follows, of course, from previous work in linguistic contextualism, including, prominently, that of Firth Widdowson (2020).
13. There are of course many more but these two are arguably the most salient in terms of current work in Natural Language Processing, computational linguistics, computational lexicography, and the digital humanities.
14. This kernel can be shared by different linguistic layers, however, so a better, but slightly more involved analogy would be to see the lexical sense as the planetary atmosphere through which we see the light of a particular star (the intension).

15 https://www.w3.org/2016/05/ontolex/#semantics (accessed on 18 May 2024).

16 https://www.w3.org/2016/05/ontolex/#lexical-sense-reference (accessed on 18 May 2024).

17 For instance, our interpretation differs considerably from that set out by Cimiano et al. (2013), which describes the theoretical significance of senses in *lemon*, the predecessor to the OntoLex-Lemon model, and as laid out by some of the contributors to that model. In this case, we would not have aligned our classes with those of the original model so freely, since there is less scope for interpretation; our understanding of the word–sense–concept relationship so clearly differs from that of Cimiano et al. (2013).

18 https://www.w3.org/2016/05/ontolex/#variation-translation-vartrans (accessed on 18 May 2024).

19 By reification here, we mean the representation of a relationship R that holds between two individuals s and t, i.e., $R(s,t)$, as a separate individual r, of which we can predicate properties in the same way we do for other individuals, rather than, or in addition to, being a relation. This is useful in the case of formalisms such as RDF because it allows us to more easily describe the particulars of the relationship itself.

20 https://www.w3.org/2019/09/lexicog/ (accessed on 18 May 2024).

21 This draft can be found at https://github.com/ontolex/frequency-attestation-corpus-information (accessed on 18 May 2024).

22 The Ontolex-Lemon W3C Community Report in its description of OntoLex-Lemon's treatment of word meaning introduces a further class: Lexical Concept, (a subclass of skos:Concept) that 'represents a mental abstraction, concept or unit of thought that can be lexicalised by a given collection of senses'. Lexical concepts are related to lexical entries through the evokes property. This is equivalent to the property chain sense o isLexicalizedSenseOf and to Lexical Senses through the lexicalizedSense property; further, they are related to references (potentially any subclass, not proper of owl:Thing) through the concept. It is not entirely clear what lexical concept really adds to the description of word meaning over and above lexical senses and their relationship to ontologies (it is not found in related standards/models such as the Lexical Markup Framework, or in the Dictionary chapter of the Text Encoding Initiative guidelines). Accordingly we decided to make no reference to it in the following.

23 Note that although the IOM is compatible with OntoLex-Lemon, it does not derive from it.

24 Enhanced interoperability being the most obvious one, however, we would like to be able to reason over our datasets and to derive new facts too since the Semantic Web stack includes several technologies and standards allowing for this.

25 https://github.com/anasfkhan81/lemonEty (accessed on 18 May 2024).

26 https://lila-erc.eu/#page-top (accessed on 17 May 2024).

27 By keeping the ontology static here, we mean that we do not explicitly represent the process of change among concepts as part of the ontology.

28 http://www.lateralmag.com/articles/issue-29/when-whales-were-fish (accessed on 18 May 2024).

29 This snapshot could potentially summarise the state of the lexicon over a number of years, but as the term 'snapshot, suggests, it is treated as a single point in time.

30 And here, we need to emphasise, just in case it was not already clear, that we are talking about ontologies from the point of view of Computer Science and not of philosophy, that is, as computational artefacts.

31 https://www.dbpedia.org/ (accessed on 17 May 2024).

32 https://lexinfo.net/ (accessed on 18 May 2024).

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