

BFO: Basic Formal Ontology¹

J. Neil Otte^{a,*}, John Beverley^a and Alan Ruttenberg^b

^a *Johns Hopkins University Applied Physics Laboratory, MD, USA*

E-mails: neil.otte@jhu.edu, johnbeverley2021@u.northwestern.edu

^b *University at Buffalo, State University of New York, NY, USA*

E-mail: alanruttenberg@gmail.com

Abstract. Basic Formal Ontology (BFO) is a top-level ontology consisting of thirty-six classes, designed to support information integration, retrieval, and analysis across all domains of scientific investigation, presently employed in over 350 ontology projects around the world. BFO is a genuine top-level ontology, containing no terms particular to material domains, such as physics, medicine, or psychology. In this paper, we demonstrate how a series of cases illustrating common types of change may be represented by universals, defined classes, and relations employing the BFO framework. We provide discussion of these cases to provide a template for other ontologists using BFO, as well as to facilitate comparison with the strategies proposed by ontologists using different top-level ontologies.

Keywords: BFO, top-level ontology, ontological analysis, formal ontology

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1. Introduction

In this paper, we demonstrate how Basic Formal Ontology (BFO) may be used to represent six cases involving change. These cases, their goals, and their accompanying focus statements are discussed in order to provide a template for other ontologists using BFO, as well as to facilitate comparison with the strategies proposed by ontologists using different top-level ontologies. Basic Formal Ontology² is a top-level ontology designed to support information integration, retrieval, and analysis across all domains of scientific investigation. Containing only general terms common across disciplines, BFO serves as the top-level ontology of the Open Biomedical and Bioinformatic Ontology (OBO) Foundry [Smith et al., 2007] and the Industrial Ontology Foundry (IOF) [Smith et al., 2019]. Moreover, BFO provides a starting point for over 350 known ontology extensions³ covering more specific domains, such as infectious disease [Cowell & Smith, 2010], plant development [Walls et al., 2019], and processed materials [Smith et al., 2019]. BFO has been designated an ISO standard [Smith et. al., 2021] and BFO's ISO 21838-2 specification has been axiomatized in First-Order Logic, OWL 2, and CLIF [Ruttenberg, 2020].⁴ BFO

¹ Each author contributed equally to this work.

* Corresponding author. E-mail: neil.otte@jhu.edu.

² International Organization for Standardization. (2021). Information technology – Top-level ontologies (TLO) – Part 2: Basic Formal Ontology (BFO) (ISO Standard No. 21838-2:2020). Retrieved from [https://standards.iso.org/ittf/PubliclyAvailableStandards/c074572_ISO_IEC_21838-2_2021\(E\).zip](https://standards.iso.org/ittf/PubliclyAvailableStandards/c074572_ISO_IEC_21838-2_2021(E).zip).

³ Users of BFO. Accessed December 25, 2020 at <http://basic-formal-ontology.org/users.html>.

⁴ To see the full axiomatization and track issues, see <https://github.com/BFO-ontology/BFO-2020/tree/master/21838-2>.

is committed to the following principles, which distinguish it from other top-level ontologies [Masolo et al., 2004]:

- *Ontological Realism* – The goal of an ontology is to describe reality. Scientific investigation is concerned with general features of reality and relations among them. Consequently, BFO consists fundamentally of representations of reality rather than language, concepts, or mental representations about reality [Arp, Smith, & Spear, 2015].
- *Fallibilism* – Whereas universals themselves do not change, our understanding of them must in light of new discoveries. While present scientific theories are assumed to be our best sources of accurate statements about reality, BFO recognizes, of course, that present scientific theories may be incorrect. Consequently, BFO is committed to tracking scientific developments over time, and updating ontologies in accordance with scientific developments [Arp, Smith, & Spear, 2015].
- *Adequatism* – Entities in a domain should not be assumed to be reducible to other kinds of entities. All scientific disciplines are worthy of representation in their own terms, and it is not necessary to paraphrase talk of these entities in terms of a privileged set of entities (e.g. those described by physics). This commitment contrasts with *reductionism*, which seeks to reduce entities described by some domain of science to another deemed more fundamental [Arp, Smith, & Spear, 2015].

2. Principles and structure of BFO

BFO adopts the following fundamental categories [Arp, Smith, & Spear, 2015, Smith & Ceusters, 2010, Bittner & Smith, 2001]:

- universal and particular – Particulars are individual denizens of reality restricted to specific times and places, which instantiate universals, but which cannot be instantiated. Universals are repeatable across time and space and may have an indefinite number of instantiated particulars [Grenon, 2003, Arp & Smith, 2008].
- *continuant and occurrent* – BFO is largely partitioned into disjoint universals.⁵ The upper bifurcation is distinguished by how particulars relate to time. Continuants endure through time maintaining identity, have no temporal parts, and are fully-present at any time they exist. Examples include house cats, the color of an apple, the function of mitochondria. By contrast, occurrent entities unfold over time or have temporal parts. Examples include: the history of Japan, drinking a cup of coffee, the temporal interval on which a mitotic division occurs [Smith & Mulligan, 1982].
- *relations* – BFO adopts three basic relation types: universal-universal, universal-particular, and particular-particular, the latter two of which may be time indexed. Universal-universal relations in BFO relate subtypes to parent types, whereas the sole universal-particular relation is the *instance of* relation, which holds between particulars and the universals under which they fall [Zemach, 1970].

We discuss here only those classes necessary for the comprehension of the cases.⁶ In what follows, definitions are indicated with the use of “=_{def}”, and those entries regarding classes that lack this symbol are elucidations. First, subclasses of *continuant*:

⁵The exceptions to disjointedness are BFO’s classes *fiat object part*, *object*, and *object aggregate*. Some instances may belong to more than one of these classes.

⁶We leave aside discussion of *fiat object part*, *spatial region* and its subclasses, *process boundary*, *spatiotemporal region*, *relational quality*, *history*, and *continuant fiat boundary* and its subclasses, as these classes were not necessary to represent the cases under discussion.

- a is an independent continuant =_{def} a is a continuant which is such that there is no b such that a specifically depends on b and no b such that a generically depends on b .
- * material entity – an independent continuant that at all times at which it exists has some portion of matter as continuant part.
 - * object – a material entity that manifests causal unity and is of a type instances of which are maximal relative to the sort of causal unity manifested.
 - * object aggregate – a material entity consisting exactly of (≥ 1) object(s) as member(s).
- * a is an immaterial entity =_{def} a is an independent continuant which is such that there is no time t when it has a material entity as continuant part.
 - * site – a three-dimensional immaterial entity whose boundaries either (partially or wholly) coincide with the boundaries of one or more material entities or have locations determined in relation to some material entity.

An independent continuant may bear dependent continuants, including:

- generically dependent continuant – an entity that exists in virtue of the fact that there is at least one of what may be multiple copies; it is the content or the pattern that the multiple copies share.
- b is a specifically dependent continuant =_{def} b is a continuant and there is some independent continuant c which is not a spatial region and which is such that b specifically depends on c .
- * realizable entity – a specifically dependent continuant that inheres in some independent continuant that is not a spatial region and is of a type some instances of which are realized in processes of a correlated type.
- * role – a realizable entity that exists because there is some single bearer that is in some special physical, social, or institutional set of circumstances in which this bearer does not have to be and which is not such that, if it ceases to exist, then the physical make-up of the bearer is thereby changed.
- * disposition – a realizable entity such that if it ceases to exist, then its bearer is physically changed, and whose realization occurs when and because its bearer is in some special physical circumstances, and this realization occurs in virtue of the bearer's physical make-up.
 - function – a disposition that exists in virtue of the bearer's physical make-up and this physical make-up is something the bearer possesses because it came into being either through evolution (in the case of natural biological entities) or through intentional design (in the case of artifacts), in order to realize processes of a certain sort.
- * quality – a specifically dependent continuant that, in contrast to roles and dispositions, does not require any further process in order to be realized.

From the occurrent portion of the hierarchy, we include the following:

- p is a process =_{def} p is an occurrent that has some temporal proper part and for some time has some material entity as participant.
- temporal region – an occurrent over which processes can unfold.
 - * temporal instant – a zero-dimensional temporal region that has no proper temporal part.
 - * temporal interval – a one-dimensional temporal region that is continuous, thus without gaps or breaks.

There is often a practical need to accommodate terms in scientific discourse that do not correspond to universals. Examples of such terms include ‘medical doctor’ and disjunctions such as ‘dog or cat’. BFO uses ‘defined classes’ to accommodate such terms. The extension of a defined class is characterized by necessary and sufficient conditions whose non-logical symbols denote relations, universals, or instances of universals. Thus, ‘medical doctor’ is only a short-hand way of referring to instances of persons who bear a medical doctor role, and to be a ‘dog or cat’ is nothing over and above being an instance of dog or an instance of cat. All defined classes are characterized by necessary and sufficient conditions, but the converse is not true. The distinction between a defined class and a universal is unique to BFO.

3. Formalization of BFO in first-order logic

We describe a fragment of the BFO ISO 21838-2 First-Order Logic (FOL) axiomatization [Ruttenberg, 2020]. The domain is comprised of particulars that stand in the primitive **instance of** relation to universals at times. BFO’s hierarchy of universals can be represented by defining the relation:⁷

$$\forall x, t, A, B \text{ is a}(A, B) =_{\text{def}} \text{instance of}(x, A, t) \rightarrow \text{instance of}(x, B, t)$$

For example, material entity **is a** independent continuant. Visual representation of BFO’s hierarchy can be found in *Fig. 1* and *Fig. 2*.

By rigid universal U_r , we mean any entity that is instantiated by U_r , instantiates U_r for the whole of its existence. All classes in BFO are rigid other than the three subclasses of material entity: fiat object part, object, and object aggregate. For example, an **instance of** object aggregate at some time may later instantiate object.

BFO’s theory of parts is modeled after Minimal Extension Mereology (MEM) [Simons, 1987]. MEM is described in terms of binary part relations, but is extended to handle the time-indexed relations. The MEM axioms state that a part relation is reflexive, antisymmetric, transitive, weakly supplemented, and exhibits the unique product property. Any time-indexed relation implies that the first two relata exist,

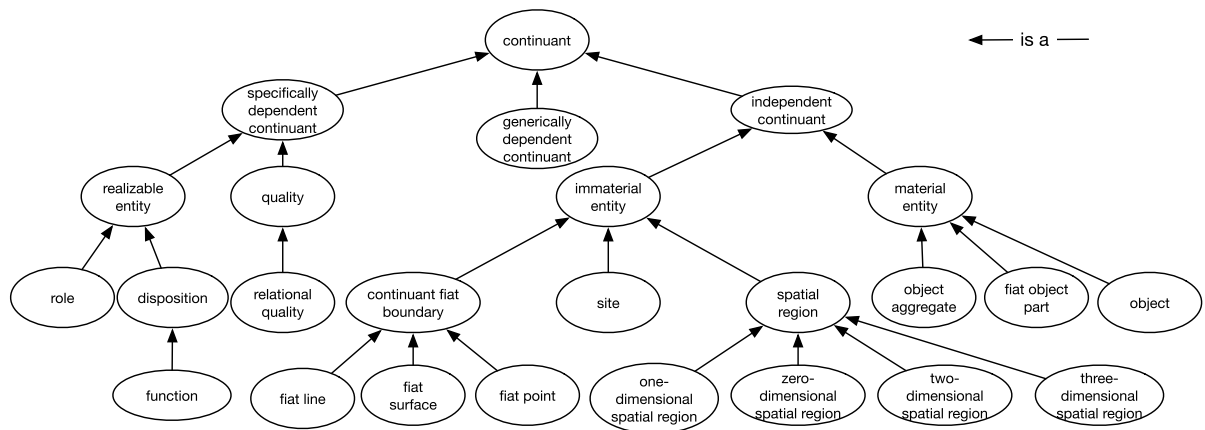


Fig. 1. BFO continuant hierarchy.

⁷This relation is not included in the BFO-ISO specification, but is defined here to simplify discussion.

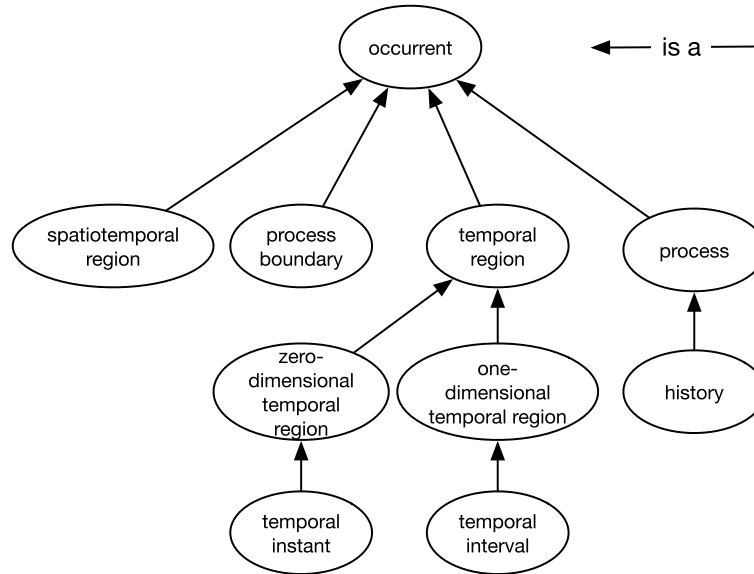


Fig. 2. BFO occurrent hierarchy.

and holds at any time the relata exist. For instance, when a time-indexed relation is reflexive we mean that the self-relationship refers to the first two relata and it must hold at any time the relata exist.

BFO has two part of relations, one for continuants, called **continuant part of** and one for occurrents called **occurent part of**. **Continuant part of** is time indexed, whereas **occurent part of** is not. Worth noting is the treatment of the anti-symmetry of **continuant part of** applied to object aggregates. If a **continuant part of** b at some t and b **continuant part of** a at the same time t , we do not conclude that $a = b$.

Using these relations we can define irreflexive, asymmetric, transitive **proper occurent part of** and **proper continuant part of** relations in the usual way.

Starting at the continuant side of the BFO hierarchy in Fig. 1, an independent continuant is distinguished from other continuants in that they neither generically nor specifically depend on other entities. In contrast, a specifically dependent continuant **specifically depends on** an independent continuant⁸ rigidly. If x **specifically depends on** y , then as long as x exists, the relation holds. If y ceases to exist, then x does as well.

A specifically dependent continuant is said to **inhere in** – a relation defined in terms of **specifically depends on** – an **instance of** independent continuant. The inverse of **inheres in** is **bearer of**. A generically dependent continuant is **concretized by** a process or specifically dependent continuant. When the concretization is a specifically dependent continuant the generically dependent continuant **generically depends on** the specifically dependent continuant's bearer.

All independent continuants other than spatial regions occupy a spatial region, and so are extended in space and time. Some may be **located in** others at some time, as the food you ingest is at some point located in the lumen of your stomach after you have eaten. **Located in** is transitive.

⁸In a number of relations involving independent continuants the relation is actually valid only if the entity is a spatial region. In order to keep the discussion simpler, we do not mention it in the body.

A material entity can be **continuant part of** another material entity at some time. Material entities can have material and immaterial parts. An object can be **member part of** an object aggregate. **Member part of** is not transitive but implies **continuant part of**. An object aggregate always has at least one member, and must, at some time, have more than one.

Any independent continuant, specifically dependent continuant, or generically dependent continuant can **participate in** a process. In the latter two cases, it is implied that their bearer also **participates in** the process. When a process **realizes** a realizable entity, the realizable entity's bearer also **participates in** the process. When a generically dependent continuant **participates in** a process p , some concretization of the generically dependent continuant **participates in** p . If that concretization is a process, it is **temporal part of** p .

A process **occupies temporal region** some temporal region. Processes have at least one process boundary as part. The temporal region that a process occupies must have as part a temporal interval. A process boundary can only occupy a temporal instant.

An occurrent can be a **temporal part of** some other. Occurrent parts can differ from what they are part of both spatially and temporally (e.g. the process which occurs in the left half of a soccer field during the first period of a game). By contrast, temporal part of an occurrent differs in that there is no difference in the spatial extent of the part and the whole.

Temporal regions provide the indices for all the time-indexed ternary relations in BFO. A temporal region **has first instant** and **has last instant** a temporal instant marking its extrema. A first or last instant can be **temporal part of** the region or not. A temporal instant that **precedes** the last instant of a temporal interval and are **preceded by** the interval's first instant are necessarily part of the interval. Using these relations, the familiar and widely used Allen's interval algebra may be formulated [Smith, et. al., 2011].

4. Analysis and formalization in BFO: Examples

In this section, we examine several cases reflecting composition, roles, property and event change, and scientific progress. As BFO is a small top-level ontology comprised of domain-neutral terms, the examples use either terms we define in this paper, or wherever possible, existing terms from BFO-aligned ontologies within the OBO Foundry library⁹ and The Common Core Ontologies (CCO) [Rudnicki, 2016].

Since the cases reflect changes over time, temporal intervals will be used throughout. We introduce some formalization here to avoid repetitions. In each case, we will use " i " to represent the interval during which the case unfolds. We will use subscripts on " i " to represent proper¹⁰ interval parts of i ordered by precedence. Formally:

- (1) **instance of**(i , temporal interval, i)
- (2) $\bigwedge_{1 \leq k \leq n}$ **instance of**(i_k , temporal interval, i_k)
- (3) $\bigwedge_{1 \leq k \leq n}$ **proper temporal part**(i_k , i)
- (4) $\bigwedge_{1 \leq k < n}$ **precedes**(i_k , i_{k+1})

In our examples, there are cases where we mention the possibility of enrichment using representations of **information content entities**. The term originates in the Information Artifact Ontology (IAO), an ontology that extends BFO. In what follows, we attempt to convey the flavor of such representations.

⁹<https://obofoundry.org/>

¹⁰Any "proper" relation $R(x, y)$ used here should be understood as $R(x, y) \wedge x \neq y$.

An information content entity (ICE) is a **generically dependent continuant** that **is about** some entity and can be **concretized** as, e.g., as one's name may be **concretized in** the shape quality of the ink that **inheres in** a piece of paper. We say the ICE **generically depends on** one or more material entities. An **information bearing entity** (IBE) is a material entity designed to be a carrier of information content e.g., a piece of paper.

In Fig. 3 we illustrate¹¹ one representation involving a measurement ICE that is about a process of walking. ICEs can be concretized on multiple bearers. A novel may be **concretized by** patterns of ink in multiple physical books or may be **concretized by** the digital patterns in different network servers; when this occurs, the novel (an information content entity) then **generically depends on** the physical books and network servers.

In Fig. 3, the concretization of the measurement ICE can be understood as some text (understood as a quality) written on the IBE. The relationship “has text value”, with the target being a string, should be understood as a shorthand representation of the relationship of the IBE to the concretization that is the phrase “2 miles per hour” recorded on the IBE.

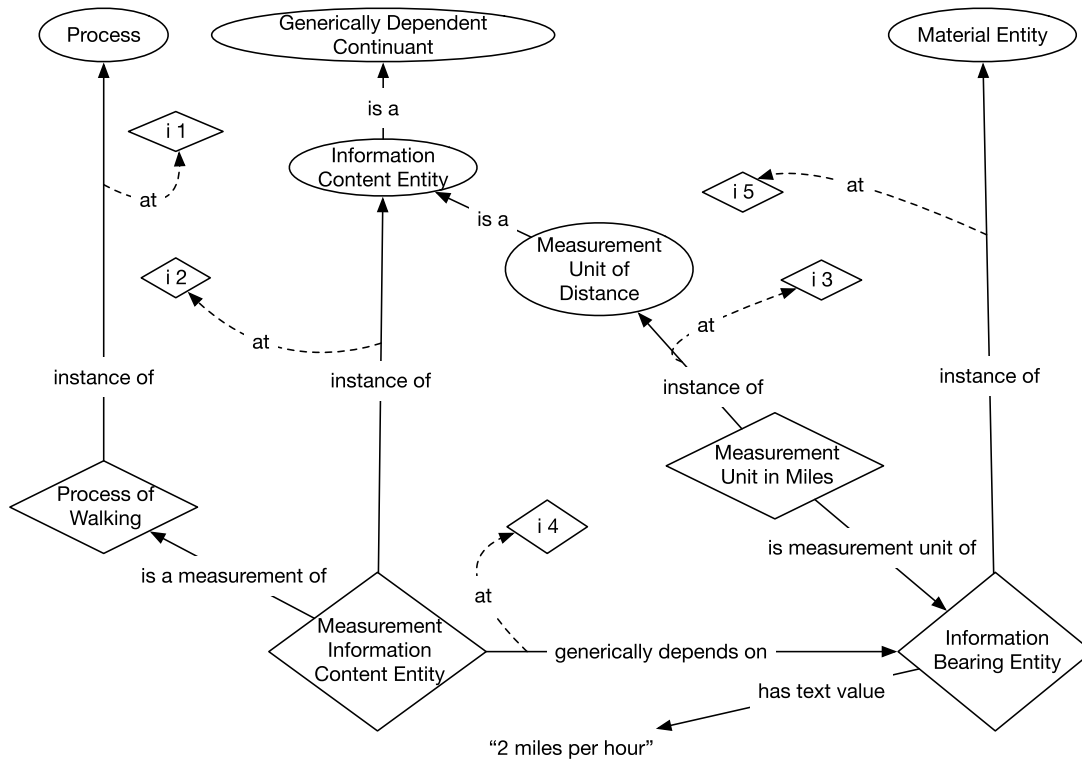


Fig. 3. Relationships among information content entities and bearers.

¹¹In figures throughout, we use circular nodes to represent both universals and defined classes, and diamonds to represent particulars.

4.1. Composition/constitution

CASE 1: *There is a four-legged table made of wood. Sometime later, a leg of the table is replaced. Even later, the table is demolished so it ceases to exist although the wood is still there after the demolition.*

GOAL: *The example aims to show if and how the ontology models materials, objects, and components and the relationships among them.*

FOCUS: *The relationship between the wood and the table and the table's parts over time. (Artefacts and functions are not the focus.)*

BFO does not have a constitution relation such as “made of”, typically related to an entity described as a mass noun. Instead, our example directly represents the particular portion of wood and its parts which are, when the table exists, part of the table. In *Tables 1–3*, we describe the classes, particulars, and relations we will use in our discussion. The portion of wood exists throughout the interval but changes. At the beginning of the interval, the portion of wood bears a table function and has parts that bear leg functions. The portion of wood **participates in** a leg replacement process, during which one of its proper parts that bears a leg function is replaced by a material entity bearing a leg function. After the replacement, the original leg is no longer part of the portion of wood, and the replacement leg is now

Table 1
Classes used to formalize Case 1

| Class | Definition or elucidation |
|---------------------------|---|
| Portion of wood | A material entity that was formerly part of one or more tree trunks or branches |
| Table function | A function that inheres in a material entity with a flat surface that has realization a process during which a material entity is placed on the bearer without it falling off |
| Leg function | A function that inheres in a stiff object and which has realization a process of support and elevation of other objects |
| Table destruction process | A process during which a material entity bearer of a table function loses that table function |

Table 2
Particulars used to formalize Case 1

| Particular | Description |
|----------------------------------|---|
| <i>wood</i> | The portion of wood that has continuant part <i>leg 1</i> at <i>i2</i> and <i>leg 2</i> at <i>i5</i> |
| <i>leg 1</i> | The object that is bearer of <i>leg function 1</i> . <i>leg 1</i> is replaced in the example. |
| <i>leg 2</i> | The object that is bearer of <i>leg function 2</i> . <i>leg 2</i> replaces <i>leg 1</i> in the example. |
| <i>table function</i> | The table function that inheres in <i>wood</i> |
| <i>leg function 1</i> | The leg function that inheres in <i>leg 1</i> |
| <i>leg function 2</i> | The leg function that inheres in <i>leg 2</i> |
| <i>leg replacement process</i> | A process during which <i>leg 1</i> is replaced by <i>leg 2</i> |
| <i>table destruction process</i> | A process resulting in <i>wood</i> losing <i>table function</i> |
| <i>i1</i> | The temporal interval during which <i>wood</i> is bearer of <i>table function</i> |
| <i>i2</i> | The temporal interval during which <i>leg 1</i> is proper continuant part of <i>wood</i> |
| <i>i3</i> | The temporal interval during which <i>leg 1</i> is bearer of <i>leg function 1</i> |
| <i>i4</i> | The temporal interval occupied by <i>leg replacement process</i> , which <i>leg 1</i> , <i>leg 2</i> , and <i>wood</i> participate in |
| <i>i5</i> | The temporal interval during which <i>leg 2</i> is proper continuant part of <i>wood</i> |
| <i>i6</i> | The temporal interval at which <i>leg 2</i> exists at |
| <i>i7</i> | The temporal interval occupied by <i>table destruction process</i> in which <i>wood</i> loses <i>table function</i> |

Table 3
Relations used to formalize Case 1

| Relation | Usage |
|----------------------------------|---|
| bearer of | Holding between a portion of wood and a function it bears. bearer of is the inverse of inheres in |
| exists at | Holding between an entity and a temporal interval when it exists |
| occupies temporal region | Holding a process and just those temporal intervals over which the process unfolds. |
| has participant | Holding between a process, a material entity involved in that process, and the temporal region at which the process occurs |
| proper continuant part of | Holding between a proper mereological part of <i>wood</i> and <i>wood</i> itself, at the temporal region during which they are parts. |

part of it. Afterward, the portion of wood **participates in** a destruction process, during which it loses its table function.

wood is an **instance of** portion of wood throughout *i1–i7* and so throughout the interval *i*¹² which they comprise:

- (1) **is a**(portion of wood, material entity)
- (2) **instance of**(*wood*, portion of wood, *i*)

wood bears a table function and **has proper continuant part** several legs. We focus on *leg 1*. We relate respective functions and material bearers:

- (3) **instance of**(*leg function 1*, leg function, *i3*)
- (4) **instance of**(*table function*, table function, *i1*)
- (5) **instance of**(*leg 1*, object, *i3*)
- (6) **instance of**(*wood*, object, *i2*)
- (7) **bearer of**(*wood*, *table function*)
- (8) **bearer of**(*leg 1*, *leg function 1*)
- (9) **proper continuant part of**(*leg 1*, *wood*, *i2*)

wood, *leg 1*, and *leg 2* **participate in** *leg replacement process*:

- (10) **instance of**(*leg function 2*, leg function, *i6*)
- (11) **instance of**(*leg 2*, object, *i6*)
- (12) **bearer of**(*leg 2*, *leg function 2*)
- (13) **¬continuant part of**(*leg 2*, *wood*, *i3*)¹³
- (14) **instance of**(*leg replacement process*, leg replacement process, *i4*)
- (15) **occupies temporal region**(*leg replacement process*, *i4*)
- (16) **participates in**(*leg 1*, *leg replacement process*, *i4*)
- (17) **¬continuant part of**(*leg 1*, *wood*, *i5*)¹⁴
- (18) **participates in**(*leg 2*, *leg replacement process*, *i4*)
- (19) **proper continuant part of**(*leg 2*, *wood*, *i5*)

Afterwards, *wood* and its parts **participate in** an **instance of** table destruction process:

¹²See the introduction to Section 4 for formalization of the relationship between *i* and its sub-intervals.

¹³Strictly speaking, *leg 2* is also not a **continuant part of** *wood* at earlier times. Corresponding axioms are assumed but not displayed here.

¹⁴Strictly speaking, *leg 1* is also not a **continuant part of** *wood* at later times. Corresponding axioms are assumed but not displayed here.

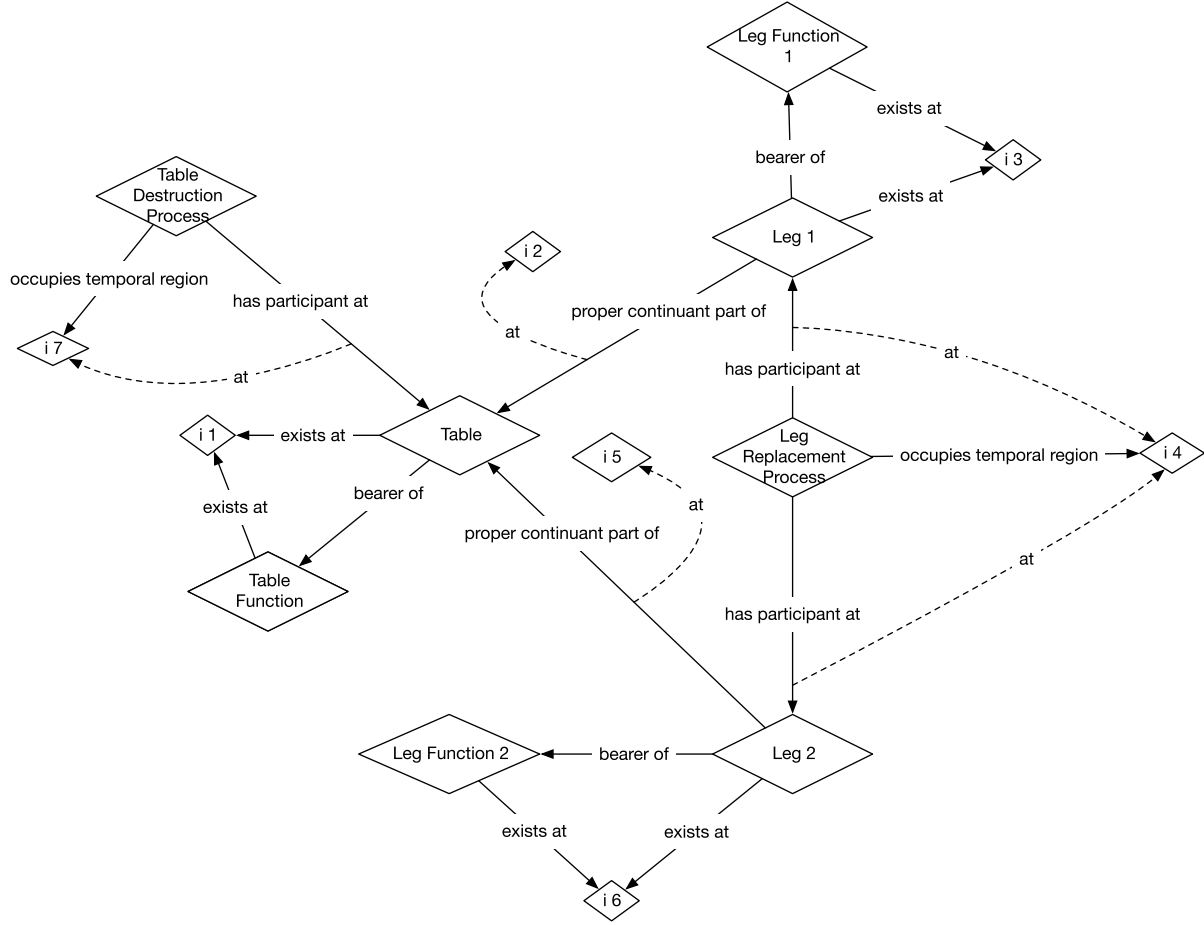


Fig. 4. Wood undergoing change in Case 1.

- (20) **instance of**(*table destruction process*, table destruction process, *i7*)
- (21) **occupies temporal region**(*table destruction process*, *i7*)
- (22) **participates in**(*wood*, table destruction process, *i7*)
- (23) $\exists t$ **occurent part of**(*t*, *i7*) $\wedge \neg$ **exists at**(*table function*, *t*)

We leave open whether proper parts of *wood* maintain their respective functions. That is compatible with the case that most proper parts of *wood* parts maintain their functions but are arranged such that *wood* loses *table function*. In any event, *wood* **exists at** *i7* though *table function* does not. Fig. 4 provide an illustration of the change described in this case.

4.2. Roles

CASE 2: *Mr. Potter is the teacher of class 2C at Shapism School and resigns at the beginning of the spring break. After the spring break, Mrs. Bumblebee replaces Mr. Potter as the teacher of 2C. Also, student Mary left the class at the beginning of the break and a new student, John, joins in when the break ends.*

GOAL: *The example aims to show if and how the ontology models the relationships between roles, players and organizations.*

FOCUS: *The change of roles/players; the vacancy of the teaching position; persistence of the class while students come and go.*

Mr. Potter is – we assume – the only teacher of class 2C prior to Spring Break and participates in an act of resignation prior to this break. Classes at Shapism School are not in session during the break, but during this time Mrs. Bumblebee and Shapism School agree that Mrs. Bumblebee will bear a 2C teacher role at the end of Spring Break. We focus on only Mr. Potter and Mrs. Bumblebee in our formalization, as the loss of student Mary and gain of student John during this interval does not differ greatly from the loss of teacher Mr. Potter and gain of teacher Mrs. Bumblebee. We use the following assignment in our formalization (Tables 4–6).

Mr. Potter and *Mrs. Bumblebee* are **instances of** person [Rudnicki, 2016]. *Shapism School* is an **instance of** organization [Bandrowski, 2016, Smith, et. al., 2019]. Organizations may have other organizations as member parts, allowing for class 2C to be **member part of** *Shapism School*:

- (1) **is a**(person, object)
- (2) **is a**(organization, object aggregate)
- (3) **instance of**(*Mr. Potter*, person, *i*)
- (4) **instance of**(*Mrs. Bumblebee*, person, *i*)

Table 4
Classes used to formalize Case 2

| Class | Definition or elucidation |
|--------------|---|
| Person | An object belonging to the species <i>Homo sapiens</i> and distinguished by a high level of intelligence. |
| Organization | An independent continuant that can bear roles, has members, and has a set of organization rules. |

Table 5
Particulars used to formalize Case 2

| Particulars | Descriptions |
|----------------------------|---|
| <i>Mr. Potter</i> | An instance of person |
| <i>Mrs. Bumblebee</i> | An instance of person |
| <i>Shapism School</i> | An instance of organization, the academic employer of <i>Mr. Potter</i> and <i>Mrs. Bumblebee</i> |
| 2C | A member part of <i>Shapism School</i> , including the teachers and the students they teach |
| 2C teacher role 1 | The role borne by <i>Mr. Potter</i> as the teacher of class 2C |
| 2C teacher role 2 | The role borne by <i>Mrs. Bumblebee</i> as the teacher of class 2C |
| act of resignation | The process during which <i>Mr. Potter</i> resigns from his role as teacher of class 2C |
| act of teaching assignment | The process during which <i>Shapism School</i> and <i>Mrs. Bumblebee</i> coordinate resulting in <i>Mrs. Bumblebee</i> becoming teacher of 2C |
| spring break | A process during which Spring Break occurs |
| i1 | The interval during which <i>Mr. Potter</i> is a member part of 2C |
| i2 | The interval during which 2C is a member part of <i>Shapism School</i> |
| i3 | The interval during which <i>Mr. Potter</i> participates in act of resignation |
| i4 | The interval during which <i>Mrs. Bumblebee</i> participates in an act of teaching assignment |
| i5 | The interval occupied by the act of teaching assignment in which <i>Mrs. Bumblebee</i> and <i>Shapism School</i> participate |
| i6 | The interval during which <i>Shapism School</i> participates in an act of teaching assignment |
| i7 | The interval during which <i>Mrs. Bumblebee</i> is a member part of 2C |

Table 6
Relations used to formalize Case 2

| Relations | Descriptions |
|---------------------------------|---|
| bearer of | Holds between instances of person and the teacher roles which inhere in that person |
| proper temporal part of | Holds between temporal intervals and the larger interval of which they are occurent part |
| occupies temporal region | Holds between processes and just those temporal intervals over which they unfold |
| participates in | Holds between material entities and the processes in which they are involved |
| member part of | Holds between object aggregates and their members |
| has specified output | Holds between <i>act of teaching assignment</i> and <i>Mrs. Bumblebee's 2C teacher role</i> |

(5) **instance of**(*Shapism School*, organization, *i*)

(6) **member part of**(*2C*, *Shapism School*, *i*)

Mr. Potter was a **member part of** *2C* prior to the start of *spring break*. *Mrs. Bumblebee* was not a **member of** *2C* during this time. Before *spring break* begins, *Mr. Potter* **participates in** an *act of resignation* so that during and after *spring break* *Mr. Potter* is no longer a **member part of** *2C*. We leave open whether *Mr. Potter* remains a **member of** *Shapism School* during and after *spring break*:

(7) **member part of**(*Mr. Potter*, *2C*, *i1*)

(8) \neg **member part of**(*Mrs. Bumblebee*, *2C*, *i1*)

(9) **instance of**(*spring break*, process, *i*)

(10) **instance of**(*act of resignation*, process, *i3*)

(11) **participates in**(*Mr. Potter*, *act of resignation*, *i3*)

(12) \neg **member part of**(*Mr. Potter*, *2C*, *i4*)¹⁵

Shapism School and *Mrs. Bumblebee* **participate in** *act of teaching assignment* resulting in *Mrs. Bumblebee* being a **member part of** *2C* after *spring break*.

(13) **occupies temporal region**(*act of teaching assignment*, *i5*)

(14) **proper temporal part of**(*i4*, *i5*)

(15) **proper temporal part of**(*i6*, *i5*)

(16) **participates in**(*Shapism School*, *act of teaching assignment*, *i6*)

(17) **participates in**(*Mrs. Bumblebee*, *act of teaching assignment*, *i4*)

(18) **member part of**(*Mrs. Bumblebee*, *2C*, *i7*)

With respect to relevant roles, *Mr. Potter* bears *2C teacher role 1* – a role borne by a unique person who is a **member part of** *2C* at a given time. Following the *act of teaching assignment* in which *Shapism School* and *Mrs. Bumblebee* participate, *Mrs. Bumblebee* is the unique bearer of *2C teacher role 2*. There is, to date, no well developed treatment of titles, organizational positions, and offices as such, where these are understood to be independent of the particular role that persons bear when holding such offices. This may arise in cases, for instance, where one wishes to refer to advertise an open teaching position at the school. A plausible representation might be as generically dependent continuants.

(19) **bearer of**(*Mr. Potter*, *2C teacher role 1*)

(20) \neg **exists at**(*2C teacher role 1*, *i4*)¹⁶

(21) **has specified output**(*act of teaching assignment*, *2C teacher role 2*)¹⁷

(22) **bearer of**(*Mrs. Bumblebee*, *2C teacher role 2*)

¹⁵*Mr. Potter* is, additionally, not a **member part of** *2C* during subsequent intervals.

¹⁶*2C teacher role* does not exist during subsequent intervals.

¹⁷*2C teacher role* does not exist before interval *i5*.

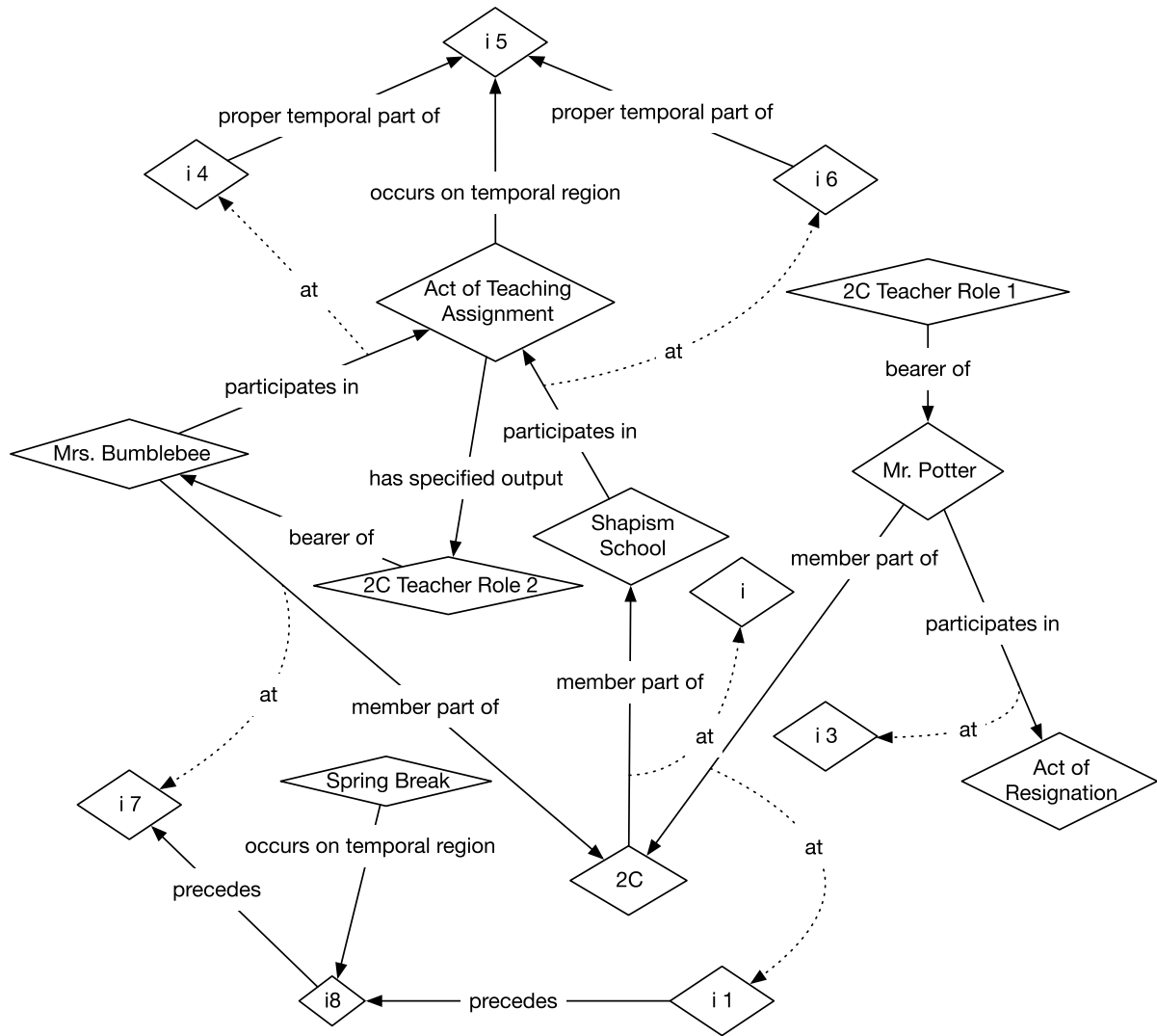


Fig. 5. Resignation and assignment of 2C teacher roles in Case 2.

4.3. Property change

CASE 3: A flower is red in the summer. As time passes, the color changes. In autumn the flower is brown.

GOAL: The example aims to show if and how the ontology models change in qualities/properties.

FOCUS: The change of the color of a flower.

Color is a messy phenomenon. Color ascriptions can be described at different levels of granularity, for example, the whole flower, flower petals, or proper surface parts of petals. Distributions of colors at one level of granularity often determine color at higher levels of granularity. For example, classification of a petal as “red” depends on the distribution of red on proper parts of the petal’s surface. Additionally, color may be understood as qualities, or dispositions to cause color experiences, or the color experiences

themselves. We will thus need to simplify our formalization. We focus on a specific petal of the flower for simplicity, noting our formalization can be applied to lower or higher levels of granularity. Moreover, we focus on colors as qualities of entities, rather than dispositions to cause experiences or as experiences. Broadly speaking then, the petal bears a red color quality during summer, the type of which changes to brown during fall. During this time, the flower participates in an act of withering. We use the following assignments in our formalization (Tables 7–9).

We use the classes *flower* and *petal* [Walls et al., 2019, Jaiswal et al., 2005] and assert the instance *flower* of the former has **continuant part** *petal*, which is an **instance of** the latter:

- (1) **instance of**(*flower*, *flower*, *i*)
- (2) **instance of**(*petal*, *petal*, *i*)
- (3) **proper continuant part of**(*petal*, *flower*, *i*)

Table 7
Classes used to formalize Case 3

| Class | Definition or elucidation |
|--------|--|
| Petal | A material entity that often surrounds reproductive parts of some flower |
| Flower | A material entity that generates seeds during a reproductive cycle |
| Color | A quality borne by a material entity that underwrites the reflection of light |
| Red | A color with wavelength between 625 and 740 nanometers |
| Brown | A color with wavelength of approximately 600 nanometers, with low saturation and luminance |

Table 8
Particulars used to formalize Case 3

| Particular | Description |
|-----------------------------|--|
| <i>petal</i> | The petal that bears a color quality that changes from red to brown |
| <i>flower</i> | The flower whose <i>petal</i> continuant part changes color through the season change |
| <i>color</i> | The color borne by the <i>petal</i> that changes from red to brown |
| <i>summer</i> | The process during which the <i>petal</i> begins as red and gradually becomes closer in color to brown |
| <i>fall</i> | The process during which the <i>petal</i> begins as reddish brown, but gradually becomes brown |
| <i>process of withering</i> | The process during which the <i>flower</i> loses elasticity and vibrancy |
| <i>i1</i> | The interval occupied by <i>summer</i> |
| <i>i2</i> | The interval occupied by <i>fall</i> |
| <i>i3</i> | The interval during which <i>color</i> is an instance of red, which is an occurrent part of both <i>i1</i> and <i>i6</i> |
| <i>i4</i> | The interval occupied by <i>process of withering</i> , which is an occurrent part of <i>i2</i> |
| <i>i5</i> | The interval during which <i>color</i> is an instance of brown, which is an occurrent part of both <i>i4</i> and <i>i6</i> |
| <i>i6</i> | The interval during which <i>color</i> is an instance of color |

Table 9
Relations used to formalize Case 3

| Relation | Usage |
|----------------------------------|---|
| participates in | Holds between <i>flower</i> and <i>process of withering</i> |
| occupies temporal region | Holds between <i>summer</i> , <i>fall</i> , <i>process of withering</i> , and the respective <i>temporal regions</i> they each occupy |
| occurrent part of | Holds between <i>temporal intervals</i> and larger <i>intervals</i> of which they are parts |
| proper continuant part of | Holds between <i>petal</i> and the <i>flower</i> of which it is a part |
| bearer of | Holds between <i>petal</i> and the <i>color</i> that it bears |

Color is a specifically dependent continuant in BFO [Smith, 2012]. We assert two subclasses of color: red and brown, and we furthermore assert that *petal* bears an **instance of** color:

- (4) **is a**(color, quality)
- (5) **is a**(red, color)
- (6) **is a**(brown, color)
- (7) **instance of**(color, color, *i6*)
- (8) **bearer of**(*petal*, color)

The color borne by *petal* is an **instance of** red during *summer*, and an **instance of** brown during *fall*:

- (9) **instance of**(summer, process, *i1*)
- (10) **instance of**(fall, process, *i2*)
- (11) **occupies temporal region**(summer, *i1*)
- (12) **occupies temporal region**(fall, *i2*)
- (13) **instance of**(color, red, *i3*)
- (14) **instance of**(color, brown, *i5*)
- (15) **occurrent part of**(*i3*, *i1*)
- (16) **occurrent part of**(*i3*, *i6*)
- (17) **occurrent part of**(*i5*, *i4*)
- (18) **occurrent part of**(*i5*, *i6*)

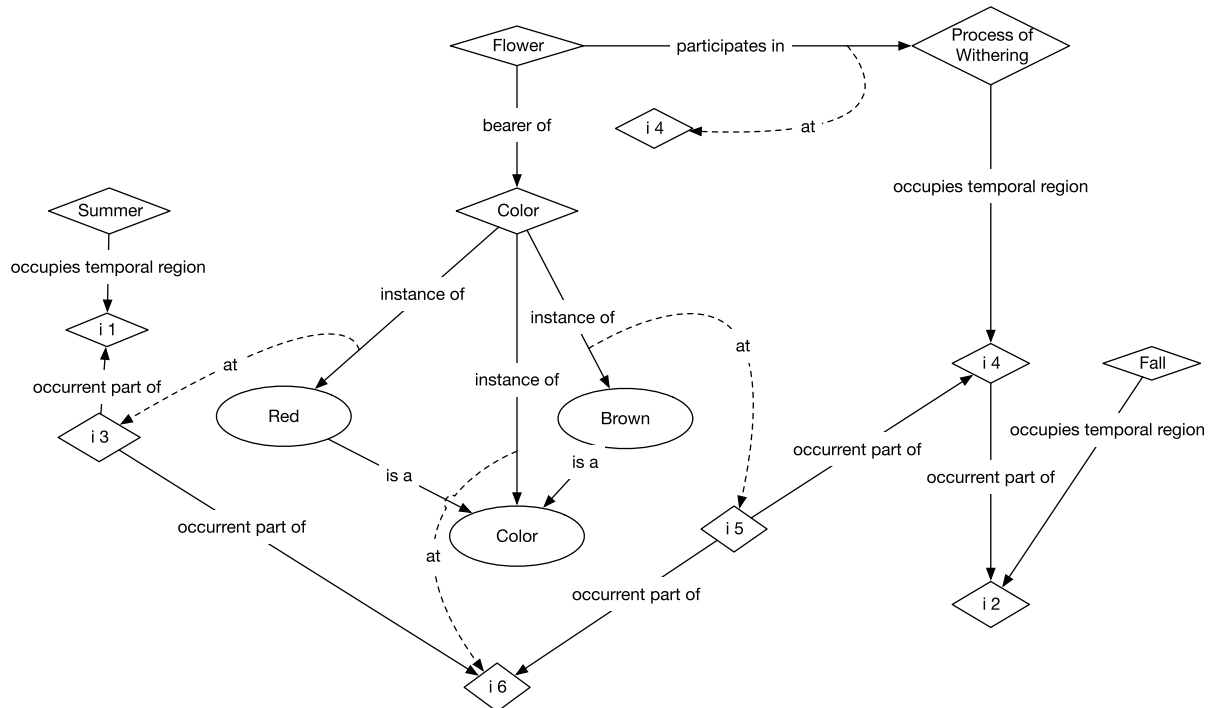


Fig. 6. Petal changing color in Case 3.

The *flower* **participates in** a process of *withering* that occurs during *fall*:

- (19) **instance of**(*process of withering*, process, *i4*)
- (20) **occupies temporal region**(*process of withering*, *i4*)
- (21) **occurrent part of**(*i4*, *i2*)

CASE 4: A man is walking when suddenly he starts walking faster and then breaks into a run.

GOAL: The example aims to show if and how the ontology models change during an event.

FOCUS: The change in the speed and mode of locomotion.

Processes do not change; they are changes. Participating in an act of locomotion, however, may have proper process walking, accelerating, and running parts. Intuitively, walking and running consist of sequences involving an agent who makes patterned contact with the ground using their feet, over some duration. For a given agent and given duration, walking is distinguished from running based on the number of moments of contact between the agent's feet and the ground. If this number is above some threshold, which may vary given the agent's size and shape, then it will count as running. An individual is accelerating when there is a patterned decrease in the duration between contacts with the ground and an increase in the spatial distance traversed by the agent.

In this case, a *man* is participating in an act of locomotion having proper process parts an act of walking, act of running, and act of accelerating. Our formalization uses the following assignments (Tables 10 and 11).

The *man* participates in an *act of locomotion*.

- (1) **instance of**(*man*, person, *i*)
- (2) **instance of**(*act of locomotion*, process, *i*)
- (3) **participates in**(*man*, *act of locomotion*, *i*)

Table 10
Particulars used to formalize Case 4

| Particulars | Descriptions |
|----------------------------|--|
| <i>man</i> | An instance of <i>person</i> who bears some male gender |
| <i>act of locomotion</i> | An instance of process in which the <i>man</i> changes spatial position |
| <i>act of walking</i> | An instance of process in which the <i>man</i> changes spatial position exerting little effort, at a low speed |
| <i>act of accelerating</i> | An instance of process in which the <i>man</i> increases speed at which he changes spatial position |
| <i>act of running</i> | An instance of process in which the <i>man</i> changes spatial position, while exerting significant effort, at a high speed |
| <i>i1</i> | The interval during which the <i>man</i> participates in an <i>act of walking</i> |
| <i>i2</i> | The interval during which the <i>man</i> participates in an <i>act of accelerating</i> |
| <i>i3</i> | The interval during which the <i>man</i> participates in an <i>act of running</i> |

Table 11
Relations used to formalize Case 4

| Relations | Usage |
|---------------------------------|---|
| proper occurrent part of | Holds between acts of accelerating, walking, and the larger act of locomotion of which they are parts |
| participates in | Holds between the <i>man</i> and processes in which he participates |

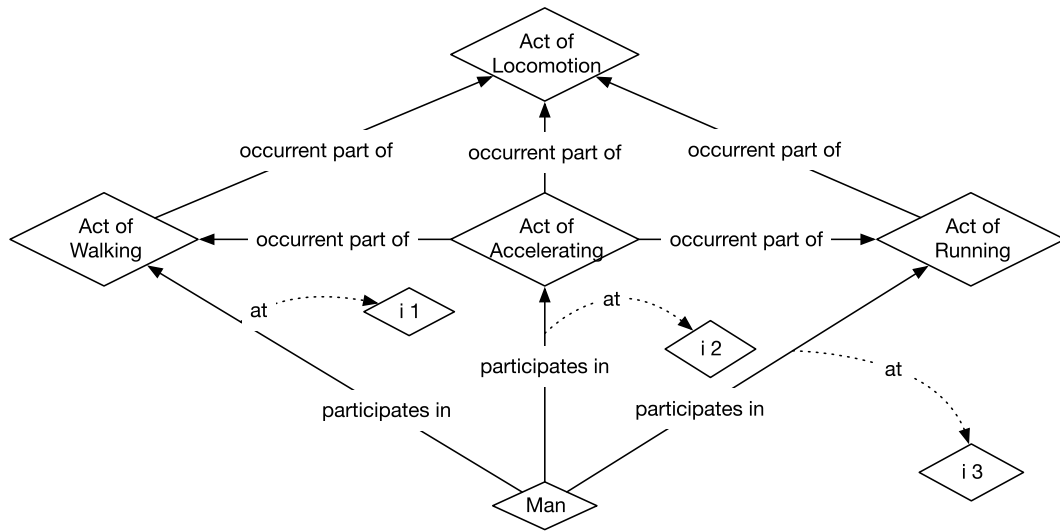


Fig. 7. Man moving with increasing speed in Case 4.

This process is comprised of **proper occurrent parts** [Smith, 2012] – an *act of walking*, *act of accelerating*, and *act of running*. The man **participates in** each. Fig. 7 illustrates our formalization of the case.

- (4) **proper occurrent part of**(*act of walking*, *act of locomotion*)
- (5) **proper occurrent part of**(*act of accelerating*, *act of locomotion*)
- (6) **proper occurrent part of**(*act of running*, *act of locomotion*)
- (7) **proper occurrent part of**(*act of accelerating*, *act of walking*)
- (8) **proper occurrent part of**(*act of accelerating*, *act of running*)
- (9) **participates in**(*man*, *act of walking*, *i 1*)
- (10) **participates in**(*man*, *act of accelerating*, *i 2*)
- (11) **participates in**(*man*, *act of running*, *i 3*)

While our characterization of this case is general, complementary refinements could be added. For example, the man's changing speed at times during this case might be represented as measurements taken at temporal parts of the interval. Fig. 3 provides a recipe for characterizing measurements using instances of generically dependent continuant, as evidenced in the next case. Moreover, our analysis of the next case illustrates a further complementary characterization of changing motion.

4.4. Event change

CASE 5: A man is walking to the station, but before he gets there, he turns around and goes home.
GOAL: The example aims to show if and how the ontology models change in goal-directed activities.

FOCUS: An activity/event is not completed and another activity/event is completed instead.

The man commits himself to a plan to walk to the station, which is specified in terms of actions he might take and the objective he seeks. Prior to arriving at the station, the man abandons his initial plan, and forms another, this time to turn around and walk home. As before, the man's plan to walk home is specified in terms of actions he might take and the objective he seeks. In this case, the man achieves his objective.

Table 12
Classes used to formalize Case 5

| Class | Definition or elucidation |
|----------------------------|---|
| Plan | A realizable entity that inheres in a bearer who is committed to realizing it as a planned process |
| Plan specification | An information entity with action specifications and objective specifications as continuant parts that, when concretized, is realized in a process in that the bearer tries to achieve the objectives by taking the actions specified |
| Information content entity | A generically dependent entity that depends on some artifact and stands in a relation of aboutness to some entity |
| Action specification | An information entity that describes an action the bearer of the information entity will take |
| Objective specification | An information entity that describes an intended process endpoint. When continuant part of a plan specification the concretization is realized in a planned process in which the bearer tries to effect the world so that the process endpoint is achieved |
| Facility | A material entity that is designed as a building or campus dedicated to some specific purpose |
| Planned process | A process that realizes a plan that is the concretization of a plan specification |

The *man* bears *plan 1* [Smith & Ceusters, 2015, Ruttenberg et al., 2017], which is a concretization of *station plan specification*. *Station plan specification* has continuant part both the *station action specification* that *prescribes* the steps the *man* might take to walk to the *station* and the *station objective specification* that describes the goal of *plan 1*:

- (1) **is a**(plan, realizable entity)
- (2) **is a**(plan specification, information content entity)
- (3) **instance of**(*plan 1*, plan, *i*)
- (4) **instance of**(*station plan specification*, plan specification, *i2*)
- (5) **instance of**(*station action specification*, action specification, *i2*)
- (6) **instance of**(*station objective specification*, objective specification, *i2*)
- (7) **inheres in**(*plan 1*, *man*)
- (8) **concretized by**(*station plan specification*, *plan 1*, *i3*)
- (9) **continuant part of**(*station action specification*, *station plan specification*, *i2*)
- (10) **continuant part of**(*station objective specification*, *station plan specification*, *i2*)

Station is an **instance of** facility [Rudnicki, 2016]. Because *plan 1* is an **instance of** realizable entity, it is not strictly speaking about anything, as only information content entities may be about some entity. Nevertheless, there is an **instance of** information content entity that is **part of** the *station objective specification* and **concretized by** *plan 1*, which includes the *station* in its description. We can thus say *man's plan 1* (derivatively) **is about** the *station*. Moreover, the *station action specification* includes the walking plan he intends to take in pursuit of that objective. Additionally, the *man* **participates in** a *4mph walk*:

- (11) **instance of**(*station*, facility, *i*)
- (12) **instance of**(*station description*, information content entity, *i*)
- (13) **continuant part of**(*station description*, *station objective specification*, *i2*)
- (14) **described by**(*station*, *station description*)
- (15) **participates in**(*man*, *4mph walk*, *i4*)

At some time, the *man* forms *plan 2* to walk back *home*, then **participates in** an **instance of** *180 turn*, then **participates in** a *3mph walk* until he arrives *home*.

- (16) **instance of**(*plan 2*, plan, *i*)
- (17) **instance of**(*home plan specification*, plan specification, *i*)

Table 13
Particulars used to formalize Case 5

| Particulars | Descriptions |
|--|---|
| <i>man</i> | The person who bears some male gender in the scenario |
| <i>plan 1</i> | The plan that the <i>man</i> forms to walk to the <i>station</i> |
| <i>plan 2</i> | The plan that the <i>man</i> forms to turn around and walk <i>home</i> |
| <i>station plan specification</i> | The plan specification having continuant part <i>station action specification</i> and <i>station objective specification</i> |
| <i>station action specification</i> | An action specification describing the steps the <i>man</i> intends to take to walk to the <i>station</i> |
| <i>station objective specification</i> | The objective specification describing reaching the <i>station</i> as the objective of the <i>station plan specification</i> |
| <i>home plan specification</i> | The plan specification having parts <i>home action specification</i> and <i>home objective specification</i> |
| <i>home action specification</i> | The action specification describing the steps the <i>man</i> intends to take to turn around and walk <i>home</i> |
| <i>home objective specification</i> | The objective specification describing reaching <i>home</i> as the objective of the <i>home objective plan</i> |
| <i>station</i> | The facility to which the <i>man</i> initially intends to walk |
| <i>home</i> | The facility to which the <i>man</i> later walks |
| <i>station description</i> | The information content entity describing the <i>station</i> , that is continuant part of the <i>station objective specification</i> |
| <i>home description</i> | The information content entity describing the <i>home</i> , that is continuant part of the <i>home objective specification</i> |
| <i>4mph walk</i> | The process during which the <i>man</i> walks at an approximate velocity of 4 mph |
| <i>3mph walk</i> | The process during which the <i>man</i> walks at an approximate velocity of 3 mph |
| <i>180 turn</i> | The process during which the <i>man</i> turns 180 degrees |
| <i>i1</i> | Interval during which the <i>station plan specification</i> exists, and during which the <i>station action specification</i> and <i>objective specification</i> are proper continuant parts of the <i>station plan specification</i> |
| <i>i2</i> | Interval during which is <i>station plan specification</i> concretized by <i>plan 1</i> |
| <i>i3</i> | Interval during which the <i>man</i> participates in the <i>4mph walk</i> process |
| <i>i4</i> | Interval during which the <i>man</i> participates in the <i>180 turn</i> process |
| <i>i5</i> | Interval during which the <i>man</i> participates in the <i>3mph walk</i> process |
| <i>i6</i> | Interval during which <i>home plan specification</i> is concretized by <i>plan 2</i> |
| <i>i7</i> | Interval during which the <i>home plan specification</i> exists, and during which the <i>home action specification</i> and <i>objective specification</i> are proper continuant parts of the <i>home plan specification</i> |

- (18) **instance of**(*home action specification*, action specification, *i6*)
- (19) **instance of**(*home objective specification*, objective specification, *i6*)
- (20) **continuant part of**(*home action specification*, *home plan specification*, *i6*)
- (21) **continuant part of**(*home objective specification*, *home plan specification*, *i6*)
- (22) **inheres in**(*plan 2*, *man*)
- (23) **concretized by**(*home plan specification*, *plan 2*, *i6*)
- (24) **prescribes**(*home plan specification*, *180 turn*)
- (25) **prescribes**(*home plan specification*, *3mph walk*)
- (26) **participates in**(*man*, *180 turn*, *i4*)
- (27) **participates in**(*man*, *3mph walk*, *i5*)
- (28) **realized in**(*plan 2*, *180 turn*)
- (29) **realized in**(*plan 2*, *3mph walk*)

Table 14
Relations used to formalize Case 5

| Relations | Descriptions |
|-----------------------------------|--|
| concretized by | Holds between <i>station plan specification</i> , <i>home plan specification</i> , and <i>plan 1</i> and <i>plan 2</i> , respectively |
| proper continuant part of | Holds between the action and objective specifications and the respective plan specifications, as well as between the descriptions and objective specifications |
| exists at | Holds between the plan specifications and the temporal intervals at which they exist |
| is about | Holds between descriptions and the entities they describe |
| bearer of | Holds between the <i>man</i> and <i>plan 1</i> and <i>plan 2</i> |
| prescribes | Holds between an action specification and the processes that the specification prescribes |
| achieves planned objective | Holds between a planned process and objective specification when the criteria specified in the objective specification are met at the end of the planned process |
| participates in | Holds between <i>man</i> and the processes in which he participates |

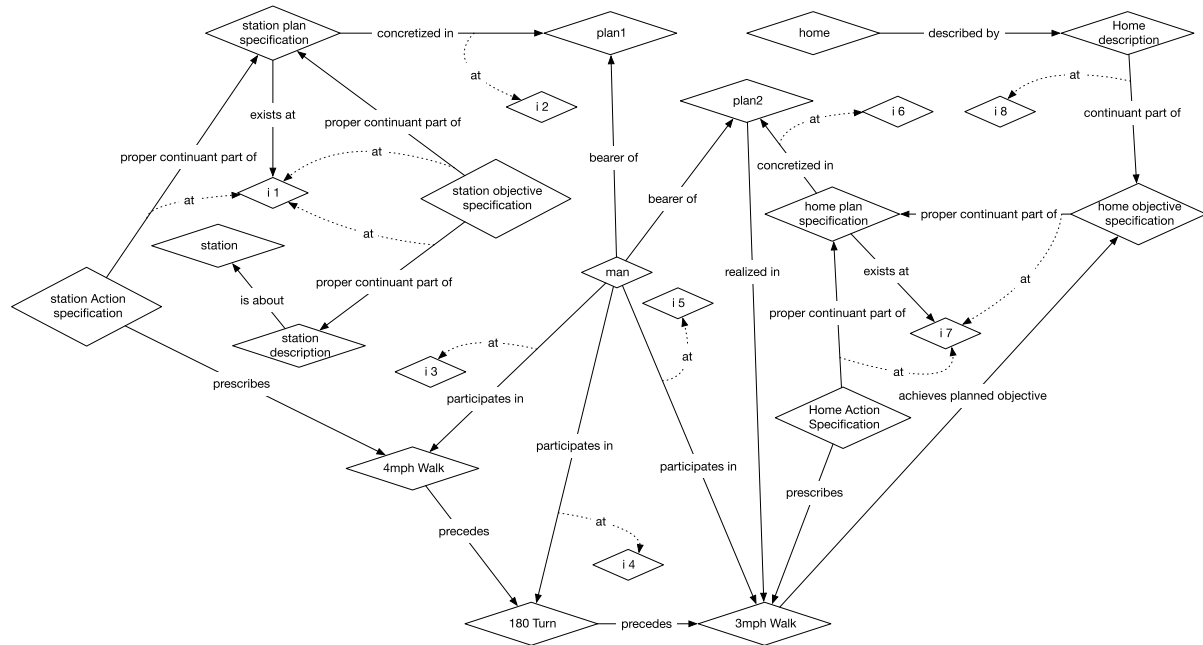


Fig. 8. Man walking to station, then home in Case 5.

The *man's home* is a facility. There is an **instance of** information content entity that is **part of** the *home objective specification* and **concretized by** *plan 2*, where *plan 2* includes *home* in its description. We can thus say the *man's plan 2* is (derivatively) **about** the *home*. As before, the *home action specification* includes the walking plan the *man* intends to take. In this case, the *man* does achieve his planned objective, which we can represent by the *man's participating in an instance of planned process* and bearing an **achieves objective** relation to the *home objective specification*, which we import from [Bandrowski, 2016].¹⁸

¹⁸<http://purl.obolibrary.org/obo/obi>

- (30) **is a**(planned process, process)
- (31) **instance of**(planned process, planned process, i)
- (32) **instance of**(home, facility, i)
- (33) **instance of**(home description, information content entity, i7)
- (34) **continuant part of**(home description, home objective specification, i7)
- (35) **described by**(home, home description)
- (36) **participates in**(man, planned process, i6)
- (37) **achieves planned objective**(planned process, home objective specification)

Fig. 8 illustrates our description of the case. For further specification of the *man's* walk, formalizations of distance measurement using BFO and its extensions illustrated in Fig. 3 can be leveraged to describe how far the *man* traveled in his initial trip before turning back.

4.5. Concept evolution

CASE 6: *A marriage is a contract that is regulated by civil and social constraints. These constraints can change but the meaning of marriage continues over time.*

GOAL: *The example aims to show if and how the ontology models the evolution of the meaning of a term.*

FOCUS: *The continuity/discontinuity of the meaning of marriage in the presence of changing qualifications.*

Speaking of ‘the meaning’ of marriage is spurious. Like most words, ‘marriage’ is polysemous. It can refer to a process in which spouses participate; it can refer to information content entities (i.e. the *idea* of marriage in the minds of particular people, or as represented in legal documents); and it can refer to a pair of mutually dependent spousal roles and their associated powers and privileges. Some uses of ‘marriage’ pull together all three meanings, as when we speak of the institution of marriage and denote a set of practices (processes) realizing marital powers (roles) that are prescribed by social or religious doctrine and law (information content entities). In representing marriage, we should take care not to conflate these different notions. As Groucho Marx once quipped: “Marriage is a wonderful institution, but who wants to live in an institution?”

Marriage license regulations vary by geographical region, population, and organizational affiliation. In the U.S., for example, marriage requirements, laws, and associated rights are established by states. All states impose eligibility requirements on individuals. For example, individuals entering marriage must have the capacity to consent to the arrangement and must be above a certain age. States also impose eligibility requirements on the couple. For example, at least one member of the union must be a U.S. citizen, before 1967 several states prohibited interracial marriage, and until 2015 several prohibited same-sex marriage [Smith, 2014]. Governments also grant obligations to spouses – married partners bear financial responsibilities to one another – and privileges – married partners are not required to testify against one another in court. Obligations and privileges can, like eligibility requirements, be changed by governing agencies.

We focus on the present status of a marriage contract issued in the U.S. between 1967 and 2015, and subsequent legal changes after 2015.

The *marriage license* is an instance of the class marriage license, which is a subclass of document [Almeida, Slaughter, & Brochhausen, 2012, Almeida et al., 2017]. *State government*, which issues the *marriage license*, is an instance of government, which is a type of organization able to exercise judicial, legislative, or executive authority over a site.

Table 15
Classes used to formalize Case 6

| Class | Definition or elucidation |
|---------------------|--|
| Document | A collection of information content entities intended to be understood together as a whole |
| Government | An organization that exercises executive, legislative, or judicial authority over a region |
| Marriage license | A document issued by a government, which legally binds agents as spouses, and invests them with associated instances of deontic role |
| Deontic declaration | A social act that creates or revokes a deontic role |
| Social act | A planned process that is carried out by a person or an organization, and is self-generated, directed towards another person or an aggregate of persons, an organization or an aggregate of organizations, and that needs to be perceived |
| Deontic role | A role that inheres in a person and that is externally grounded in the normative expectations that other persons within a social context have concerning how that person should behave |
| Action regulation | An information content entity that prescribes an act as required, prohibited, or permitted, and is the output of an act that realizes some authority role |
| Authority role | A role that is realized by actions that create, modify, transfer, or eliminate action regulations or other authority roles, and inheres in an agent in virtue of collective acceptance of that agent's ability to issue binding directives |

Table 16
Particulars used to formalize Case 6

| Particulars | Descriptions |
|------------------------------------|--|
| <i>U.S. Supreme Court</i> | The branch of government able to legally create or revoke deontic powers of <i>state government</i> |
| <i>deontic declaration 1</i> | The deontic declaration that has specified output <i>marriage license</i> |
| <i>deontic declaration 2</i> | The deontic declaration that has specified output <i>action regulation 1</i> |
| <i>deontic declaration 3</i> | The deontic declaration that legally revokes <i>deontic role 1</i> and <i>deontic role 3</i> |
| <i>deontic role 1</i> | The deontic role inhering in <i>Alex</i> realized in <i>Alex</i> legally refraining from testifying against <i>Bailey</i> in court |
| <i>deontic role 2</i> | The deontic role inhering in <i>Alex</i> realized in <i>Alex's</i> legal permission to file income taxes jointly with <i>Bailey</i> |
| <i>deontic role 3</i> | The deontic role inhering in <i>Bailey</i> realized in <i>Bailey</i> legally refraining from testifying against <i>Alex</i> in court |
| <i>deontic role 4</i> | The deontic role inhering in <i>Bailey</i> realized in <i>Bailey's</i> legal permission to file income taxes jointly with <i>Alex</i> |
| <i>marriage license</i> | The marriage license issued by <i>state government</i> , which legally binds <i>Alex</i> and <i>Bailey</i> together as spouses, and invests them with associated instances of deontic role |
| <i>state government</i> | The government participating in the marriage of <i>Alex</i> and <i>Bailey</i> |
| <i>Alex</i> | The person acquiring a <i>marriage license</i> with <i>Bailey</i> |
| <i>Bailey</i> | The person acquiring a <i>marriage license</i> with <i>Alex</i> |
| <i>marriage licensure document</i> | A document describing the objective of issuing, and steps that must be taken to issue <i>marriage license</i> |
| <i>action regulation 1</i> | An action regulation requiring <i>state government</i> to issue instances of marriage license for consenting same-sex couples |
| <i>authority role 1</i> | An authority role borne by <i>state government</i> , prescribed by <i>action regulation 1</i> |
| <i>i1</i> | The interval during which <i>state government</i> , <i>Alex</i> , and <i>Bailey</i> participate in <i>deontic declaration 1</i> resulting in the creation of <i>marriage contract</i> |
| <i>i2</i> | The interval during which <i>U.S. Supreme Court</i> participates in <i>deontic declaration 2</i> requiring <i>state government</i> to recognize same-sex marriage |
| <i>i3</i> | The interval during which <i>state government</i> legally revokes <i>deontic role 1</i> and <i>deontic role 3</i> |

Table 17
Relations used to formalize Case 6

| Relations | Descriptions |
|-----------------------------|--|
| participates in | Holds between agents and instances of deontic declaration |
| has specified input | Holds between <i>deontic declaration 1</i> and <i>marriage licensure document</i> |
| has specified output | Holds between instances of deontic declaration and document, and <i>action regulation 1</i> |
| inheres in | Holds between instances of deontic role and <i>Alex</i> and <i>Bailey</i> , respectively |
| prescribes | Holds between <i>action regulation 1</i> and <i>authority role 1</i> |
| legally revokes | Holds between <i>deontic declaration 3</i> and <i>deontic role 1</i> and <i>deontic role 3</i> |

- (1) **is a**(document, information content entity)
- (2) **is a**(marriage license, document)
- (3) **is a**(government, organization)
- (4) **instance of**(*marriage license*, marriage license, *i*)
- (5) **instance of**(*state government*, government, *i*)

State government **participates in** *deontic declaration 1*, a type of social act [Almeida, Slaughter, & Brochhausen, 2012, Almeida et al., 2017] which **has specified input** a *marriage licensure document* that has, as part, a plan specification. This plan specification **describes** the intended legal entities created according to the objective specification, as well as the manner in which the deontic declaration should be performed to achieve that objective – as described by the action specification. For simplicity, we do not include these continuant parts of *marriage licensure document*. The *deontic declaration 1*, moreover, **has specified output** the *marriage license*:

- (6) **is a**(deontic declaration, social act)
- (7) **instance of**(*deontic declaration 1*, deontic declaration, *i1*)
- (8) **participates in**(*state government*, *deontic declaration 1*, *i1*)
- (9) **has specified input**(*deontic declaration 1*, *marriage licensure document*)
- (10) **has specified output**(*deontic declaration 1*, *marriage license*)

Alex and *Bailey* each **participates in** *deontic declaration 1* as well. Instances of deontic declaration involve the creation or revoking of deontic roles. Instances of deontic role **inhere in** persons or organizations, but are externally grounded in the normative expectations others have concerning how bearers should behave. In this case, instances of deontic role **inhere in** *Alex* and *Bailey*, respectively. These respective roles are **realized in** processes typically associated with marriage, such as filing taxes jointly and making medical decisions on behalf of the spouse. For simplicity, we focus on only two such deontic roles each for *Alex* and *Bailey*.

- (11) **instance of**(*Alex*, person, *i*)
- (12) **instance of**(*Bailey*, person, *i*)
- (13) **participates in**(*Alex*, *deontic declaration 1*, *i1*)
- (14) **participates in**(*Bailey*, *deontic declaration 1*, *i1*)
- (15) **is a**(deontic role, role)
- (16) **instance of**(*deontic role 1*, deontic role, *i1*)
- (17) **instance of**(*deontic role 2*, deontic role, *i1*)
- (18) **instance of**(*deontic role 3*, deontic role, *i1*)
- (19) **instance of**(*deontic role 4*, deontic role, *i1*)
- (20) **inheres in**(*deontic role 1*, *Alex*)

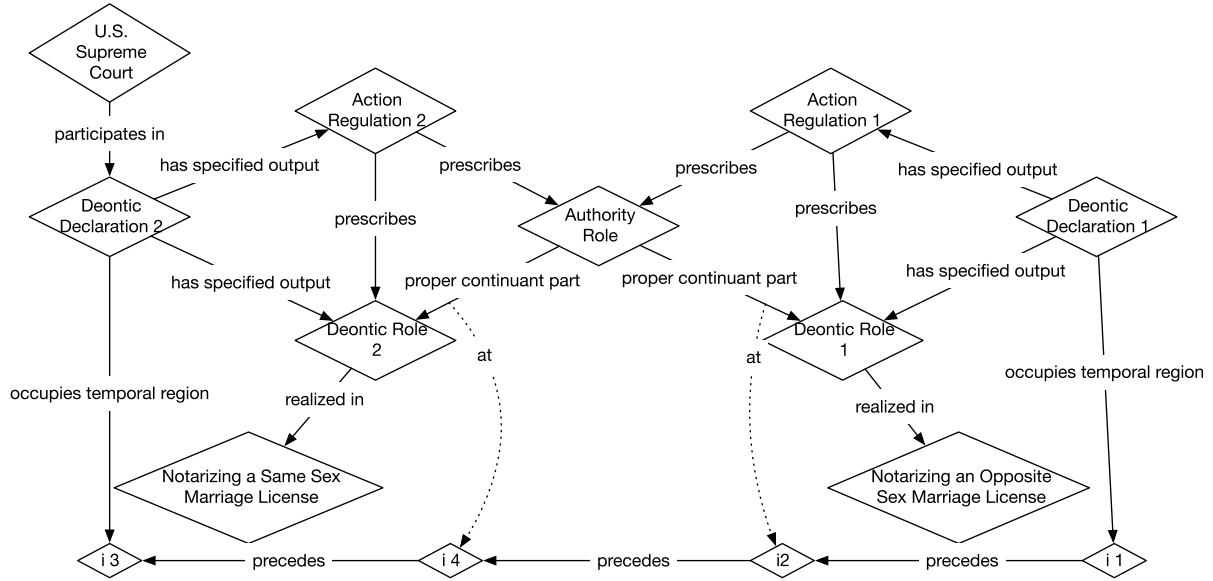


Fig. 9. Changing deontic roles in Case 6.

- (21) **inheres in**(*deontic role 2*, *Alex*)
- (22) **inheres in**(*deontic role 3*, *Bailey*)
- (23) **inheres in**(*deontic role 4*, *Bailey*)

At some point, following *deontic declaration 1* that results in the *state government* issuing *marriage license* for *Alex* and *Bailey*, the *U.S. Supreme Court* **participates in** *deontic declaration 2* resulting in all state prohibitions on same-sex marriage being deemed unconstitutional. *Deontic declaration 2* **has specified output** *action regulation 1* permitting the authorization of same-sex marriage. This prescription sanctions new realizations of state and local agent **instances of** authority role relevant to marriage contracts, by broadening the class of those eligible to participate in an act of marrying.

- (24) **instance of**(*U.S. Supreme Court*, organization, *i*)
- (25) **instance of**(*deontic declaration 2*, deontic declaration, *i2*)
- (26) **participates in**(*U.S. Supreme Court*, *deontic declaration 2*, *i2*)
- (27) **is a**(action regulation, information content entity)
- (28) **instance of**(action regulation, action regulation, *i2*)
- (29) **has specified output**(*deontic declaration 2*, *action regulation 1*)
- (30) **is a**(authority role, role)
- (31) **instance of**(*authority role 1*, authority role, *i2*)
- (32) **prescribes**(action regulation, *authority role 1*)
- (33) **inheres in**(*authority role 1*, *state government 1*)

The expansion of sanctioned realizations of **instances of** authority role by *state government* does not undermine that *Alex* and *Bailey* have a *marriage license*. This is because **instances of** deontic role borne by *Alex* and *Bailey* are not altered by *action regulation 1*, since *action regulation 1* targets eligibility constraints on marriage.

Table 18
Relations used in cases from other BFO-conformant ontologies

| Relation name and source* | Definition or elucidation |
|---|---|
| is about (IAO) | A primitive relation that relates an information artifact to an entity. |
| describes (CCO) | x <i>describes</i> y iff x is an instance of information content entity, and y is an instance of entity, such that x is about the characteristics by which y can be recognized or visualized. |
| achieves planned objective (OBI) | This relation obtains between a planned process and a objective specification when the criteria specified in the objective specification are met at the end of the planned process. |
| prescribes (CCO) | x <i>prescribes</i> y iff x is an instance of information content entity and y is an instance of entity, such that x serves as a rule or guide for y if y an occurrent, or x serves as a model for y if y is a continuant. |
| has specified output (OBI) | A relation between a planned process and a continuant which participates in that process. The presence of the continuant at the end of the process is explicitly specified in the objective specification which the process realizes the concretization of. |
| legally revokes (D-Acts) | d socio-legally revokes s if s participates in d and at the end of d s no longer exists. s going out of existence is complete and unlike the going out of existence for material entities which are always transformed into something else. After the declaration nothing is left of the socio-legal generically dependent continuant in question. |

*These relations come from ontologies using Basic Formal Ontology (BFO), including: The Common Core Ontologies (CCO), The Ontology for Biomedical Investigations (OBI), The Information Artifact Ontology (IAO), and The Ontology of Document Acts (D-Acts).

As discussed, governments may alter marriage contracts in another way, by changing spousal obligations and powers. To illustrate, suppose *state government* **participates in** *deontic declaration 3* which **legally revokes** the *deontic role 1* that **inheres in** *Alex* and *deontic role 2* that **inheres in** *Bailey*, which we assume correspond to privileges bearers have to refrain from testifying against their spouse. This results in *Alex* and *Bailey* losing these respective roles, though they maintain *deontic role 2* and *deontic role 4*.

- (34) **participates in**(*state government*, *deontic declaration 3*, $i3$)
- (35) **legally revokes**(*deontic declaration 3*, *deontic role 1*, $i3$)
- (36) **legally revokes**(*deontic declaration 3*, *deontic role 3*, $i3$)
- (37) $\exists t$ **occurrent part of**(t , $i3$) \wedge \neg **exists at**(*deontic role 1*, t) \wedge \neg **exists at**(*deontic role 3*, t)

At least two types of change to marriage licenses can be represented with BFO, reflecting changes to eligibility requirements – which either narrow or extend participants – or changes to associated roles – which either narrow or extend spousal rights and obligations. In each case, the meaning of marriage, in some sense, remains the same.

5. Ontology usage and community impact

BFO is committed to there being a single reality, with scientific investigation often resulting in clarifications of our picture of this reality. As science updates, ontology should follow. Other *conceptions*, past or present, of the way the world is, or might be, are merely informational entities and impose no further ontological commitments.

As the core architecture of The Open Biological and Biomedical Ontology (OBO) Foundry and The Industrial Ontology Foundry (IOF) [Smith et al., 2005, Smith et al., 2007, Smith et al., 2019], BFO is widely used across a range of scientific disciplines. BFO is used extensively in the biomedical domain [Bandrowski, 2016], providing domain specialists foundational support when modeling pheno-

types [Buttigieg, et. al., 2013], disease [Grenon, Smith, & Goldberg, 2004, Köhler et al., 2013, Scheuermann, Ceusters, & Smith, 2009, Beverley, Babcock, Cowell, & Smith 2020], diagnosis [He et al., 2020, Babcock, Beverley, Cowell, & Smith, 2021], and resistance [Goldfain, Smith, & Cowell, 2011]. BFO is presently used in over 350 ontology products, and with its recent standardization, this number will no doubt increase in the coming years.

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