Applied Ontology 3 (2006) 1–3
IOS Press

YAMATO: Yet-Another More Advanced Top-level Ontology

Riichiro Mizoguchi [a,*] and Fumiaki Toyoshima [b]
[a] *Research Center for Service Science, Japan Advanced Institute of Science and Technology (JAIST), 1-1 Asahidai, Nomi, Ishikawa 923-1292, Japan.*
E-mail: mizo@jaist.ac.jp
[b] *Graduate School of Advanced Science and Technology, Japan Advanced Institute of Science and Technology (JAIST), 1-1 Asahidai, Nomi, Ishikawa 923-1292, Japan.*
E-mail: fumiaki.toyoshima@jaist.ac.jp

Abstract. A late-comer upper ontology YAMATO is described in this paper. YAMATO sharply distinguishes itself from other existing upper ontologies in the following respects. (1) Most importantly, YAMATO is designed with both engineering and philosophical minds. (2) YAMATO is based on a sophisticated theory of roles, given that the world is full of roles. (3) YAMATO has a tenable theory of functions which helps to deal with artifacts effectively. (4) Information is a 'content-bearing' entity and it differs significantly from the entities that philosophers have traditionally discussed. Considering into account the modern society in which a flood of information occurs, YAMATO has a sophisticated theory of informational objects (representations). (5) Quality and quantity are carefully organized for the sake of greater interoperability of real-world data. (6) The philosophical contribution of YAMATO includes a theory of objects, processes, and events. Those features are illustrated with several case studies, leading to the intensive application of YAMATO in some domains such as biomedicine and learning engineering.

Keywords: YAMATO, foundational ontology, ontological analysis, formal ontology

Introduction

Upper ontology plays a key role in enhancing ontology development by giving developers a general guideline about how to view the target domain. There now exist several upper ontologies such as DOLCE (Borgo and Masolo, 2010), BFO (Arp, Smith and Spear, 2015), GFO (Herre, 2010), and UFO (Guizzardi and Wagner, 2010). Despite this, a new upper ontology YAMATO (Yet Another More Advanced Top-level Ontology) has been proposed in order to solve the theoretical and practical problems that other upper ontologies mishandle (Mizoguchi, 2010). Although it is currently being axiomatized and is not yet fully so, YAMATO is implemented with the ontology editor Hozo[1] and in OWL.[2]

Each upper ontology accepts as a rationale of ontology design its own combination of *ontological choices* (Borgo and Masolo, 2010). For example, BFO takes a realist approach (Smith and Ceusters, 2010). Designed with both engineering and philosophical minds, YAMATO currently possesses approximately 500 classes so that it will be conceptually rich enough to help effectively to build developers domain-specific ontologies. Although its structure might be criticized for being too large and complex, YAMATO causes no practical difficulty; and its users are simply recommended to employ the higher-level categories that suit their needs, ignoring the lower-level ones. YAMATO has the following distinguishing features:

I YAMATO accepts fundamental distinctions such as continuant vs. occurrent, independent entity vs. dependent entity, and quality vs. quantity as well as several meta-level properties with which to define fundamental types of entities (e.g., integrity, unity, and dissectivity). For example, an object

*Corresponding author: Riichiro Mizoguchi, Research Center for Service Science, Japan Advanced Institute of Science and Technology (JAIST), 1-1 Asahidai, Nomi, Ishikawa 923-1292, Japan.

[1] `http://www.hozo.jp/`

[2] The Hozo and OWL files of YAMATO are freely available for use at `http://www.ei.sanken.osaka-u.ac.jp/hozo/onto_library/upperOnto.htm`.

is elucidated as an integral, unitary, and non-dissective continuant. Used in the YAMATO hierarchy is strict single is-a inheritance in which is-a and instance-of relations are carefully defined in terms of set membership and the notion of *essential property*. Within its is-a hierarchy YAMATO does not place a role (e.g., a teacher class) under the category of an independent entity (e.g., a person class).

II To deal with engineering problems (especially interoperability of engineering data), YAMATO offers a careful treatment of properties and qualities, thereby preventing terminological confusions over them (Mizoguchi, 2010). Roughly speaking, a quality is defined as the value-free attribute that inheres in a particular object and a property is as a complex attribute that can be represented as a pair of quality and some value.[3] For instance, John's height *simplicitier* is a quality (but not John's height of 160cm) and the attribute represented by <height, 160cm> is a property.

III Taking it that functions are at the heart of artifacts (Borgo, Fransse, Garbacz, Kitamura, Mizoguchi and Vermass, 2014), YAMATO deals well with not only organisms but also artifacts on the basis of the fully developed notion of function (Kitamura, Koji and Mizoguchi, 2006; Kitamura and Mizoguchi, 2013; Mizoguchi and Kitamura, 2009; Mizoguchi, 2010). Its idea of systemic function covers both biological and artifact functions in a single framework (Mizoguchi, Kitamura and Borgo, 2016; Borgo, Mizoguchi and Kitamura, 2016). It strictly distinguishes behaving and functioning, since function is defined as a role played by a behavior in a context. In other words, whether a behavior can perform a function or not depends entirely on in what context it is performed. For example, waving your hands is said to be functioning only in the case where it is performed towards persons; otherwise, it is just moving your hand (mere behavioring but not functioning).

IV YAMATO sharply distinguishes processes from events to capture the 'unfolding' process during a 'completed' event (Galton and Mizoguchi, 2009). An event is to be treated as a whole which extends in its full interval and is constituted by a process, whose occurrence models well the 'unfoldingness' of an occurrent during the event. A sequence of events (e.g., a sequence of impulses) can form a process. A process is intrinsically progressive (ongoing) and hence it is 'wholly present' at any time at which it exists. Therefore, a process can change but no event can.

V Given that the real world is full of roles, YAMATO develops a theory of roles which divides the traditional conception of role into a *role* (the object to be played) and a *role-holder* (the player playing the role), thus handling the problem of a vacant role, namely a role without a player. Interpreted from this perspective, any part of an object has some role with respect to the object as a whole which provides a context on which the role depends. YAMATO is thus based on a principle of mutual dependence of parts and the whole. Furthermore, it distinguishes two types of parts: a genuine part and a replaceable part. For instance, a genuine part of a bike corresponds to the front wheel and its replaceable part to a wheel that is purchased at a bike shop. This distinction is of vital importance for a correct way of modeling objects (Mizoguchi and Borgo, 2017).

VI To deal with informational objects in the modern world, YAMATO elaborates a theory of representation according to which a representation is composed of (representation) form and content; and a representhing thing is composed of a representation and a representation medium. Examples of representations include an algorithm, a procedure, a plan, a computer program, a musical score, a novel, a painting, data, a letter, and a sentence.

Regarding Features (I) and (IV), Section 1 explains fundamental distinctions in categories and attributes, meta-level attributes, is-a relation, top-level categories, and the distinction between objects, processes, and events. Section 2 presents part of the first-order formalization of YAMATO. Section 3 illustates mainly Features (II), (IV), (V), and (VI) with several case stuides. Section 4 offers some application examples of YAMATO, a fair number of which pertain to Feature (III).

[3]The term 'attribute' here and henceforth is used as the most generic term for properties/qualities. Note that the term 'essential property' is exceptionally employed in the paper instead of 'essential attribute' in conformity with its conventional usage.

1. Principles and structures of YAMATO

1.1. Fundamental distinctions in categories and attributes

The following list includes basic distinctions in YAMATO categories and attributes:

1. *Substrate vs. entity*. Space and time are indispensable for the mode of existence of entities, i.e. the individuals that are said to exist in space and time. Taking into account engineering utility, YAMATO assumes Newtonian spacetime: three-dimensional Euclidean space and absolute time. Matter is less fundamental to reality than, but have a close affinity with, space and time in the sense that every physical individual is made of/from matter. Examples of matter include water and iron (represented by the chemical formulas 'H_2O' and 'Fe', respectively).
2. *Independent entity vs. dependent entity.* An entity is independent if it exists independently of anything else and independent entities exist by themselves. Examples include a human, a car, and to walk. An entity is dependent if it depends existentially on another entity and some dependent entities inhere in an object. Examples include a height, a husband, and a fragility. Typical examples of dependent entities include qualities (e.g., a height) and dispositions (e.g., fragility).
3. *Basic type vs. role.* Roles are entities that depend on a context and can be played by another entity (Mizoguchi, Sunagawa, Kozaki and Kitamura, 2007). YAMATO possesses a broad classification of roles (Mizoguchi, Galton, Kozaki and Kitamura, 2015). Some roles (e.g., a teacher) are object roles, i.e. roles played by objects, while others (e.g., a preparation) are occurrent roles, i.e. roles played by occurrents. Roles can be also divided into object-dependent roles (e.g., a wife) and occurrent-dependent roles (e.g., a murderer). Interestingly enough, the part-whole relation and the participation relation between an object and an occurrent are interpretable in terms of the relation between a role and the context on which it depends.
4. *Continuant (Object) vs. occurrent (process).*[4] There is a long-standing debate between the object-centered (three-dimensionalist) view and the process-centered (four-dimensionalist) view of reality. Taking it that neither of them succeeds, YAMATO attaches equal importance to objects and occurrents and defines an object as 'a unity which enacts its external process' or as 'an *interface* between its internal and external processes' (Galton and Mizoguchi, 2009). See Section 1.4 for details.
5. *Process vs. event*. YAMATO sharply distinguishes between processes and events in accordance with ordinary people's differentiation between processes (e.g., "Mary is walking.") and events (e.g., "Mary walked a mile.") in their natural language activity (Galton and Mizoguchi, 2009). A process is 'wholly present' at any time at which it exists and it can change; whereas, an event is to occupy a time interval as a whole and it cannot change. See Section 1.4 for details.
6. *Object and quality/property/attribute*. No object can exist without having any attribute; and every physical object exemplifies a couple of attributes (e.g., a color, a mass, and a size). At the same time, no attribute exists by itself since it needs an object as its bearer. Thus both an object and a quality/property intrinsically depend on each other and they are completely inseparable. The difference between a property and a quality is discussed in Section 3.3 and in Mizoguchi (2010).
7. *Quality vs. quantity*. It is tempting to think, as is supported by some upper ontologies, that quantity is an instance of quality because, e.g., the 15 cm length of my pencil seems to be an instance of length (quality). YAMATO nevertheless draws a marked distinction between quality and quantity. As a result, quantity is defined as a generically dependent continuant and, independently of quality, quantity has its own is-a hierarchy according to which there are four subtypes of quantiy based on Steven's (1946) theory of scales of measurement: *nominal*, *ordinal*, *interval*, and *ratio*.
8. *Physical and abstract*. Independent entities fall into physical entities, semi-abstract entities, and abstract entities. A physical entity depends existentially on both space and time. Examples include continuants and occurrents. A semi-abstract entity depends only on time (but not on space). Ex-

[4]We mean by 'process' occurents in general until we discuss the difference between processes and events.

amples include contents (e.g., propositions) and representations. An abstract entity depends neither on space nor on time. Examples include numbers, sets, and truth-values. A non-paradigmatic but interesting abstract entity may be a structure (e.g., a crystal structure).

9. *Entity and relation*. A relation holds between entities and it is something 'higher-order' in this respect. Examples of relations include friendship, a marital relation, and the part-whole relation. Although it is intangible, a relation is not to be understood as abstract because it is time-depedent in the sense of coming into existence at a particular time in the world. One serious issue with relations is that formalistic thinking sometimes leads to the confusion between entities and relations. Actions and attributes are often misconceived as relations but they are existing entities, for example, because an action and an attribute can be formalized as a relation between an actor and an occurrent and as a relation between an object and a value, respectively.
10. *Entity stacking*. To address the problem of material coincidence, YAMATO adopts the entity stacking theory to allow two different entities (e.g., a vase and amount of clay) to occupy the same spaciotemporal region (Vieu, Borgo and Masolo, 2008).
11. *Informational object (representation) vs. non-informational object*. As compared to non-informational objects (e.g., objects, processes,attributes, and relations), examples of informational objects include music, novels, texts, and symbols. Less attention has been paid to informational objects in upper ontologies in general than to non-informational objects, but YAMATO elaborates a theory of the former since a fine-grained model of the real (especially modern) world requires an in-depth discussion of representation, e.g., on what the instances of representations are like (including a computer program and an algorithm as well as what exists on the Web) (Mizoguchi, 2004).

1.2. Meta-level attributes

YAMATO employs the following six mete-level attributes in order to define fundamental types of entities:

1. *Sortal*. Sortal is the most fundamental principle. Whether an entity is countable or uncountable can be recognized by the nature of the noun that refers to that entity. For instance, the noun 'desk' is countable and so is a desk; but 'water' is a mass noun and water is uncountable. Thus the term 'yellow thing' fails to be accepted in YAMATO. Consider the question "How many yellow things are there in the room?", assuming that there is exactly one yellow table in the room.
2. *Identity*. Identity is crucial but mysterious. For the sake of practical ontological modeling, YAMATO exploits identity criterion of entities to determine the subsumption relation between two types of entities, although it is extremely difficult to specify identity criteria of most entities. At a domain-specific level, for instance, a group of people fails to subsume a company because a company preserves its identity despite a change in its group-of-people identity (e.g., in its employees).
3. *Integrity*. An entity is integral if its parts are identifiable. Examples of non-integral entities include 10g of salt. 10g of salt preserves its identity irrespective of the replacement of any grain thereof because reference to 10g of salt (as compared to a pile of salt which is 10g in weight on this particular table) does not identify *which* grain of salt is to belong to it.
4. *Unity*. An entity is unitary if the mereological sum of its parts are said to be a whole in virtue of the nature of those parts and the relations among them. Examples of non-unitary entities include arbitrary aggregations of entities (e.g., an aggregation consisting of the Moon and the number 3).
5. *Dissectivity*. An entity is dissective if its parts fall into the same type of that of the entity. Examples of dissective entities include a forest, a network, and a lump of butter.
6. *Rigidity*. A class is rigid if its instances belong to the class in virtue of their essential property (see Section 1.3) and a class is anti-rigid if there is no essential property in virtue of which any instance of the class belong to it. A paradigmatic example of anti-rigid classes is 'role classes' e.g., a student class and a president class. *Is-a* relation holds only between rigid classes in YAMATO.

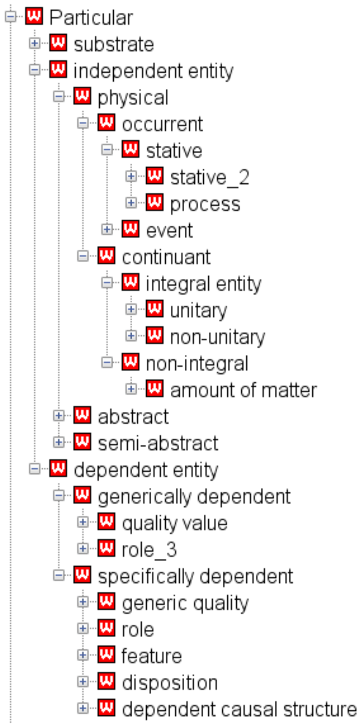

Fig. 1. Top-level categories.

1.3. *Is-a relation and top-level categories*

Strongly influenced by Guarino's (1995) view of upper ontology, YAMATO adopts is-a single inheritance so that its taxonomic structure will be as simple as those of BFO and DOLCE (see Figure 1). The basic assumption behind the set-theoretic formalization of is-a and instance-of relations in YAMATO is that each entity has its own *essential property*: a property in virtue of which the entity preserves its identity.[5] A set X is a *class* when and only when, for every element x of X, x has an essential property in common and this property satisfies the intension of X; and *at the same time*, x bears *instance-of* relation to (that is to say, x is an *instance* of) X. *Is-a* relation holds between a set X and a set Y when and only when X and Y are classes and the *set of the instances* of X is a subset of the *set of the instances* of Y.

Is-a relation in YAMATO implies inheritance of essence and an identity criterion by a certain class (X) from its superclass (Y). Thus, is-a multiple inheritances should be avoided because no entity can have multiple essential natures in theory. The problem of is-a multiple inheritance can be, for the most part, circumvented through a sharp distinction between is-a relation and role-playing relation (Mizoguchi, Sunagawa, Kozaki and Kitamura, 2007). Consider for instance "Apple class *is-a* Fruit class" and "Apple class *is-a* Goods class". The latter is-a relation is incorrect because goods are to be conceptualized as a role. In a domain ontology, however, the simple use of is-a single inheritance may not be useful enough to encompass domain experts' different viewpoints on the same entity. This practical issue is to be addressed with the application of the methodology of dynamic *is-a* hierarchy generation that is based on is-a single inheritance and implemented in the Hozo ontology editor (Kozaki, Hihara and Mizoguchi, 2012).

1.4. *Objects, processes and events*

The conception of objects, processes, and events in YAMATO is owed to Galton and Mizoguchi (2009). The three-dimensionalist (3D) and four-dimensionalist (4D) views of reality say that objects are prior to processes and that processes are prior to objects, respectively. Taking it that neither of them is plausible,

[5]The work on the YAMATO set-theoretic axiomatization of is-a and instance-of relations is currently under review in a journal.

Table 1
The YAMATO categories here used.

Category	Description	Category	Description
EVNT	event	INST	temporal instant
INTR	temporal interval	OBJ	whole object
PROC	process	ROLE	role
TIME	time		

YAMATO takes, so to speak, a three-and-a-half dimensionalist (3.5D) view of reality: objects and processes are mutually dependent on each other. This worldview leads to the characterization of an object as 'a unity which enacts its external process' or as 'an interface between its internal and external processes'. For instance, a river as an object has, as its external process, changing its course of water flowing (but not water flowing, which is its internal process).

Concerning processes and events, both kinds of occurents are temporally extended unlike objects. On the one hand, a process is intrinsically 'ongoing' and it is 'wholly present' at any time at which it exists. Therefore, processes are mutable and preserve their identities like objects: they can have different properties at different times. On the other hand, an event is essentially 'completed' and it occupies exactly an entire spacetime region.[6] Events differ significantly from processes in the sense of being immutable. Each event (e.g., a walk event) is constituted by a process (e.g., a walking process).

Further elucidation of the difference between processes and events is offered in terms of two kinds of parts of occurrents in YAMATO: temporal parts and causal parts. A temporal part of an occurrent corresponds to a mereological part of an object. A causal part of an occurrent is the part which contributes functionally to the occurrent. Processes and events have causal parts, whereas events (but not processes) have temporal parts. Suppose for instance that John sneezes while he is walking. The alternate motion of John's legs is a causal part of John's walking process since John's walking depends essentially on the motion of his legs; in contrast, John's sneezing is not a causal part of John's walking process. Neither the motion of John's legs nor John's sneezing is a temporal part of John's walking process. In short, every temporal part of an occurrent is a causal part of the occurrent, but not vice versa.

2. The formalization of YAMATO in first-order language

YAMATO is partially axiomatized: for instance, its process/event-related module (Borgo and Mizoguchi, 2014) and its role-related module (Mizoguchi, Galton, Kozaki and Kitamura, 2015) have been formalized. This section presents part of the former formalization. Extracted from Borgo and Mizoguchi (2014), Table 1 and Table 2 show the relevant categories and the relations among them, respectively. They are also graphically shown in Figure 2. Future formal development of YAMATO includes to deepen the current axiomatization and to formalize the rest, e.g., regarding the categories of quality/quantity and representation so that, ontologically and formally, YAMATO will be closely comparable to other upper ontologies.

The parthood relation P used in YAMATO has the axiomatization of Closed Extensional Mereology (CEM) (Casati and Varzi, 1999). it is binary on events and temporalized, thus ternary, on processes and objects. The other mereological relations and operators, like O ($\mathsf{O}(x, y$ stands for "x and y overlap"), PP ($\mathsf{PP}(x, y)$ for "x is a proper part of y"), SUM ($\mathsf{SUM}(z, x, y)$ for "z is the sum of x, y") and PROD ($\mathsf{PROD}(z, x, y)$ for "z is the product of x, y"), are defined as usual in CEM (Casati and Varzi, 1999). When P is applied to processes it is written $\mathsf{P}(x, y, t)$ and reads "process x is part of process y at instant t." The temporal parameter must be a temporal instant since in YAMATO a process can be part of another only relatively to an instant. From these constraints and the theory of processes in YAMATO, the notion of a

[6] One way to delineate ongoingness of processes and completedness of events is to base them on A-series and B-series of times, respectively (McTaggart, 1908). This issue being included, the YAMATO overall formalization of time is currently under investigation.

Table 2

Some YAMATO relations. Relations marked ∗ are defined.

Relation	Description	Relation	Description
CCNTR	causally contributes	CNTX	context
ENCT	enacts	$\mathsf{EVNT_T}$	event spans time
EVNTKND	event-kind	IntFnPRC	process playing an internal role
KONST	constitutes	P	part of
PC	participates in	PLAY	play
PRE	present at	PROCKND	process-kind
$\mathsf{PROC_T}$	process at time	*HasPRC	has internal process
O	overlap	*PP	proper part
PROD	product	*SUM	sum

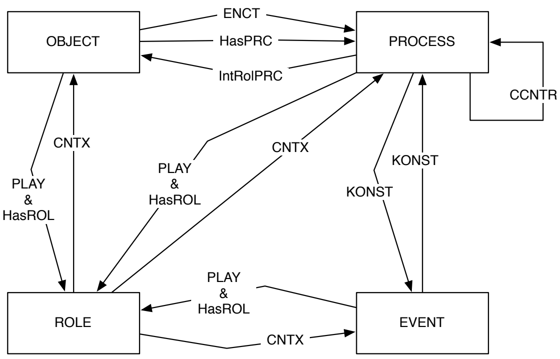

Fig. 2. YAMATO structure (partial).

'whole process' (a process from its beginning to its end) is either understood as an event or is conceptually incoherent.

(A1) says that P is additive on the category of objects OBJ (as usual, we assume that free variables in formulas are universally quantified)

(A1) $\mathsf{OBJ}(x) \wedge \mathsf{OBJ}(y) \wedge \mathsf{SUM}(z,x,y) \rightarrow \mathsf{OBJ}(z)$ (additivity on OBJ)

This holds as well on events EVNT and processes PROC which are also additive. For processes, we need to introduce the binary relation 'being present at', written PRE, which has as second argument a time, and is itself dissective:

(A2) $\mathsf{EVNT}(x) \wedge \mathsf{P}(y,x) \rightarrow \mathsf{EVNT}(y)$ (dissectivity on EVNT)

(A3) $\mathsf{EVNT}(x) \wedge \mathsf{EVNT}(y) \wedge \mathsf{SUM}(z,x,y) \rightarrow \mathsf{EVNT}(z)$ (additivity on EVNT)

(A4) $\mathsf{PRE}(x,t) \rightarrow \mathsf{TIME}(t)$

(A5) $\mathsf{PRE}(x,t) \wedge \mathsf{P}(t',t) \rightarrow \mathsf{PRE}(x,t')$ (dissectivity on PRE)

(A6) $\mathsf{PRE}(x,t) \wedge \mathsf{PROC}(x) \wedge \mathsf{P}(y,x,t) \rightarrow \mathsf{PRE}(y,t) \wedge \mathsf{PROC}(y)$ (dissectivity on PROC)

(A7) $\mathsf{PRE}(x,t) \wedge \mathsf{PROC}(x) \wedge \mathsf{PRE}(y,t) \wedge \mathsf{PROC}(y) \wedge \mathsf{SUM}(z,x,y,t) \rightarrow \mathsf{PRE}(z,t) \wedge \mathsf{PROC}(z)$ (additivity on PROC)

We anticipate that $\mathsf{P}(x,y,t)$, with x, y processes, holds only if t is an instant, both x, y exist at this instant t, and all the (active) participants in y are (active) participants in x.[7] Furthermore, the notion of enactor, which we can model logically as the sum of all the active participants, would suffice to define P on processes.

[7] An active participant is a participant that is relevant for the given process like the person in a walking process and the shopfloor in a production process. This notion is not further characterized here.

The relation of participation, PC (participates in), applies to an object and an event or process (A8); each event and process has at least one participant (A9); each object participates in some event or process (A10); a participant in an event or process is participant also in any larger event/process (A11); and any part of an object participates in the events and processes in which the object itself participates (A12). See also Borgo and Masolo (2009):

(A8) $\mathsf{PC}(x, y, t) \to \mathsf{OBJ}(x) \wedge (\mathsf{EVNT}(y) \vee \mathsf{PROC}(y)) \wedge \mathsf{TIME}(t)$
(A9) $(\mathsf{EVNT}(x) \vee \mathsf{PROC}(x)) \wedge \mathsf{PRE}(x, t) \to \exists y(\mathsf{PC}(y, x, t))$
(A10) $\mathsf{OBJ}(x) \wedge \mathsf{PRE}(x, t) \to \exists y(\mathsf{PC}(x, y, t))$
(A11) $\mathsf{PC}(x, y, t) \wedge \mathsf{P}(y, y', t) \to \mathsf{PC}(x, y', t)$
(A12) $\mathsf{PC}(x, y, t) \wedge \mathsf{P}(x', x, t) \to \mathsf{PC}(x', y, t)$

Finally, we assume that instants form a complete dense order. This is used in the formalization to model the special relationship between events and processes. Intervals could be reconstructed from instants as usual in knowledge representation (Tsang, 1987) but in practice here we consider both as primitives. In particular, we assume that a time is an instant or an interval but not both (A13); an instant is a time with no proper part (A14); and an interval is a time that has a time as proper part (A15). We assume that time (intervals and instants) is modeled by the real line but this is not enforced by the axiomatization itself.

(A13) $\mathsf{TIME}(t) \to (\mathsf{INST}(t) \dot{\vee} \mathsf{INTR}(t))$
(A14) $\mathsf{INST}(t) \to \mathsf{TIME}(t) \wedge \forall x \neg \mathsf{PP}(x, t)$
(A15) $\mathsf{INTR}(t) \to \mathsf{TIME}(t) \wedge \exists x\ (\mathsf{TIME}(x) \wedge \mathsf{PP}(x, t))$

We write $\mathsf{EVNT_T}(x, t)$ when t is the instant or interval spanned by the event x; and $\mathsf{PROC_T}(x, t)$ when the process x is ongoing at instant t.

(A16) $\mathsf{EVNT_T}(x, t) \to \mathsf{EVNT}(x) \wedge \mathsf{TIME}(t)$
(A17) $\mathsf{PROC_T}(x, t) \to \mathsf{PROC}(x) \wedge \mathsf{INST}(t)$

We will write $t < t'$ for $\mathsf{TIME}(t)$ and $\mathsf{TIME}(t')$ to mean that time t is (starts) earlier than time t'. We use the relation $<$ (or $\leqslant$ as well as their inverses) only over TIME.

3. Analysis and formalization in YAMATO: examples

3.1. Composition/constitution

1) "There is a four-legged table made of wood. Some time 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.)

Composition and constitution of an object is explicable in terms of the role-based characterization of parts of the object (Mizoguchi and Borgo, 2017).[8] The underlying assumption is the constitution view of objects: except for, e.g., subatomic particles, every physical object is made of/from some amount of matter (see Section 1.1). According to the role interpretation of parthood, an entity (potential player) plays a part role (role) with respect to an object (context), thereby becoming a part (role-holder) of the object. In this formalization, the entity is a *replaceable part* because it can be substituted by another entity that is of the

[8]The reader is recommended to read first Section 3.2 to understand the YAMATO theory of roles.

Table 3
Categories and relations for composition/constitution and case analysis

Notation	Description	Notation	Description
MAT	matter, material (see Section 1.1)	$\mathsf{PRE}(x,t)$	present at (from Table 2)
TIME	time (from Table 1)	$\mathsf{consti}(x,y,t)$	x constitutes y at t
OBJ	object (from Table 1)	$\mathsf{CNTX}(x,y)$	role x has y as context (from Table 2)
ROLE	role (from Table 1)	$\mathsf{depend}(x,y)$	x depends on y
QUAL	quality (see Section 3.3)	$\mathsf{bear}(x,y,t)$	object x bears quality y at t
$\mathsf{inhere}(x,y)$	x inheres in y (see Section 3.3)	$\mathsf{PLAY}(x,y,t)$	object x plays role y at time t
P	part of (from Table 2)		(from Table 2)
SUM	sum (from Table 2)	$\mathsf{hold}(x,y,t)$	object x holds role y at time t
$\mathsf{ROHO}(x,t)$	role-holder x is present at time t		

same kind; and the part of the object is a *genuine part* because it is spatiotemporally located exactly to the specification of the part role under consideration.

Part of the issue of identity over time is to be addressed with a distinction between replaceable parts and genuine parts of an object. An object persists unless the specification given by part roles of the object is violated, even if the object undergoes various changes, including the replacement of its parts (or more precisely, of its replaceable parts). An object perishes when its specification fails to be met and the amount of matter that constitutes the object still persists after the demolition.[9]

Core formalization of composition and constitution (see Table 3; see also Section 3.2)
(♠) $\mathsf{OBJ}(x) \wedge \mathsf{TIME}(t) \wedge \mathsf{PRE}(x,t) \rightarrow \exists y\,(\mathsf{MAT}(y) \wedge \mathsf{consti}(y,x,t))$
$\mathsf{ROLE}(x) \rightarrow \exists y,z\,(\mathsf{CNTX}(x,y) \wedge \mathsf{QUAL}(z) \wedge \mathsf{depend}(z,y) \wedge \mathsf{inhere}(z,x))$
(♣) $\mathsf{PLAY}(x,y,t) \wedge \mathsf{QUAL}(z) \wedge \mathsf{inhere}(z,y) \rightarrow \mathsf{hold}(x,y,t) \wedge \mathsf{bear}(x,z,t)$
(♢) $\mathsf{P}(x,y,t) \wedge \mathsf{OBJ}(y) \wedge \mathsf{TIME}(t) \rightarrow \exists z\,(\mathsf{CNTX}(z,y) \wedge \mathsf{hold}(x,z,t))$
(♡) $\mathsf{ROHO}(x,t) \leftrightarrow \exists y\,(\mathsf{ROLE}(y) \wedge \mathsf{hold}(x,y,t))$

Formalization for case analysis (see Table 3)
"There is a four-legged table (T_1) made of an amount of wood (W_1) at t_1. T_1 is composed of a top-board ($\mathsf{TB_1}$) and four legs ($\mathsf{L_1}$, $\mathsf{L_2}$, $\mathsf{L_3}$, and $\mathsf{L_4}$). $\mathsf{TB_1}$ is made of a board (B_1); and $\mathsf{L_1}$, $\mathsf{L_2}$, $\mathsf{L_3}$, and $\mathsf{L_4}$ are made of four rods R_1, R_2, R_3, and R_4, respectively. At t_2, a leg $\mathsf{L_4}$ of the table is replaced in such a way that $\mathsf{L_4}$ and T_1 are made of another rod (R'_4) and another amount of wood (W_2), respectively. The table is demolished at t_3 and it ceases to exist." The notations TB_1R, L_iR, TBP, and L_iP are also introduced so that $\mathsf{ROLE}(TB_1R) \wedge \bigwedge_{1\leqslant i\leqslant 4} \mathsf{ROLE}(L_iR) \wedge \mathsf{QUAL}(TBP) \wedge \bigwedge_{1\leqslant i\leqslant 4} \mathsf{QUAL}(L_iP)$ holds. Note that TBP and L_iP are semantically read as "being in an appropriate position for a top-board"and "being in an appropriate position for L_i", respectively.

The following holds: $\mathsf{OBJ}(T_1) \wedge (\mathsf{PRE}(T_1,t) \rightarrow t < t_3) \wedge \mathsf{MAT}(W_1) \wedge \mathsf{MAT}(W_2) \wedge \mathsf{MAT}(B_1) \wedge \bigwedge_{1\leqslant i\leqslant 4} \mathsf{MAT}(R_i) \wedge \mathsf{MAT}(R'_4) \wedge W_1 = \mathsf{SUM}(TB_1,R_1,R_2,R_3,R_4) \wedge W_2 = \mathsf{SUM}(TB_1,R_1,R_2,R_3,R'_4) \wedge \mathsf{depend}(TBP,T_1) \wedge \bigwedge_{1\leqslant i\leqslant 4} \mathsf{depend}(L_iP,T_1) \wedge \mathsf{inhere}(TBP,TB_1R) \wedge \bigwedge_{1\leqslant i\leqslant 4} \mathsf{inhere}(L_iP,L_iR) \wedge (\mathsf{TB_1}(x,t) \leftrightarrow \mathsf{hold}(x,TB_1R,t)) \wedge \bigwedge_{1\leqslant i\leqslant 4}(\mathsf{L_i}(x,t) \leftrightarrow \mathsf{hold}(x,L_iR,t))$.[10]

$t_1 \leqslant t < t_2 \rightarrow \mathsf{PLAY}(B_1,TB_1R,t) \wedge \bigwedge_{1\leqslant i\leqslant 4} \mathsf{PLAY}(R_i,L_iR,t) \wedge \mathsf{QUAL}(TBP) \wedge \bigwedge_{1\leqslant i\leqslant 4} \mathsf{QUAL}(L_iP) \wedge \mathsf{inhere}(TBP,TB_1) \wedge \bigwedge_{1\leqslant i\leqslant 4} \mathsf{inhere}(L_iP,L_iR)$
$\therefore t_1 \leqslant t < t_2 \rightarrow \mathsf{hold}(B_1,TB_1R,t) \wedge \bigwedge_{1\leqslant i\leqslant 4} \mathsf{hold}(R_i,L_iR,t) \wedge \mathsf{bear}(B_1,TBP,t) \wedge \bigwedge_{1\leqslant i\leqslant 4} \mathsf{bear}(R_i,L_iP,t)$ ($\because$ (♣))

[9]It is assumed in this section that composition is *restricted*: composition occurs only in some appropriate situations (a full explanation of which is beyond the scope of the present paper).

[10]A rod is here treated as a kind of material (wood) for the sake of simplicity, although it is used in compounds frequently enough to be modeled better as a role-holder which an amount of wood plays a rod role in some context, thereby becoming.

Table 4

Categories and relations for roles and case analysis

Notation	Description	Notation	Description
ROLE	role (from Table 1)	$\mathsf{CNTX}(x, y)$	role x has y as context (from Table 2)
OBJ	object (from Table 1)	$\mathsf{PLAY}(x, y, t)$	object x plays role y at time t (from Table 2)
TIME	time (from Table 1)	$\mathsf{depend}(x, y)$	x depends on y
QUAL	quality (see Section 3.3)	$\mathsf{bear}(x, y, t)$	object x bears quality y at t
TERO	teacher role	$\mathsf{hold}(x, y, t)$	object x holds role y at time t
TEER	teacher	$\mathsf{inhere}(x, y)$	x inheres in y (see Section 3.3)
HUM	human	PRE	present at (from Table 2)
STRO	student role	$\mathsf{ROHO}(x, t)$	role-holder x is present at t
STU	student		

$\therefore t_1 \leqslant t < t_2 \rightarrow \mathsf{TB_1}(B_1, t) \wedge \bigwedge_{1 \leqslant i \leqslant 4} \mathsf{L_i}(R_i, t)$ (see ($\heartsuit$)) ("A board and four rods (including R_4) become a top-board and legs respectively, the structutal combination of which is a table.")
$t_1 \leqslant t < t_2 \rightarrow \mathsf{consti}(W_1, T_1, t) \wedge \mathsf{P}(B_1, T_1, t) \wedge \bigwedge_{1 \leqslant i \leqslant 4} \mathsf{P}(R_i, T_1, t)$ (see ($\spadesuit$)($\diamondsuit$))
$t_2 \leqslant t < t_3 \rightarrow \mathsf{PLAY}(B_1, TB_1R, t) \wedge \bigwedge_{1 \leqslant i \leqslant 3} \mathsf{PLAY}(R_i, L_iR, t) \wedge \mathsf{PLAY}(R_4', L_4R, t) \wedge \mathsf{QUAL}(TBP) \wedge \bigwedge_{1 \leqslant i \leqslant 4} \mathsf{QUAL}(L_iP) \wedge \mathsf{inhere}(TBP, TB_1R) \wedge \bigwedge_{1 \leqslant i \leqslant 4} \mathsf{inhere}(L_iP, L_iR)$
$\therefore t_2 \leqslant t < t_3 \rightarrow \mathsf{hold}(B_1, TB_1R, t) \wedge \bigwedge_{1 \leqslant i \leqslant 3} \mathsf{hold}(R_i, L_iR, t) \wedge \mathsf{hold}(R_4', L_4R, t) \wedge \mathsf{bear}(B_1, TBP, t) \wedge \bigwedge_{1 \leqslant i \leqslant 3} \mathsf{bear}(R_i, L_iP, t) \wedge \mathsf{bear}(R_4', L_4P, t)$ ($\because$ ($\clubsuit$))
$\therefore t_2 \leqslant t < t_3 \rightarrow \mathsf{TB_1}(B_1, t) \wedge \bigwedge_{1 \leqslant i \leqslant 3} \mathsf{L_i}(R_i, t) \wedge \mathsf{L_4}(R_4', t)$ (see ($\heartsuit$)) ("A board and four rods (including R_4') become a top-board and legs respectively, the structutal combination of which is a table.")
$t_2 \leqslant t < t_3 \rightarrow \mathsf{consti}(W_2, T_1, t) \wedge \mathsf{P}(B_1, T_1, t) \wedge \bigwedge_{1 \leqslant i \leqslant 3} \mathsf{P}(R_i, T_1, t) \wedge \mathsf{P}(R_4', T_1, t)$ (see ($\spadesuit$)($\diamondsuit$))
$t \geqslant t_3 \rightarrow \neg\mathsf{hold}(B_1, TB_1R, t) \wedge \bigwedge_{1 \leqslant i \leqslant 3} \neg\mathsf{hold}(R_i, L_iR, t) \wedge \neg\mathsf{hold}(R_4', L_4R, t)$
$\therefore t \geqslant t_3 \rightarrow \neg\mathsf{P}(B_1, T_1, t) \wedge \bigwedge_{1 \leqslant i \leqslant 3} \neg\mathsf{P}(R_i, T_1, t) \wedge \neg\mathsf{P}(R_4', T_1, t)$ ($\because$ ($\diamondsuit$))

3.2. Roles

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.

In YAMATO, roles are anti-rigid, dynamic, and externally grounded (Masolo et al., 2004). The core of the YAMATO conception of roles can be summarized in the schema: "A potential player plays a role in a context, thereby becoming a role-holder." A *context* is one or more entities (or a mereological sum of them) on which a role depends, hence a role as a dependent continuant. A *role* is an entity to be played, a *potential player* is an entity that *can* play a role, and a potential player becomes a *role-holder* in playing some role. The sharp distinction between a role and a role-holder helps to conceptualize well the change in players (but not in roles as such) and vacant roles, i.e. roles with no player.

Core formalization of roles [11](See Table 4)
$\mathsf{ROLE}(x) \rightarrow \exists y, z\, (\mathsf{CNTX}(x, y) \wedge \mathsf{QUAL}(z) \wedge \mathsf{depend}(z, y) \wedge \mathsf{inhere}(z, x))$
($\clubsuit$) $\mathsf{PLAY}(x, y, t) \wedge \mathsf{QUAL}(z) \wedge \mathsf{inhere}(z, y) \rightarrow \mathsf{hold}(x, y, t) \wedge \mathsf{bear}(x, z, t)$

[11]See Mizoguchi, Galton, Koji and Kitamura (2015) and Borgo and Mizoguchi (2014) a fuller formalization.

($\heartsuit$) $\mathsf{ROHO}(x,t) \leftrightarrow \exists y\,(\mathsf{ROLE}(y) \wedge \mathsf{hold}(x,y,t))$

Formalization for case analysis (see Table 4)
"Mr. Potter (P) has been the teacher (T1) of class 2C at Shapism School (SH) since t_1. At t_2, Mr. Potter resigns and student (S1) Mary (M) leaves the class. At t_3, Mrs. Bumblebee (B) replaces Mr. Potter as the teacher of 2C and a new student (S2), John (J), joins in." The notations TERO, STRO, SCH, HUM, TR_1, SR_1, SR_2, $T2C$, and $S2C'$ are also introduced so that $(\mathsf{TERO}(x) \rightarrow \mathsf{ROLE}(x)) \wedge (\mathsf{TERO}(x) \wedge \mathsf{CNTX}(x,y) \rightarrow \mathsf{SCH}(y)) \wedge (\mathsf{TERO}(x) \wedge \mathsf{PLAY}(y,x,t) \rightarrow \mathsf{HUM}(y) \wedge \mathsf{PRE}(y,t)) \wedge (\mathsf{STRO}(x) \rightarrow \mathsf{ROLE}(x)) \wedge (\mathsf{STRO}(x) \wedge \mathsf{CNTX}(x,y) \rightarrow \mathsf{SCH}(y)) \wedge (\mathsf{STRO}(x) \wedge \mathsf{PLAY}(y,x,t) \rightarrow \mathsf{HUM}(y) \wedge \mathsf{PRE}(y,t)) \wedge \mathsf{TERO}(TR_1) \wedge \mathsf{STRO}(SR_1) \wedge \mathsf{STRO}(SR_2) \wedge \mathsf{QUAL}(T2C) \wedge \mathsf{QUAL}(S2C')$ holds. Note that $T2C$ is semantically read as "being the teacher of 2C"; and $S2C'$ is as "being a student of 2C".

The following holds: $\mathsf{HUM}(P) \wedge \mathsf{HUM}(M) \wedge \mathsf{HUM}(B) \wedge \mathsf{HUM}(J) \wedge \mathsf{PRE}(P,t) \wedge \mathsf{PRE}(M,t) \wedge \mathsf{PRE}(B,t) \wedge \mathsf{PRE}(P,t) \wedge \mathsf{SCH}(SH) \wedge \mathsf{CNTX}(TR_1,SH) \wedge \mathsf{CNTX}(SR_1,SH) \wedge \mathsf{CNTX}(SR_2,SH) \wedge \mathsf{depend}(T2C,SH) \wedge \mathsf{depend}(S2C',SH) \wedge \mathsf{inhere}(T2C,TR_1) \wedge \mathsf{inhere}(S2C',SR_2) \wedge (\mathsf{T1}(x,t) \leftrightarrow \mathsf{hold}(x,TR_1,t)) \wedge (\mathsf{S1}(x,t) \leftrightarrow \mathsf{hold}(x,SR_1,t)) \wedge (\mathsf{S2}(x,t) \leftrightarrow \mathsf{hold}(x,SR_2,t))$.

$t < t_1 \rightarrow \neg\exists x\,(\mathsf{TERO}(x) \wedge \mathsf{CNTX}(x,SH) \wedge \mathsf{PLAY}(P,x,t))$ ("Mr. Potter plays no teacher role.")
$t_1 \leqslant t < t_2 \rightarrow \mathsf{PLAY}(P,TR_1,t) \wedge \mathsf{QUAL}(T2C) \wedge \mathsf{inhere}(T2C,TR_1)$
$\therefore t_1 \leqslant t < t_2 \rightarrow \mathsf{hold}(P,TR_1,t) \wedge \mathsf{bear}(P,T2C,t)$ ($\because$ ($\clubsuit$))
$\therefore t_1 \leqslant t < t_2 \rightarrow \mathsf{T1}(P,t)$ (see ($\heartsuit$)) ("Mr. Potter is the teacher of 2C.")
$t \geqslant t_2 \rightarrow \neg\mathsf{hold}(P,TR_1,t) \wedge \neg\mathsf{hold}(M,SR_1,t)$
$\therefore t \geqslant t_2 \rightarrow \neg\mathsf{T1}(P,t) \wedge \neg\mathsf{S1}(M,t)$ (see ($\heartsuit$)) ("Mr. Potter resigns and Mary leaves 2C.")
$t_2 \leqslant t < t_3 \rightarrow \mathsf{PRE}(TR_1,t) \wedge \neg\exists x\,\mathsf{hold}(x,TR_1,t)$ ("The vacant teacher role TR_1 persists.")
$t \geqslant t_3 \rightarrow \mathsf{PLAY}(M,TR_1,t) \wedge \mathsf{QUAL}(T2C) \wedge \mathsf{inhere}(T2C,TR_1)$
$\therefore t \geqslant t_3 \rightarrow \mathsf{hold}(M,TR_1,t) \wedge \mathsf{bear}(M,T2C,t)$ ($\because$ ($\clubsuit$))
$\therefore t \geqslant t_3 \rightarrow \mathsf{T1}(M,t)$ (see ($\heartsuit$)) ("Mrs. Bumblebee replaces Mr. Potter as the teacher of 2C.")
$t \geqslant t_3 \rightarrow \mathsf{PLAY}(J,SR_2,t) \wedge \mathsf{QUAL}(S2C') \wedge \mathsf{inhere}(S2C',SR_2)$
$\therefore t \geqslant t_3 \rightarrow \mathsf{hold}(J,SR_2,t) \wedge \mathsf{bear}(J,S2C',t)$ ($\because$ ($\clubsuit$))
$\therefore t \geqslant t_3 \rightarrow \mathsf{S2}(J,t)$ (see ($\heartsuit$)) ("John joins in as a student of 2C.")

Vital for persistence of an organization is the nature of roles that depend on the organization as their context, or technically speaking, whether those roles are *functional* with respect to the organization (Mizoguchi and Borgo, 2017). Consider persistence of 2C. On the one hand, student roles (SR_1 and SR_2) are not functional with respect to Shapism School, much less 2C, because students in general are *operands* (the object of input and output) that merely receive education in and make no meaningful contribution to school. The replacement of students is therefore irrelevant to persistence of 2C. On the other hand, teacher roles (TR_1) are functional with respect to Shapism School, let alone 2C, because teachers are typically necessary for their school to perform its function. Thus the change of teacher roles, if not the replacement of teacher players, may affect persistence of 2C.

3.3. Property change

3.a) "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.

Discussions of ontology of qualities/properties are complicated by significantly different usages of the terms 'property' and 'quality' in a number of different domains, including philosophy, formal logic, and computer science. The YAMATO theory of qualities/properties possesses two central features together with

Table 5

Categories and relations for quality/quantity and case analysis

Notation	Description [Example]	Notation	Description [Example]
ROLE	role (from Table 1)	$\mathsf{CNTX}(x, y)$	x has y as context (from Table 2)
TIME	time (from Table 1)	$\mathsf{PLAY}(x, y, t)$	x plays y at t (from Table 2)
DPEN	dependent entity (see Section 1.1)	$\mathsf{hold}(x, y, t)$	object x holds role y at t
OBJ	object (from Table 1)		(See Section 3.2)
GQT	generic quality type [length]	$\mathsf{inhere}(x, y)$	x inheres in y
QRT	quality role type [height role]	$\mathsf{quanfy}(y, z, x)$	y is combined with z,
QRHT	quality role-holder type [height (role-holder)]		thereby becoming x
QUAL	(instance-level) quality [John's height]	$\mathsf{qualat}(x, t)$	x is a quality at t
QVA	quality value [160cm, large]	$\mathsf{realof}(x, y, t)$	x is a realization of y at t
QUAN	quantity [160cm, 1.6m]	$\mathsf{instof}(x, y)$	x is an instance of y
NUM	number [160, 1.6]	$\mathsf{ocurof}(x, y, t)$	x is an occurrence of y at t
UNIT	unit, dimension [centimeter(cm), meter(m)]	QRE	quality realization [John's height at t]
PROP	property [<height, 160cm>, <height, large>]	INTR	temporal interval (from Table 1)
PRE	present at (from Table 2)	PROC	process (from Table 1)

its own terminology.[12] First, 'quality' and its related terms are characterized in terms of roles as follows: "A generic quality type (potential player) plays a quality role type (role) with respect to a specific measured object (context), thereby becoming a quality role-holder type (role-holder)." A *quality generic type* is the most general kind of quality and it represents basic physical parameters (e.g., length, mass, and temperature). A *quality role type* is a role played by a generic quality type. Examples include a height, a weight, and a body temperature. By playing a quality role instance, a quality generic instance becomes an instance of a *quality role-holder type*. A *quality* is the *value-free* kind of quality role-holder instance that inheres in a particular object. Examples include John's height, Mary's weight, and Suzy's body temperature.

Second, quality is conceptually so sharply distinguished from quantity that a quality in the above-defined sense of the term can persist irrespective of change in its quantities and Steven's (1946) four types of scales of measurement (nominal, ordinal, interval, and ratio) are available in the YAMATO is-a hierarchy of quantity. Being a kind of *quality value* (e.g., 160cm and largeness), a *quantity* consists of number and a unit (e.g., 160cm). Quite importantly, a qualtity is said to have a quantity only when it is *realized* at a particular time. For instance, a nurse keeps track of Suzy's body tempeature since it exists at both times t_1 and t_2; and *quality realizations* at t_1 and t_2 of Suzy's body temperature are *occurrences of* 36.5 and 36.6 degrees Celsius, respectively. Finally, a *property* is defined as the complex kind of attribute that can be represented as a pair of a quality and a quality value (e.g., <height, 160cm>).

Core formalization of quality and quantity (see Table 5)

Note: large-case variables (e.g., 'X') represent universals or class-level entities; and lowercase variables (e.g., 'x') represent particulars or instance-level entities.

$\mathsf{QRT}(x) \rightarrow \mathsf{ROLE}(x)$

$\mathsf{QRT}(x) \leftrightarrow \exists y, z, t\ (\mathsf{GQT}(y) \wedge \mathsf{TIME}(t) \wedge \mathsf{CNTX}(x, z) \wedge \mathsf{PLAY}(y, x, t))$

$\mathsf{GQT}(x) \wedge \mathsf{QRT}(y) \wedge \mathsf{TIME}(t) \wedge \mathsf{PLAY}(x, y, t) \rightarrow \mathsf{QRHT}(x) \wedge \mathsf{hold}(x, y, t)$

$\mathsf{inhere}(x, y) \rightarrow \mathsf{DPEN}(x) \wedge (\mathsf{OBJ}(y) \vee \mathsf{PROC}(y))$

$\mathsf{QRHT}(x) \rightarrow \mathsf{DPEN}(x)$

$\mathsf{QUAL}(x) \leftrightarrow \mathsf{QRHT}(x) \wedge \exists y\ (\mathsf{inhere}(x, y))$

$\mathsf{QUAL}(x) \wedge \mathsf{inhere}(x, y) \wedge \mathsf{inhere}(x, z) \rightarrow y = z$ (*Non-migration of qualities*)

$\mathsf{QUAN}(x) \rightarrow \mathsf{QVA}(x)$

$\mathsf{QUAN}(x) \leftrightarrow \exists y, z\ (\mathsf{NUM}(y) \wedge \mathsf{UNIT}(z) \wedge \mathsf{quanfy}(y, z, x))$

[12]The theory of qualities/properties presented below is primarily about qualities (in the below-defined sense of the term) *of actually measured objects*, but not about the results (representations) of measurement of those objects.

Table 6

Categories and relations for process/event and case analysis

Notation	Description	Notation	Description
OBJ	object (from Table 1)	ENCT	object x enacts process y (from Table 2)
PROC	process (from Table 1)	KONST	process x constitutes event y (from Table 2)
EVNT	event (from Table 1)	PC	participates in (from Table 2)
QUAL	quality (see Case 3.a)	$\mathsf{PROC_T}$	process at time (from Table 2)
realof	x is a realization of y at t (see Case 3.a)	$\mathsf{EVNT_T}$	event spans time (from Table 2)
ocurof	x is an occurrence of y at t (see Case 3.a)		

$\mathsf{qualat}(x,t) \rightarrow \mathsf{QUAL}(x) \wedge \mathsf{TIME}(t)$

$\mathsf{realof}(x,y,t) \wedge \mathsf{QUAL}(y) \rightarrow \mathsf{qualat}(x,t) \wedge \exists z,v,W\ (\mathsf{inhere}(x,z) \wedge \mathsf{inhere}(y,z) \wedge \mathsf{QRT}(v) \wedge \mathsf{CNTX}(v,z) \wedge \mathsf{hold}(x,v,t) \wedge \mathsf{QRHT}(W) \wedge \mathsf{instof}(x,W) \wedge \mathsf{instof}(y,W))$

$\mathsf{realof}(x,y,t) \wedge \mathsf{realof}(z,y,t) \wedge x = z$ (*Uniquity of realizations*)

$\mathsf{QRE}(x) \leftrightarrow \exists y,t\ (\mathsf{QUAL}(y) \wedge \mathsf{realof}(x,y,t))$

$\mathsf{ocurof}(x,y,t) \rightarrow \mathsf{QRE}(x) \wedge \mathsf{QVA}(y) \wedge \mathsf{TIME}(t)$

$\mathsf{ocurof}(x,v,t) \wedge \mathsf{ocurof}(y,w,t) \wedge \mathsf{inhere}(x,l) \wedge \mathsf{inhere}(y,m) \wedge v = w \rightarrow \mathsf{QUAN}(v) \wedge \mathsf{QUAN}(w)$ (*Weak form of uniquity of quantity*)

$\mathsf{ocurof}(x,v,t) \wedge \mathsf{ocurof}(y,w,t) \wedge \mathsf{inhere}(x,l) \wedge \mathsf{inhere}(y,m) \wedge l \neq m \wedge v = w \rightarrow \mathsf{QUAN}(v) \wedge \mathsf{QUAN}(w)$ (*Strong form of uniquity of quantity*)

$\mathsf{PROP}(x,y) \rightarrow \mathsf{QUAL}(x) \wedge \mathsf{QVA}(y)$

Formalization for case analysis (see Table 5)

“A flower (F) is red (R) in the summer (S). The color of the flower (FC) changes with the passage of time. In the autumn (A) the flower is brown (B).” The following holds: $\mathsf{OBJ}(F) \wedge \mathsf{INTR}(S) \wedge \mathsf{INTR}(A) \wedge \mathsf{QUAL}(FC) \wedge \mathsf{QVA}(R) \wedge \mathsf{QVA}(B) \wedge \mathsf{inhere}(FC,F)$. (Note that, although color is to be modeled not as a quality but as a disposition to reflect a particular range of wavelength of the light, talk of color as a quality is momentarily accepted for the sake of simplicity.)

$\mathsf{PRE}(F,S) \wedge \mathsf{PRE}(F,A)$ ("The flower persists: it exists both in the summer and in the autumn.")
$\mathsf{PRE}(FC,S) \wedge \mathsf{PRE}(FC,A)$ ("The color quality of the flower persists.")
$\mathsf{QRE}(FCS)$ ("FCS is the realization in the summer of the color quality of the flower.")
$\mathsf{QRE}(FCA)$ ("FCA is the realization in the autumn of the color quality of the flower.")
$\mathsf{ocurof}(FCS,R,S)$ ("FCS is an occurrence of redness.")
$\mathsf{ocurof}(FCA,B,A)$ ("FCA is an occurrence of brownness.")

3.b) “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.

Assuming that an event to be discussed in *GOAL* is a ‘completed’ and immutable occurrent, change during an event is modeled upon change in the ‘ongoing’ and mutable process that constitutes the event (see Section 1.4 for details). Change in processes shows itself mainly in two ways. First, a process can have qualities since it is ‘wholly present’ at any time at which it is ongoing. This enables talk of ‘quality change’ in the realm of occurrents as well as in that of occurrents (compare: the color change of a flower discussed in Case 3.a). Second, since a process changes and no event does, change in the ‘aspect’ or ‘mode’ of an event is explicable in terms of the change involved in the process that constitutes the event.

Core formalization of process and event [13] (see Table 6)
($\flat$) $\mathsf{ENCT}(x, y) \wedge \mathsf{KONST}(y, z) \wedge \mathsf{PROC_T}(y, t) \rightarrow \mathsf{PC}(x, z, t)$

Formalization for case analysis (see Table 6)
"A man (O) is walking (W_p) and walks at steady speed (S) from t_0 until t_1, when O starts walking faster and walks at an increasing speed until t_2. In short, O walks (W_e) from t_0 until t_2. At t_2, O breaks (B_e) into a run, is running (R_p), and runs (R_e) from t_2 until t_3. Seen from a wider perspective, O is moving (M_p) and moves (M_e) from t_0 until t_3." The following holds: $\mathsf{OBJ}(O) \wedge \mathsf{QUAL}(S) \wedge \mathsf{PROC}(W_p) \wedge \mathsf{PROC}(R_p) \wedge \mathsf{PROC}(M_p) \wedge \mathsf{EVNT}(W_e) \wedge \mathsf{EVNT}(B_e) \wedge \mathsf{EVNT}(R_e) \wedge \mathsf{EVNT}(M_e) \wedge \mathsf{ENCT}(O, W_p) \wedge \mathsf{ENCT}(O, R_p) \wedge \mathsf{ENCT}(O, M_p) \wedge \mathsf{KONST}(W_p, W_e) \wedge \mathsf{KONST}(R_p, R_e) \wedge \mathsf{KONST}(M_p, M_e)$.

$t_0 < t \leqslant t_2 \rightarrow \mathsf{PROC_T}(W_p, t) \quad \therefore t_0 < t \leqslant t_2 \rightarrow \mathsf{PC}(O, W_e, t)(\because (\flat))$
$t_0 < t_x \leqslant t_y \leqslant t_1 \wedge \mathsf{realof}(S_{t_x}, S, t_x) \wedge \mathsf{realof}(S_{t_y}, S, t_x) \wedge \mathsf{ocurof}(S_{t_x}, Sx, t_x) \wedge \mathsf{ocurof}(S_{t_y}, Sy, t_y) \rightarrow S_x = S_y$ ("The man O walks at steady speed from from t_0 until t_1.")
$t_1 < t_x \leqslant t_y \leqslant t_2 \wedge \mathsf{realof}(S_{t_x}, S, t_x) \wedge \mathsf{realof}(S_{t_y}, S, t_x) \wedge \mathsf{ocurof}(S_{t_x}, Sx, t_x) \wedge \mathsf{ocurof}(S_{t_y}, Sy, t_y) \rightarrow S_x \leqslant S_y$ ("The man O walks at an increasing speed from t_1 until t_2.")
$t_0 \leqslant t \leqslant t_2 \rightarrow \mathsf{EVNT_T}(W_e, t) \wedge \mathsf{PC}(O, W_e, t)$
$t = t_2 \rightarrow \mathsf{EVNT_T}(B_e, t) \wedge \mathsf{PC}(O, B_e, t)$
$t_2 < t < t_3 \rightarrow \mathsf{PROC_T}(R_p, t) \quad \therefore t_2 < t < t_3 \rightarrow \mathsf{PC}(O, R_e, t)(\because (\flat))$
$t_2 \leqslant t \leqslant t_3 \rightarrow \mathsf{EVNT_T}(R_e, t) \wedge \mathsf{PC}(O, R_e, t)$
$t_0 < t < t_3 \rightarrow \mathsf{PROC_T}(M_p, t) \quad \therefore t_0 < t < t_3 \rightarrow \mathsf{PC}(O, M_e, t)(\because (\flat))$
$t_0 \leqslant t \leqslant t_3 \rightarrow \mathsf{EVNT_T}(M_e, t) \wedge \mathsf{PC}(O, M_e, t)$

Consider the change in the mode of O's locomotive activity, which is to be examined from either the event (M_e) or the process (M_p) viewpoint. O's moving process is mutable and its walking and running sub-processes share the nature of mobility or locomotivity with each other. By comparison, O's movement event is immutable and its walk and run sub-events have nothing in common because they are just temporal parts of the movement event. The change in the mode of O's locomotion is explainable in terms of the walking and running aspects of his moving process.

3.4. Event change

4) "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.

Change in goal-directed activities in general is modeled upon a complex interrelationship among the executions (whether completed or not) of plans, processes, and events.[14] Activities are described either as processes or as events. While actions are classified in YAMATO as processes, activities with goal accomplishment are well modeled as events because goal-directedness of an occurrent needs its *completion*. In addition, goal-directedness, completion, and incompletion of an activity is to be captured in terms of the specification nature of a plan (to be detailed below), the execution of the plan, and the abandonment (and thus the uncompleted execution) of the plan, respectively.

A plan is interpretable from the viewpoint of the YAMATO notion of representation.[15] For the discussion to be manageable, a plan is here conceptualized as a representation whose content is a specification of the ordering of actions to be made and whose (representation) form is a sequence of identifiers of those

[13] See Borgo and Mizoguchi (2014) for a fuller formalization.
[14] A detailed study of goal-directed activities requires robust ontology of action as well as ontology of mind (e.g., the belief-desire-intention (BDI) model of agency), which are outside the scope of the current investigation.
[15] The reader is recommended to read through Section 3.5 to understand an overview of the YAMATO theory of representation.

Table 7

Categories and relations for plans and case analysis

Notation	Description	Notation	Description
OBJ	object (from Table 1)	ENCT	object x enacts process y (from Table 2)
PROC	process (from Table 1)	KONST	process x constitutes event y (from Table 2)
EVNT	event (from Table 1)	PC	participates in (from Table 2)
PLAN	plan	$\mathsf{PROC_T}$	process at time (from Table 2)
REPR	representation	$\mathsf{EVNT_T}$	event spans time (from Table 2)
ACT	action	P	part of (from Table 2)
SPEC	specification	$\mathsf{contof}(x, y)$	x is a content of y
$\mathsf{refoof}(x, y)$	x is a representation form of y	$\mathsf{denote}(x, y)$	x denotes y
SPAD	sequence of planned actions ID	$\mathsf{plpart}(x, y)$	x is a plan part of y
PLAC	planned action	$\mathsf{plexec}(x, y)$	x is a plan execution of y
ID	ID	$\mathsf{compli}(x, y)$	x is compliant with y
$\mathsf{plcomp}(x, t)$	plan x is completed at t	$\mathsf{plaban}(x, t)$	plan x is abandoed at t
TIME	time (from Table 1)		

actions.[16] A plan is executed when its content is realized, namely when a planned action (or a sequence of planned actions) is taken. A plan is abandoned when its content is no longer realized, namely when not all of the planned actions are taken.

A configuration of those concepts is to be used for analyzing goal-directed activities and their change. A goal-directed process is an action that is a realization of the content (specification) of a plan. It constitutes an event with goal accomplishment when the plan is completed (fully executed). When the plan is abandoned, however, the action process constitutes an event with the goal unachieved. What follows this is the situation in which either the action process persists and constitutes another event; or the action process fails to persist, another action process occurs, and it constitutes yet another event.

Core formalization of plans (see Table 7)

$\mathsf{PLAN}(x) \to \mathsf{REPR}(x)$

$\mathsf{ACT}(x) \to \mathsf{PROC}(x)$

$\mathsf{contof}(x, y) \wedge \mathsf{PLAN}(y) \to \mathsf{SPEC}(x)$

$\mathsf{refoof}(x, y) \wedge \mathsf{PLAN}(y) \to \mathsf{SPAD}(x)$

$\mathsf{plpart}(x, y) \to \mathsf{PLAC}(x) \wedge \mathsf{PLAN}(y) \wedge \exists w, z\ (\mathsf{ID}(w) \wedge \mathsf{refoof}(z, y) \wedge \mathsf{P}(w, z) \wedge \mathsf{denote}(w, x))$

$\mathsf{plexec}(x, y, t) \to \mathsf{ACT}(x) \wedge \mathsf{TIME}(t) \wedge \exists w, z\ (\mathsf{contof}(z, w) \wedge \mathsf{plpart}(y, w) \wedge \mathsf{compli}(x, z))$

$(\flat)\ \mathsf{plcomp}(x, t_c) \to \forall z\ \exists y, s, t\ (t \leqslant t_c \to (\mathsf{SPEC}(s) \wedge \mathsf{plpart}(z, x) \wedge \mathsf{plexec}(y, z, t) \wedge \mathsf{compli}(y, s) \wedge \mathsf{contof}(s, x)))$

$(\sharp)\ \mathsf{plaban}(x, t_0) \to \forall t \geqslant t_0\ \exists z\ \neg\exists y\ (\mathsf{plpart}(z, x) \wedge \mathsf{plexec}(y, z, t)))$

Formalization for case analysis (see Table 7)

"A man (O) is walking (W_p) with a plan (P) in mind to walk to the station and he walks (W_{e1}) halfway from t_0 until t_1. At t_1, he turns around (T_e) and walks (W_{e2}) home from t_1 until t_2. At t_2, he arrives (A_e) home."[17] The notation W_{plan} is also introduced so that $\mathsf{plpart}(W_{plan}, P)$ holds. The following holds: $\mathsf{OBJ}(O) \wedge \mathsf{PROC}(W_p) \wedge \mathsf{EVNT}(W_{e1}) \wedge \mathsf{EVNT}(T_e) \wedge \mathsf{EVNT}(W_{e2}) \wedge \mathsf{EVNT}(A_e) \wedge \mathsf{PLAN}(P) \wedge \mathsf{ENCT}(O, W_p) \wedge \mathsf{KONST}(W_p, W_{e1}) \wedge \mathsf{KONST}(W_p, W_{e2}) \wedge \mathsf{plexec}(W_p, W_{plan})$.

$t_0 < t \leqslant t_1 \to \mathsf{PROC_T}(W_p, t)$

$t = t_1 \to \mathsf{plaban}(P, t) \wedge \mathsf{EVNT_T}(T_e, t) \wedge \mathsf{PC}(O, T_e, t)$ (see ($\sharp$))

[16] Two remarks. First, see Section 3.5 for details on a specification. Second, a sequence of identifiers do not need to be described in natural language (e.g., in words). It is introduced here to identify the ordering of planned actions for the sake of a simple exposition of a representation form of a plan.

[17] The man's ad hoc plan to walk back home lies outside the scope of the investigation.

$t_0 \leqslant t \leqslant t_1 \to \mathsf{EVNT_T}(W_{e1}, t) \wedge \mathsf{PC}(O, W_{e1}, t)$
$t_1 < t \leqslant t_2 \to \mathsf{PROC_T}(W_p, t)$
$t = t_2 \to \mathsf{EVNT_T}(A_e, t) \wedge \mathsf{PC}(O, A_e, t)$
$t_1 \leqslant t \leqslant t_2 \to \mathsf{EVNT_T}(W_{e2}, t) \wedge \mathsf{PC}(O, W_{e2}, t)$
$t_0 \leqslant t \leqslant t_2 \to \neg \mathsf{plcomp}(P, t)$ (see ($\flat$))

Consider change in O's locomotive activity with the eventually unaccomplished goal of walking to the station, which is to be considered from either the process or the event perspective. O's walking process persists throughout, regardless of whether it is a realization of the content of his initial plan to walk to the station or not. In contrast, O's plan change causes the occurrence of the event with the plan incomplete, the event of his turning around, and the event of his walking back home. The change in O's entire activity is analyzed in terms of change in his walking process that constitutes three different events.

3.5. Concept evolution

Background: a marriage is a contract between two people that is present in most social and cultural systems and it can change in major (e.g. gender constraints) and minor (e.g. marriage breaking procedures) aspects.
5) "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.

Since the meaning of a term is its semantic content, close examination of the evolution of the meaning of a term is based on the complex but fairly sophisticated YAMATO theory of representation in which a representation as a 'content-bearing entity' is rigorously analyzed. The central idea is that a *representation* consists of a *(representation) form* and the *content* that depends on the representation form; and a *representing thing* is composed of a representation and a *representation medium*. For instance, a musical score (representation) consists of a sequence of musical notes (representation form) and a piece of music (content); and a music book (representing thing) is composed of some musical scores (representations) and some pieces of paper (representation media).

Characteristic of a representation is that both its form and content can be repeatedly *realized*. The form of a representation is realized on a physical continuant: e.g., a sequence of mucial notes is realized when it is written on a piece of paper. The content of a representation is realized by some process (typically by an action) when it is a *specification*. A specification is intuitively understood as a detailed description of how something is, or should be, designed or made. Examples of representations whose content is a specification include an algorithm and a recipe as well as a plan (discussed in Section 3.4). For instance, a piece of music is realized when somebody plays it.

In addition, some representation forms can have the different kind of content from that of representations. To illustrate this, consider Williams Shakespeare's *Hamlet* as a representation whose content is the tragic story about the Prince of Denmark, his father's ghost, and other characters. The representation form of *Hamlet* is a series of English sentences (including "To be or not to be: that is the question") which in turn have as content Shakespeare's wording and style of writing. In this way, a representation form has as part non-propositional content, unlike the typically propositional content of its representation.

Quite importantly, letters are ontologized but with further complications. Consider for instance the letter representation **A** that is composed of the letter representation form $\mathtt{A}$ and the letter content A. $\mathtt{A}$ means a trajectory of a linear drawing of 'A'. In this respect, $\mathtt{A}$ is 'non-migratable': there is uniquely $\mathtt{A}$ for more than one **A**s. The nature of A is such that A meets a *standard letter figure* $\mathcal{A}$ as a specification and $\mathcal{A}$ denotes a *symbol* A. Both $\mathcal{A}$ and A are contentful. $\mathcal{A}$ prescribes that A must be such that two slanting sides

Table 8

Categories and relations for representation and case analysis

Notation	Description	Notation	Description
SEAB	semi-abstract (see Section 3.1)	P	part of (from Table 2)
OBJ	object (from Table 1)	PRE	present at (from Table 2)
REPR	representation	depend(x, y)	x depends on y
REFO	representation form	realof(x, y, t)	x is a realization of y at t
CON	content	$\mathsf{PROC_T}$	process at time (from Table 2)
RETH	representing thing	denote(x, y, t)	x denotes y at t
REME	representation medium	NAME	name
SPEC	specification	MEAN	meaning
TERM	term		

of a triangle is crossed in the middle by a horizontal bar. A means the first letter of the Latin alphabet. Moreover, a letter representing thing $\mathscr{A}$ has **A** as part. Letters are ontologically multifaceted, as shown by the observation that the letter 'A' is used to refer to any of them: $\mathscr{A}$, **A**, $\mathbb{A}$, A, $\mathcal{A}$, and A.

Seen from this perspective, a term is the kind of representation whose representation form is a sequence of letters and that denotes the entity (*denotation*) to which the term essentially refers.[18] The supposed discontinuity of the meaning of a term is modeled as change in the content of the term because its denotation is *unvarying*. The term 'marriage' is the representation whose form is a sequence of alphabet letters (m-a-r-r-i-a-g-e) and that denotes (the nature of) marriage: the socio-legal union between two adults that is verified by the contract between them. When marriage qualifications change, the term 'marriage' would change at its content level while preserving its denotation.

Core formalization of representation[19] (See Table 8)

Note: a representation, and its form, and its content are semi-abstract, whereas a representing thing and its representing medium are objects. That is to say, $(\mathsf{REPR}(x) \rightarrow \mathsf{SEAB}(x)) \wedge (\mathsf{REFO}(x) \rightarrow \mathsf{SEAB}(x)) \wedge (\mathsf{CON}(x) \rightarrow \mathsf{SEAB}(x)) \wedge (\mathsf{RETH}(x) \rightarrow \mathsf{OBJ}(x)) \wedge (\mathsf{REME}(x) \rightarrow \mathsf{OBJ}(x))$ *holds.*

$\mathsf{REPR}(x) \rightarrow \exists y, z, t\ (\mathsf{REFO}(y) \wedge \mathsf{CON}(z) \wedge \mathsf{P}(y, x, t) \wedge \mathsf{P}(z, x, t) \wedge \mathsf{depend}(z, y))$
$\mathsf{REFO}(x) \rightarrow \exists y\ (\mathsf{CON}(y) \wedge \mathsf{depend}(y, x))$
$(\mathsf{REFO}(x) \wedge \mathsf{CON}(y) \wedge \mathsf{REFO}(z) \wedge \mathsf{CON}(w) \wedge \mathsf{depend}(y, x) \wedge \mathsf{depend}(w, z) \wedge y \neq w) \rightarrow x \neq z$
$\mathsf{RETH}(x) \rightarrow \exists y, z, t\ (\mathsf{REPR}(y) \wedge \mathsf{REME}(z) \wedge \mathsf{P}(y, x, t) \wedge \mathsf{P}(z, x, t))$
$\mathsf{REFO}(x) \wedge \mathsf{realof}(y, x, t) \rightarrow \mathsf{OBJ}(y) \wedge \mathsf{PRE}(y, t)$
$\mathsf{REPR}(x) \wedge \mathsf{CON}(y) \wedge \mathsf{P}(y, x, t) \wedge \mathsf{realof}(z, y, t) \rightarrow \mathsf{SPEC}(y) \wedge \mathsf{PROC_T}(z, t)$

Formalization of a term as a representation (See Table 8)

$\mathsf{TERM}(x) \rightarrow \mathsf{REPR}(x)$
$\mathsf{TERM}(x) \wedge \mathsf{REFO}(y) \wedge \mathsf{P}(y, x, t) \rightarrow \mathsf{NAME}(y) \wedge \mathsf{PRE}(y, t)$ ("The form of a term is its *name*.")
$\mathsf{TERM}(x) \wedge \mathsf{CON}(y) \wedge \mathsf{P}(y, x, t) \rightarrow \mathsf{MEAN}(y) \wedge \mathsf{PRE}(y, t)$ ("The content of a term is its *meaning*.")
$\mathsf{TERM}(x) \rightarrow \exists y\ (\mathsf{denote}(x, y) \wedge \forall z\ (\mathsf{denote}(x, z) \wedge y = z))$ ("Each term denotes exactly one entity.")
(Note that the denote *predicate is time-invariant: the denotation of a term is unvarying.)*
$\exists x, y, z, t, t'\ (\mathsf{TERM}(x) \wedge \mathsf{NAME}(y) \wedge \mathsf{NAME}(z) \wedge \mathsf{P}(y, x, t) \wedge \mathsf{P}(z, x, t'))$
("The name of a term is changeable: a term can have different names at different times.")
$\exists x, y, z, t, t'\ (\mathsf{TERM}(x) \wedge \mathsf{MEAN}(y) \wedge \mathsf{MEAN}(z) \wedge \mathsf{P}(y, x, t) \wedge \mathsf{P}(z, x, t'))$
("The meaning of a term is changeable: a term can have different meanings at different times.")

[18]Compare this with Peirce's (1977) Semiotic.

[19]Ontology of letters is outside the scope of the present axiomatization.

Formalization for case analysis (See Table 8)
"The term 'marriage' (T_m) persists from t_0. At t_1, the meaning ($M1_m$) of T_m changes into another meaning ($M2_m$) in virtue of change in socio-legal constraints on marriage (whether major or minor). T_m still persists afterwards." The notation D_m is also introduced so that $\mathsf{denote}(T_m, D_m)$ holds. The following holds: $\mathsf{TERM}(T_m) \wedge \mathsf{MEAN}(M1_m) \wedge \mathsf{MEAN}(M2_m)$.

$t \geqslant t_0 \rightarrow \mathsf{PRE}(T_m, t)$ ("The term 'marriage' persists regardless of change in its meaning.")
$t_0 \leqslant t < t_1 \rightarrow \mathsf{P}(M1_m, T_m, t)$ ("The meaning of the term 'marriage' is $M1_m$.")
$t \geqslant t_1 \rightarrow \mathsf{P}(M2_m, T_m, t)$ ("The meaning of the term 'marriage' is $M2_m$.")

The evolution of concepts (in the broad sense of the term) could be modeled upon the framework within which a concept is the content of some representation and, when concept change occurs, the representation changes at its conceptual level while maintaining its denotation. Consider for instance the fact that, generally speaking, Japan employed as a diagnosis criterion of hypertension the value 160/95 mmHg in 1990, but it uses the value 140/90 mmHg in 2017. Understood as a kind of representation, the Japanese diagnostic criterion of hypertension has as content 160/95 mmHg in 1990 and 140/90 mmHg in 2017; and the diagnostic criterion consistently denotes hypertension: a clinically abnormal high blood pressure.

Scientific hypotheses and their rejection might be analyzable as well in terms of the representational interpretation of concept evolution. For example, combusion was explained by the 'phlogiston theory' in which an unobservable substance called 'phlogiston' escapes from things when they burn, until the late eighteenth century, in which Lavoisier hypothesized that a different unobservable substance which he terms 'oxygen' is incorporated by things when they burn. Lavosier's 'oxygen theory' is currently confirmed by atomic physics.[20] Both the phlogiston theory and the oxygen theory are to be interpreted as representations whose contents are the existence of phlogiston and oxygen, respectively; and both entities are postulated to explain the object of the scientific investigation under consideration: combustion, or the process of burning. With the progress of science, the scientific hypothesis *on* combustion changes its content from phlogiston to oxygen while having combustion as denotation.

4. Ontology usage and community impact

Several application examples of YAMATO are found in biomedicine. First of all, a viable definition of disease is indispensable for the robust construction of disease ontologies. Built in compliace with the YAMATO conception of objects discussed in Section 1.4, the River Flow Model (RFM) of diseases was intially presented in Mizoguchi, Kozaki, Kou, Yamagata, Imai, Waki and Ohe (2011) and further developed in Rovetto and Mizoguchi (2015) and Toyoshima, Mizoguchi and Ikeda (2017).[21] The basic tenet of RFM is the analogy between a river and a disease. Just as a river enacts changing the course of water flowing as its external process, a disease enacts as its external process a process of, e.g., spreading and disappearing; and just as a river has water flowing as its internal process, a disease has as its internal process a number of causal chains of clinically abnormal states. In RFM, a disease is thus defined as a dependent continuant constituted of causal chains of abnormal states. RFM is theoretically comparable to, and can be of higher practical value than, the widely employed, dispositional model of disease given by the Ontology for General Medical Science (OGMS) (Scheuermann, Ceuster and Smith, 2009).

Second, and relatedly, diverse representations of abnormal states render exchanging medical data and information rather difficult. To address this issue, a unified representation model of abnormal states was proposed in accordance with the YAMATO theory of quality and quantity discussed in Section 3.3 (Yamagata, Kozaki, Imai, Ohe and Mizoguchi, 2014). An abnormal state is there described as a 'property', which can be decomposed into an 'attribute' and a 'value' in a qualitative representation, hence the <Entity,

[20] See Kitcher (1978) for a detailed theoretical discussion on phlogiston and oxygen.
[21] `http://rfm.hozo.jp/`

Attribute, Value> formalism. This model was extensively exploited in order to capture all causal relations among approximately 21,000 abnormal states from approximatelty 6,000 diseases.

Third, it was found on closer examination that, despite its widespread use as a common framework for representing genomic phenotypes, the Phenotypic Quality Ontology (PATO) has some problems with a qualitative representation owing to its use of the poorly expressive <Entity, Property> representation form. To solve them, PATO was enhanced by the YAMATO qualitative representation and expanded into PATO2YAMATO (Masuya et al., 2011).[22] This indicates an effective way of integrating biological mesurement data across various biological experiments.

Fourth, and finally, genes are fundamental to modern biomedical science. Certainly, Gene Ontology seeks to provide cross-species biological vocabularies that can be used by multiple databases to describe gene products (Gene Ontology Consortium, 2001).[23] No attempt had been nonetheless made to represent fully various complex aspects of genes until Genetics Ontology (GXO) was constructed to provide a sound foundation for a semantic model that is applicable to various fields of life science (Masuya and Mizoguchi, 2012).[24] In GXO, the multiple facets of bearers of genetic information (including genes and alleles) are accurately modeled with the help of the YAMATO theory of roles and representation. Included in GXO is, e.g., the world's first ontological definition of DNA as the representing thing that is encoded by adenine (A), cytosine (C), guanine (G), and thymine (T).

Other application examples of YAMATO include increased usage of the method of function decomposition (Kitamura and Mizoguchi, 2003) according to which approximately 90 functional terms can used be as a common vocabulary for representing a functional structure of any aritifact and that was elaborated in conformity with the YAMATO notion of function (see Feature (III) in Introduction). The approach of function decomposition was well-advanced enough to be merchandized as a tool called "OntoloGear" which has been deployed in industry, e.g., to facilitate production systems in a factory. Moreover, the idea of function decomposition was developed by the conception of actions as processes (rather than events) into the method of action decomposition that enables the modeling of any complex action in terms of approximately 500 basic action terms. The technique of action decomposition is available in an expanded version of OntoloGear: OntoGearCore.

The action decomposition method has been extensively employed in various domains. Examples include the modeling of nursing actions in hospitals (Nishimura, Kitamura, Sasajima and Mizoguchi, 2013); the development of an Ontology-based Obstacle, Prevention and Solution (OOPS) modeling framework which supports descriptions of activities and related knowledge of the users of mobile Internet services (Sasajima, Kitamura, Naganuma, Fujii, Kurakake and Mizoguchi, 2008); and the building of an ontology of learning and instructional theories that is called 'OMNIBUS' (Mizoguchi and Bourdeau, 2000; Hayashi, Bourdeau and Mizoguchi, 2009; Mizoguchi and Bourdeau, 2016) and an OMNIBUS-based theory-aware authoring tool named 'SMARTIES' that provides a modeling environment and guidelines for making theory-compliant learning and instructional scenarios (Mizoguchi, Hayashi and Bourdeau, 2007).

Other applications of YAMATO include the proposal of an ontological definition of services based on the YAMATO theory of function (Sumita, Kitamura, Sasajima and Mizoguchi, 2012). Projects in progress to apply YAMATO include (1) Structuring sustainable lifestyles in future society; (2) Reorganization of the grammar of English tense; (3) Task ontology building of demolition tasks of a nuclear power plant; (3) Ontology building of biomimetics; and (4) Building a know-how model of an expert of ferromagnetic materials. The YAMATO concepts mainly used in the project (2) and others are the process/event distinction and the method of function/action decomposition, respectively.

[22] `http://ja.brc.riken.jp/lab/bpmp/ontology/ontology_pato2yato.html`
[23] `http://www.geneontology.org/`
[24] `http://ja.brc.riken.jp/lab/bpmp/ontology/ontology_gxo.html`

Acknowledgements

I would like to express my sincere thanks to Stefano Borgo, Antony Galton, Yoshinobu Kitamura, and Kouji Kozaki for their fruitful collaboration.

References

Arp, R., Smith, B. and Spear, A. D. (2015). *Building Ontologies with Basic Formal Ontology*, MIT Press.

Borgo, S., Franssen, M., Garbacz, P., Kitamura, Y., Mizoguchi, R. and Vermaas, P. E. (2014). Technical artifacts: An integrated perspective, *Applied Ontology* **9** (3–4), 217–235.

Borgo, S. and Masolo, C. (2010.) Ontological Foundations of DOLCE. In R. Poli, M. Healy and A. Kameas (eds.), *Theory and Applications of Ontology: Computer Applications* (pp. 279–295), Springer.

Borgo, S. and Mizoguchi R. (2014). A First-order Formalization of Event, Object, Process and Role in YAMATO, In P. Garbacz and O. Kutz (eds.), *Proceedings of the 8th International Conference on Formal Ontology in Information Systems (FOIS2014), Rio de Janeiro, Brazil, September 22-26, 2014*, 79–92.

Borgo, S., Mizoguchi, R. and Kitamura, Y. (2016). Formalizing and Adapting a General Function Module for Foundational Ontologies. In R. Ferrario and W. Kuhn (eds), *Proceedings of the 9th International Conference on Formal Ontology in Information Systems (FOIS2016), Annecy, France, July 6-9, 2016*, 241–254.

Casati, R. and Varzi, A. C. (1999). *Parts and Places*, MIT Press.

Galton, A. and Mizoguchi, R. (2009). The water falls but the waterfall does not fall — New perspectives on objects, processes and events, *Applied Ontology* **4**(2), 71–108.

Gene Ontology Consortium. (2001). Creating the Gene Ontology Resource: Design and Implementation, *Genome Research*, **11**, 1425–1433.

Guarino, N. (1995). Formal Ontology, Conceptual Analysis and Knowledge Representation, *International Journal of Human and Computer Studies*, **43**(5/6), 625–640.

Guizzardi, G. and Wagner, G. (2010). Using the Unified Foundational Ontology (UFO) as a Foundation for General Conceptual Modeling Languages. In R. Poli, M. J. Healy and A. D. Kameas (eds.), *Theory and Application of Ontology: Computer Applications* (pp. 175–196), Springer.

Hayasi, Y., Bourdeau, J. and Mizoguchi, R. (2009). Strategy-centered Modeling for Better Understanding of Learning/Instructional Theories, *International Journal of Knowledge and web Intelligence,* **1**(3–4), 187–208.

Herre, H. (2010). General Formal Ontology (GFO): A foundational ontology for conceptual modelling. In R. Poli, M. J. Healy and A. D. Kameas (eds.), *Theory and Application of Ontology: Computer Applications* (pp. 297–345), Springer.

Kitamura, Y., Koji, Y. and Mizoguchi, R. (2006). An Ontological Model of Device Function: Industrial Deployment and Lessons Learned, *Applied Ontology (Special issue on "Formal Ontology Meets Industry")*, **1**(3–4), 237–262.

Kitamura, Y. and Mizoguchi, R. (2003). Organizing Knowledge about Functional Decomposition, In *Proceedings of the 14th International Conference on Engineering Design (ICED03), Stockholm, Sweden, August 19–21, 2003.*

Kitamura, Y. and Mizoguchi, R. (2013). Characterizing functions based on phase-and evolution-oriented models, *Applied Ontology* **8**(2), 73–94.

Kitcher, P. (1978). Theories, Theorists and Theoretical Change. *Philosophical Review* **87**(4): 519–547.

Kozaki, K., Hihara, K., and Mizoguchi, R. (2012). Dynamic Is-a Hierarchy Generation System Based on User's Viewpoint. In *Proceedings Joint International Semantic Technology Conference (JIST2011), Hangzhou, China, December 4–7, 2011*. 096-111.

Masolo, C., Vieu, L., Bottazzi, E., Catenacci, C., Ferrario, R., Gangemi, A. and Guarino, N. (2004). Social Roles and Their Descriptions. In D. Dubois, C. Welty and M. A. Williams (eds.), *Principles of Knowledge Representation and Reasoning, Proceedings of the Ninth International Conference (KR 2004), Whistler British Columbia, Canada, June 2-5, 2004.*

Masuya, H. et al. (2011). An Advanced Strategy for Integration of Biological Measurement Data. In *Proceedings of the 2nd International Conference on Biomedical Ontology (ICBO2011), Buffalo, NY, USA, July 28–30, 2011*, 79–86.

Masuya, H. and Mizoguchi, R. (2012). An Ontology of Gene. In *Proceedings of the 3rd International Conference on Biomedical Ontology (ICBO2012), Graz, Austria, July 21–25, 2012.*

McTaggart, J. M. E. (1908). The Unreality of Time. *Mind* **17**: 457-474.

Mizoguchi, R. (2004). Tutorial on ontological engineering - Part 3: Advanced course of ontological engineering, *New Generation Computing*, **22**(2), 198–220.

Mizoguchi, R. (2010). YAMATO: yet another more advanced top-level ontology. In *Proceedings of the Sixth Australasian Ontology Workshop* (pp. 1–16), Adelaide: Australia.

Mizoguchi, R. and Borgo, S. (2017). A Preliminary Study of Functional Parts as Roles. In *Proceedings of the 2nd Workshop on Foundational Ontology (FOUSTII), co-located with the 3rd Joint Ontology Workshop (JOWO2017), Bozen-Bolzano, Italy, September 21-23, 2017.*

Mizoguchi, R. and Bourdeau, J. (2000). Ontological Engineering to Overcome AI-ED Problems, *International Journal of Artificial Intelligence in Education,* **11**(2), 107–121.

Mizoguchi, R. and Bourdeau, J. (2016). Using Ontological Engineering to Overcome AI-ED Problems: Contribution, Impact and Perspectives, *International Journal of Artificial Intelligence in Education*, **26**(1), 91–106.

Mizoguchi, R., Galton, A., Kozaki, K. and Kitamura, Y. (2015). Families of roles: A new theory of occurrent-dependent roles, *Applied Ontology* **10**(3-4), 367–399.

Mizoguchi, R., Hayashi, Y. and Bourdeau, J. (2007). Inside Theory-Aware and Standards-Compliant Authoring System, In *Proceedings of the Fifth International Workshop on Ontologies and Semantic Web for E-Learning (SWEL2007), Marina del Rey, CA, USA, July 9, 2007,* 1–18.

Mizoguchi, R. and Kitamura, Y. (2009). A Functional Ontology of Artifacts, *The Monist* **92**(3), 387–402.

Mizoguchi, R., Kitamura, Y. and Borgo, S. (2016). A unifying definition for artifact and biological functions, *Applied Ontology* **11**(2), 129–154.

Mizoguchi, R., Kozaki, K., Kou, H., Yamagata, Y., Imai, T., Waki, K. and Ohe, K. (2011). River Flow Model of Diseases. In *Proceedings of 2nd International Conference on Biomedical Ontology (ICBO2011), Buffalo, NY, USA, July 28–30, 2011*, 63–70.

Mizoguchi, R., Sunagawa, E., Kozaki, K. and Kitamura, Y. (2007). A Model of Roles within an Ontology Development Tool: Hozo, *Applied Ontology* **2**(2), 159–179.

Nishimura, S., Kitamura, Y., Sasajima, M. and Mizoguchi, R. (2014). Systematic Description of Nursing Actions Based on Goal Realization Model, In *Proceednigs of the 15th European Conference on Knowledge Management (ECKM2014), Santarém, Portugal, September 4–5, 2014,* 730–739.

Peirce, C. S. (1977). *Semiotic and Significs: The Correspondence between Charles S. Peirce and Victoria Lady Welby*, edited by Charles S. Hardwick, Bloomington: Indiana University Press.

Rovetto, R. J. and Mizoguchi, R. (2015). Causality and the ontology of disease, *Applied Ontology*, **10**(2), 79–105.

Sasajima, M., Kitamura, Y., Naganuma, T., Fujii, K., Kurakake, S. and Mizoguchi, R. (2008). Obstacles Reveal the Needs of Mobile Internet Services - OOPS: Ontology-based Obstacles, Prevention and Solution Modeling Framework. *Journal of Web Engineering,* **7**(2), 133–157.

Scheuermann, R. H., Ceuster, W. and Smith, B. (2009). Towards an Ontological Treatment of Disease and Diagnosis. In *Summit on Translational Bioinformatics*, 116–120.

Smith, B. and Ceusters, W. (2010). Ontological realism: A methodology for coordinated evolution of scientific ontologies, *Applied Ontology*, **5**(3-4), 139–188.

Steven, S. S. (1946). On the Theory of Scales of Measurement. *Science*, **103**(2684), 677–680.

Sumita, K., Kitamura, Y., Sasajima, M. and Mizoguchi, R. (2012). Are Services Functions? In *Proceedings of the Third International Conference on Exploring Services Science (IESS2012), Geneva, Switzerland, February 15–17, 2012,* 58–72.

Toyoshima, F., Mizoguchi, R. and Ikeda, M. (2017). Causation and the River Flow Model of Diseases. In *Proceedings of the 8th International Conference on Biomedical Ontology (ICBO2017), Newcastle upon Tyne, UK, 13–15 September, 2017.* Accepted.

Tsang, E. P. K. (1987). Time Structures for AI. In *Proceedings of 10th International Joint Conference on AI (IJCAI)*, 456–461.

Yamagata, Y., Kozaki, K., Imai, T., Ohe, K. and Mizoguchi, R. (2014). An ontological modeling approach for abnormal states and its application in the medical domain, *Journal of biomedical semantics* **5**(1), 1–14.