

YAMATO: Yet Another More Advanced Top-level Ontology with Analysis of Five Examples of Change

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Abstract. A late-comer upper ontology YAMATO is summarized in this paper. YAMATO distinguishes itself from the other existing upper ontologies in the following respects. (1) One of its most salient features is that it is designed with both engineering and philosophical minds. (2) Because the world is full of roles, it is based on a solid theory of roles. (3) In order to deal with artifacts effectively, YAMATO has a sophisticated theory of functions. (4) Information is another kind of entity which differs from entities that philosophers have traditionally discussed to date in the sense of being a content-bearing thing. Considering the modern society in which a flood of information occurs, YAMATO also has a theory of informational objects (representations). (5) Quality and quantity are carefully organized for interoperability of real-world data. (6) Its philosophical contribution includes a theory of objects, processes and events. YAMATO has been intensively applied through the exploitation of those features. Five cases given by the organizers of the first edition of FOUST workshop are analyzed to demonstrate how YAMATO models the real world.

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

1. Introduction

Upper ontology is the core of ontology engineering. It plays a key role in ontology development by giving developers a guideline about how to view the target domain. There already exist several well-designed upper ontologies such as DOLCE [1], BFO [2], GFO [3], and UFO [4]. It seems that there is no need to add yet another upper ontology. The paper summarizes the reason why we adventure to develop a new upper ontology YAMATO [5] (Yet Another More Advanced Top-level Ontology). YAMATO was developed to make up for what the existing upper ontologies badly mishandle. Although it is currently being axiomatized and is not yet fully so, YAMATO is implemented in the ontology editor Hozo³ and OWL. It is freely available for use.⁴

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YAMATO claims to reveal secrets of reality so well that its utility in practice can be maximized, although some might criticize its structure for being too large and complex. If users think it specifies too much detail, they can use only categories down to the level which they think is appropriate from the top level by neglecting the rest of those at lower levels. Many of the existing upper ontologies do not seem good enough for explaining reality or for guiding domain people to help them build ontologies. What they need are not only the distinction between objects and qualities but also that between quality and quantity and that between quality and a description of quality; not only the distinction between objects and representation but also that between a copy of book and a book one writes and that between a novel and a musical score; and not only the distinction between process and event but also that between a pulse and a sequence of pulses and that between to separate and to cut. They also need to know how much similar a procedure and a piece of music are in what sense, why events cannot change while processes can, etc. YAMATO is designed to answer all of the above questions and the like.

This paper illustrates YAMATO with five-case analyses to discuss how it models a couple of crucial things for future comparison with other existing upper ontologies. The organization of this paper is based on the specified format of the first workshop of FOUST. In particular, five cases discussed in Section 3 are given by the workshop organizers and they concern various kinds of change in the real world. The heart of YAMATO is summarized below:

(1) YAMATO is designed with both engineering and philosophical minds. It accepts fundamental distinctions such as continuant vs. occurrent, independent entity vs. dependent entity, and quality vs. quantity as well as several meta-level properties such as integrity, unity, dissectivity to define fundamental types. For example, an object is defined as an integral, unitary and non-dissective continuant, and a continuant is defined as anything which enacts its external processes. It adopts strict single inheritance in is-a hierarchy which is organized according to the rigid definition of is-a and instance-of relations based on the set membership with the notion of *essential property*.⁵ Thus it does not allow to put a role under an independent entity in is-a hierarchy, e.g., teacher cannot be subsumed by person. It accepts the theory of entity stacking to deal with the issue of the occupation by multiple entities of a single spatiotemporal region like a vase and an amount of clay.

(2) To deal with engineering problems, especially the interoperability of engineering data, YAMATO takes seriously the issues of property and attribute. It adopts the trope theory and distinguishes between attribute and property. The former is a quality type and the latter a tuple of a quality type and its value (qualia). YAMATO accepts two ways of formalizing the characteristics of entities: one is the pair <entity, property> and the other is the triple <entity, attribute, value>. Note here that, by “attribute”, we do not mean the relation between an entity and its attribute value but the quality type which corresponds to the dimension of entity characterization [5].

(3) YAMATO fully develops the notion of function [6][7][8] in order to deal well with not only organisms but also artifacts [9], taking it that functions are at the heart of artifacts. We introduce the idea of systemic function [10] to cover both biological and artifact functions in a single framework. 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

⁵For YAMATO’s axiomatization of is-a and instance-of relations, see Subsection 2.1. The paper on this work is currently under review in a journal.

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 hands (not functioning).

(4) YAMATO sharply distinguishes processes from events to capture the unfolding process of an event which is usually left implicit [11]. An event must be dealt with as a whole which extends in its full interval and is constituted by a process whose progress corresponds to the unfolding process of 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 exists as a whole at any time instant after the beginning and before the ending time points. Therefore, a process can change but an event cannot.

(5) YAMATO develops a theory of roles, taking into account the fact that the real world is full of roles. Its unique feature is to cope well with a vacant role, namely a role without a player. Our theory of roles claims that any part of an object has its own role to the object as a whole which provides a context where the role is defined. 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. In the case of a bike, for example, the former corresponds to the front wheel and the latter to just a wheel that you can buy at a bike shop. This distinction plays a vital role in addressing the issue of object modeling as is shown in Subsections 3.1 and 3.2.

(6) To deal with informational objects including conceptualization, YAMATO has a theory of representation according to which a representation is composed of (representation) form and content. A written (realized) character is also dealt by with a representation whose form is the specification of the 2D image and the content is the corresponding symbol. Examples of representations include an algorithm, a procedure, a plan, a computer program, a piece of music, a novel, a painting, data, a symbol, a sentence, a musical score, and a specification,

2. Elements and Organization of YAMATO

2.1. Is-a relation and Top-level Categories

Using is-a relation, YAMATO adopts single inheritance to make its taxonomic structure clean like BFO and DOLCE. That is, the type hierarchy is made in YAMATO only when the lower type inherits its intrinsic properties from the super types. Many of the multiple context-dependencies are covered with the help of roles [12]. For the cases where genuine multiple inheritance is necessary, Hozo prepares IS-A relation which is nothing to do with identity problem of instances but only with property inheritance like subclass-of relation in OWL. It may be used only when is-a relation already exists between the two types of interest.⁶ The early version of YAMATO was designed under a considerable influence of Guarino's view on upper ontology [13].

Is-a relation in YAMATO is something more than usual property inheritance. YAMATO formalizes instance-of and is-a relations as follows:

- (A1) $\exists R \blacksquare Rx$
(D1) $Class(X) \equiv_{def.} \forall x(x \in X \rightarrow \exists R(\blacksquare Rx \wedge X = \{y|Ry\}))$
(D2) $InstOf(x, X) \equiv_{def.} \exists R(\blacksquare Rx \wedge X = \{y|Ry\})$

⁶Hozo has a graphical interface with on-line partial consistency checking, which enables it to detect such situations.

- (D3) $X_i \equiv_{def.} \{x \mid Class(X) \wedge InstOf(x, X)\}$
(D4) $IsA(X, Y) \equiv_{def.} Class(X) \wedge Class(Y) \wedge X_i \subseteq Y_i$

For every object, that object has some *essential property*: a property in virtue of which an entity preserves its identity (A1). We call the symbol ‘■’ an ‘essence operator’ and it semantically means “Essentially, ...” or “It is essential that ...”. An essential property of an object determines the essential nature of that object.

Most importantly, a class and instance-of relation are set-theoretically defined in terms of an essential property. A set X qualifies as 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 (D1); and *at the same time*, x bears *instance-of* relation to (that is to say, x is an *instance* of) X (D2). The notational definition being used (D3), *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 (D4).

Given the formalization presented above, *is-a* relation implies inheritance of identity criterion, so that when an instance of such a class loses the essential property, then it stops being an instance of all its super classes. On the other hand, whatever happen with such properties of an instance that are inherited through *IS-A* relation, no influence occurs concerning the identity of the instance. Note that a type is not a property in YAMATO. Therefore, human is a type and is not dealt with as a property. Instead, human type has properties/qualities such as height, weight, and age. Figure 1 shows the top-level categories of YAMATO. At this level, YAMATO has no significant difference from other existing upper ontologie in spite of its unique treatment of quality and quantity [5].

2.2. Relevant Axioms

YAMATO is partially axiomatized: for instance, its process/event-related module [14] and its role-related module [15] have been formalized. This section presents part of the former formalization [14]. Table 1 and Table 2 show the relevant categories and the relations among them, respectively. They are also graphically shown in Figure 2.

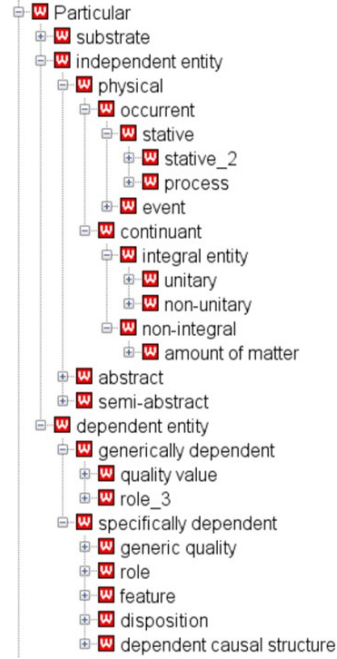


Figure 1.: Top-level categories in YAMATO

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

Table 1.: Relevant YAMATO categories [14]

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

Table 2.: Relevant YAMATO relations [14]. Relations marked with ‘*’ are defined.

The parthood relation P used in YAMATO has the axiomatization of Closed Extensional Mereology (CEM) [16]. It is binary on events and temporalized, and thus ternary, on processes and objects.

The other mereological relations and operators, such as O ($O(x, y)$ stands for “ x and y overlap”), PP ($PP(x, y)$ for “ x is a proper part of y ”), SUM ($SUM(z, x, y)$ for “ z is the sum of x and y ”) and $PROD$ ($PROD(z, x, y)$ for “ z is the product of x and y ”), are defined as usual in CEM [16]. When P is applied to processes, it is written $P(x, y, t)$ 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 ‘whole process’ (a process from its beginning to its end) is either understood as an event or is conceptually incoherent.

(A2) says that P is additive on the category of objects OBJ (as usual, we assume that free variables in formulas are universally quantified):

$$(A2) \text{ } OBJ(x) \wedge OBJ(y) \wedge SUM(z, x, y) \rightarrow OBJ(z) \quad (\text{additivity on } OBJ)$$

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:

$$(A3) \text{ } EVNT(x) \wedge P(y, x) \rightarrow EVNT(y) \quad (\text{dissectivity on } EVNT)$$

$$(A4) \text{ } EVNT(x) \wedge EVNT(y) \wedge SUM(z, x, y) \rightarrow EVNT(z) \quad (\text{additivity on } EVNT)$$

$$(A5) \text{ } PRE(x, t) \rightarrow TIME(t)$$

$$(A6) \text{ } PRE(x, t) \wedge P(t', t) \rightarrow PRE(x, t') \quad (\text{dissectivity on } PRE)$$

$$(A7) \text{ } PRE(x, t) \wedge PROC(x) \wedge P(y, x, t) \rightarrow PRE(y, t) \wedge PROC(y)$$

$$(\text{dissectivity on } PROC)$$

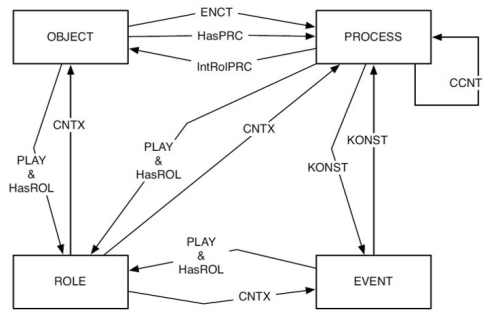


Figure 2.: Graphic representation of relevant YAMATO categories and relations [14]

(A8) $PRE(x, t) \wedge PROC(x) \wedge PRE(y, t) \wedge PROC(y) \wedge SUM(z, x, y, t) \rightarrow PRE(z, t) \wedge PROC(z)$
 (additivity on $PROC$)

We anticipate that $P(x, y, t)$, 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 . 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.

3. Analysis of Formalization by YAMATO: Five Examples

This section presents how YAMATO can formalize the five cases which were given by the organizers of the first FOUST workshop as common cases for comparing several upper ontologies in terms of the modeling results obtained by them.

3.1. Roles

Case (1) "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.

Simplified axioms of roles (see [15] for more details)

$Context-of(x, r) \rightarrow Object(x) \wedge Role(r)$

"An object x is the context of the role r ."

$Role(r) \rightarrow \exists x, q (Quality(q) \wedge Depend-on(q, x) \wedge Inhere-in(q, r) \wedge Context-of(x, r))$

"A role r has at least one quality q dependent on the context x ."

$Possess(x, y, t) \rightarrow Object(x) \wedge Quality(y) \wedge Time(t)$

$Hold(x, r, y, t) \rightarrow \exists q (Quality(q) \wedge Possess(x, q, t) \wedge Object(x) \wedge Role(r) \wedge Context-of(y, r) \wedge Play(x, r, t) \wedge Time(t))$

"An object x is playing a role r in the context y at time t , thereby becoming a role-holder, and hence it possesses a quality q at t . x is called a player of the role r ."

$Role-holder(x, t) \leftrightarrow \exists r, y Hold(x, r, y, t)$

$Teacher-role(r) \rightarrow \exists c, s (Class(c) \wedge Inhere-in(c, r) \wedge Role(r) \wedge Context-of(s, r) \wedge School(s))$

"A teacher role has a quality c inhering in it."

$Teach(x, c, t) \rightarrow \exists s (Person(x) \wedge Class(c, s))$

$Teacher(x, s, t) \rightarrow \exists r, c (Hold(x, r, s, t) \wedge Teacher-role(r) \wedge Teach(x, c, t) \wedge School(s))$

"A teacher holds a teacher role and temporarily possesses a quality c ."

$Teacher-role(Teacher-role_1); School(Shapism); Class(2C, Shapism); Person(Potter); Person(Bumblebee)$

As for Mr. Potter

Before being hired at Shapism School: Mr. Potter has no role to play.

At time t_1 : Mr. Potter is hired by Shapism School and starts to play a teacher role and to teach a class 2C, and thereby has been a teacher of Shapism School since then.

At time $t_2 \geq t_1$: $Teacher(Potter, Shapism, t)$ and $Teach(Potter, 2C, t)$,

$Hold(Potter, Teacher\text{-}role_1, Shapism, t)$ and $Role\text{-}holder(Potter, t)$ hold.

At time t_2 : Potter leaves the school and a new person Bumblebee replaces Potter.

After t_2 : Potter is just a man, so only $Person(Potter)$ holds; that is, $\neg Teacher(Potter, Shapism, t)$ where $t \geq t_2$.

As for Mrs. Bumblebee

At $t \geq t_3$: $Teacher(Bumblebee, Shapism, t)$ and $Teach(Bumblebee, C_2, t)$,

$Hold(Bumblebee, Teacher\text{-}role_1, Shapism, t)$ and $Role\text{-}holder(Bumblebee, t)$ hold.

Note that Bumblebee plays the same role instance $Teacher\text{-}role_1$ which Potter does until t_3 . In other words, $Teacher\text{-}role_1$ exists from t_1 to t_3 and exists after t_3 with keeping its identity even during the period when no one plays it. Either Shapism School or Class 2C keeps its identity through the replacement. As for replaceability, Mrs. Bumblebee replaces Mr. Potter because $Teacher\text{-}role_1$ is a functional part of Shapism School, while it is not the case that John replaced Mary. This is because $Student\text{-}role_1$ is not a functional part of Shapism School.

3.2. Composition/Constitution

Case (2) "There is a four-legged table made of wood. Some time later (at t_1), a leg of the table is replaced. Even later (at t_2), 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.)

The modeling of a table is fully based on the role theory discussed in Case (1). In terms of a role theory, there is no difference between a table and a school both of which are composed of parts that have roles in the context of the whole. Now, let the wooden table be $table_1$ which is composed of a top-board $top\text{-}board_1$ and four legs: leg_1 , leg_2 , leg_3 and leg_4 . We here identify an amount of wood as well as a table and its parts. All parts (components) used for making the table are made of wood whose total amount shares the same spatiotemporal region with the table. There are two amounts of wood in this case. One exists from the beginning until the exchange of a leg and the other after the exchange and even after demolition.

Preliminary formalization

$Made\text{-}of(x, y) \rightarrow (Object(x) \wedge Material(y) \wedge Constituted\text{-}by(x, y))$

$\exists leg_i, rod_i, top\text{-}board, board_1, table_1 (Leg\text{-}role(leg_i) \wedge Rod(rod_i) \wedge Leg(rod_i, table_1, t) \wedge Board(board_1) \wedge TopBoard(board_1, table_1, t) \wedge TopBoardRole(top\text{-}board) \wedge Table(table_1))$
 $\leftrightarrow ComposedOf(table_1, top\text{-}board, leg_1, leg_2, leg_3, leg_4, t) \wedge P(rod_i, table_1, t) \wedge P(board_1, table_1, t)$

"If leg_i roles and their players rod_i , and $top\text{-}board$ and its player $board_1$ are given, then $table_1$ is composed of those roles together with their players."

$P(x, y, t) \rightarrow \exists r (Role\text{-}holder(x, t) \wedge Role(r) \wedge Context\text{-}of(y, r) \wedge Play(x, r, t))$

"If an object x is a part of y , x is playing a role r specified by the context y ."

$Rod(x) \wedge Table(y) \wedge P(x, y, t) \rightarrow \exists r (Role\text{-}holder(x, t) \wedge LegRole(r) \wedge Context\text{-}of(y, r) \wedge Play(x, r, t))$.

"If a rod is a part of a table, there exists a leg role which the rod is playing in the context of the table."

$Board(x) \wedge Table(y) \wedge P(x, y, t) \rightarrow \exists r (Role\text{-}holder(x, t) \wedge TopBoardRole(r) \wedge Context\text{-}$

$of(y, r) \wedge Play(x, r, t)$

$Leg(x, y, t) \rightarrow Rod(x) \wedge Table(y) \wedge Time(t)$

$TopBoard(x, y, t) \rightarrow Board(x) \wedge Table(y) \wedge Time(t)$

$LegRole(r) \rightarrow \exists c, s(LegPosition(c) \wedge Inhere-in(c, r) \wedge Role(r) \wedge Table(s) \wedge Context-of(s, r))$

”A leg role of a table has a quality called the leg position inhering in it in the context of the table.”

$Leg(x, tbl, t) \rightarrow \exists r, c, bd(Hold(x, r, tbl, t) \wedge LegPosition(c) \wedge Possess(x, c, t) \wedge LegRole(r) \wedge Play(x, r, t) \wedge TopBoard(bd, tbl, t) \wedge P(bd, tbl, t) \wedge Support(x, bd, t))$

”If an object x is a leg of a table, x is a leg-role-holder of the table by playing the leg role, possesses the leg position of the table, and supports the top-board which is a part of the table.”

$TopBoardRole(r) \rightarrow \exists c, s(TopBoardPosition(c) \wedge Inhere-in(c, r) \wedge Role(r) \wedge Table(s) \wedge Context-of(s, r))$

$TopBoard(x, tbl, t) \rightarrow \exists r, c(Hold(x, r, tbl, t) \wedge TopBoardPosition(c) \wedge TopBoardRole(r) \wedge Possess(x, c, t) \wedge Play(x, r, t))$

During its life time, an artifact $table_1$ can change while keeping its identity independently of the replacement of parts unless the specification is violated. In this table example, there are five replaceable parts such as $board_1$, rod_1 , rod_2 , rod_3 and rod_4 and they play those five roles such as top-board role and leg_1 , leg_2 , leg_3 and leg_4 roles, respectively, thereby becoming $top-board_1$, leg_1 , leg_2 , leg_3 and leg_4 role-holders which are genuine parts of the table. **Before** t_1 : $Table_1$ is composed of $top-board_1$; leg_1 , leg_2 , leg_3 and leg_4 . w_1 : Amount of wood exists which is the summation of the wooden material used for all the replaceable parts. It shares the same spatiotemporal region with $table_1$. **At time** t_1 : A leg, say leg_2 , is replaced. This means that rod_2 is removed and a new rod, say rod_{2-1} starts to play the leg_2 role, thereby becoming a new leg leg_2 . Rod_2 is no longer leg_2 and it turns back to a rod as it was before it was used for leg_2 . $Table_1$ keeps its identity after this replacement. At the same time, a new amount of wooden material, $w_2 (= w_1 - rod_2 + rod_{2-1})$ appears and starts to share the same spatiotemporal region with $table_1$. **At time** t_2 : $Table_1$ is demolished and then it disappears, since the specification has been violated. Assuming that no part is broken (that is, it was decomposed), $top-board_1$, leg_1 , leg_2 , leg_3 and leg_4 turn back to the original $board_1$; and rod_1 , rod_{2-1} , rod_3 and rod_4 , respectively. W_2 continues to exist.

3.3. Property Change

Case (3) “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.

As stated earlier, YAMATO distinguishes processes and events. An event is constituted by the process. Although processes can change, events cannot. Let us assume that the change of the speed happened at t_1 and the running process started at t_2 . This case consists of three occurrents such as a walking with a steady speed, another walking with increasing speed and a running each of which is separated by a clear boundary. Since no event can change, the second occurrent needs YAMATO’s idea of process. The man apparently participates in a single moving occurrent which consists of a walking process and a running process. Because the walking process exists at any time as a whole during the process is ongoing, it can have quality, and in fact it has a speed quality. Thus the

change under consideration is naturally modeled as the change of speed attribute values of the walking process in the same way as the color change of a flower.

Preliminary formalization

$$\begin{aligned} &\forall t \text{ in } (t_0, t_1], \exists s_1, s_2 (\text{Walking}(p_1, t) \wedge \text{Participate}(\text{John}, p_1, t) \wedge \\ &\quad (\forall tx, ty \text{ in } (t_0, t_1] (\text{speed}(s_1, p_1, tx) \wedge \text{speed}(s_2, p_1, ty) \rightarrow s_1 = s_2))) \\ &\forall t \text{ in } (t_1, t_2], \exists s_1, s_2 (\text{Walking}(p_1, t) \wedge \text{Participate}(\text{John}, p_1, t) \wedge \\ &\quad \forall tx > ty \text{ in } (t_1, t_2] (\text{speed}(s_1, p_1, tx) \wedge \text{speed}(s_2, p_1, ty) \rightarrow s_1 > s_2))). \\ &\forall t \text{ in } (t_2, t_3) (\text{Running}(p_1, t) \wedge \text{Participate}(\text{John}, p_1, t) \wedge \text{speed}(s, p_1, t)) \\ &\forall t \text{ in } (t_0, t_3) (\text{Moving}(p_1, t) \wedge \text{Participate}(\text{John}, p_1, t) \wedge \text{speed}(s, p_1, t)) \\ &\text{Walking}(p_1, t) \rightarrow \text{Moving}(p_1, t); \text{Running}(p_1, t') \rightarrow \text{Moving}(p_1, t') \end{aligned}$$

This abstraction enables us to identify a moving process p_1 which comprises a walking process at time t and a running process at time t' . This is valid to the extent that either is a constituent of the same (moving) event. In our theory of processes and events [11], any event has a unique (the most abstract) and uniform process. For instance, a conference event has the conferencing process and a cooking event has the cooking process.

Imagine that John sneezes at the boundary between these two processes. In ordinary situations, sneezing is not considered as a constituent of a moving event and it is discarded in the identification of constituent processes in the moving event. In this case, therefore, only walking and running processes are considered as constituent processes of the moving event, and hence they can be considered as different modes of the same moving process. This guarantees the talk of ‘change’ in the mode of locomotion. One can go up such an abstraction hierarchy of processes as high as possible insofar as the abstracted process constitutes an event. The above observation shows that the identification of events plays a key role in our theory of occurrents (see [14] for details of axioms of processes and events). Despite its importance, the event identification requires no special treatment because we simply follow the conventional manner of how to identify events such as cooking and a conference, as is implied by the following axiom:

$$\text{Event}(e_1, \text{person}, T) \equiv_{def} \exists p_1 \forall t \text{ in } T (\text{Person}(\text{person}) \wedge \text{Process}(p_1, t) \wedge \text{Interval}(T) \wedge \text{Participate}(\text{person}, p_1, t) \wedge \text{Constituted-by}(e_1, p_1))$$

3.4. Event Change

Case (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.

We take this issue to be deeply related to the action theory. Instead of delving into details of action-theoretic issues, however, we here mainly formalize it from the viewpoint of events and processes with no much emphasis on BDI (Belief, Desire and Intention) issues. As is true of Case (3), John (the man) participates in a walking process all times. The main issues to discuss would be (i) whether there is one event or two events and (ii) in the case of the latter, how (on what basis) to identify the event boundary between the first and the second events. As stated already, there is only one walking process because there is no physical break in the walking process at the time of the change of his mind. If he stops walking, thinks for a while, turns around and starts walking back

to his home, then there are two walking processes. Insofar as processes are concerned, the issue of terminating/beginning a process lies not in the change at the BDI level but in the physical continuity of the walking process. As for an event, on the other hand, BDI matters. In the case of walking event, the goal (intended destination) matters because an event is necessarily a completion and hence requires a clear specification of how it terminates. For example, to cross a street is an event that is constituted by (usually) a walking process. If it fails, it is not a ‘crossing a street’ event; but it is nonetheless true that there exists a walking process independently of the success or failure of the event.

Following the above observation, we conclude that there are two events and that justification of the boundary identification is the change of the destination. Precisely speaking, however, there are three events: one is planned but unsuccessful, the other two are ad-hoc but successful. Assume that John starts to walk at t_1 , turns around at t_2 and returns his home at t_3 ; and that there is no time loss for the change of his mind. Let e_1 be the first walking event of the interval $[t_1, t_2]$ and e_2 be the second one of the interval $[t_2, t_3]$, respectively. There is only one walking process p_1 in (t_1, t_3) . Roughly speaking, YAMATO’s notion of time is two-fold: A-series for talking about processes and B-series for talking about events. By using A-series, YAMATO can talk about ongoing/progressive aspects of occurrents. No event can be present because either it is already terminated, not happened yet, or it is incomplete.⁷ For this reason, the following formalization does not include even the first portion of the originally planned event, and the event change is modeled by the fact that two consecutive events are constituted by one process, since talk of change requires an entity to be identical throughout the changing process.⁸

Preliminary formalization

$$\forall t \text{ in } (t_1, t_2] \text{ constituted-by}(e_1, p_1); \forall t \text{ in } [t_2, t_3) \text{ constituted-by}(e_2, p_1);$$

$$\forall t \text{ in } (t_1, t_3) \exists p_1 \text{ Walking}(p_1)$$

3.5. Concept Change

CASE (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.

A rigorous analysis of the (dis)continuity of the meaning of marriage requires that there be three different kinds of meanings of the term that have different identity conditions: the denotation of marriage; the content of marriage; and the name of marriage according to the semiotic triangle (Peirce). Generally speaking, the denotation of a term is the unvarying entity that is denoted by the term. The content of a term is the varying propositional entity to which the term refers. The name of a term is the term itself that is usually a sequence of characters.

First of all, the denotation of marriage is the entity that is denoted by the term ‘marriage’: the socio-legal union between two adults that is verified by the contract between them. Insofar as the denotation of marriage is concerned, the term ‘marriage’ refers to the socio-legal union between two adults, regardless of time and place. Second, the con-

⁷A rigorous formalization of time in YAMATO is currently under investigation.

⁸To deal with the uncompleted event we need to employ explicitly the notion of plan and its execution, which are left for future work.

tent of marriage is basically the characteristics of the denotation of marriage that are regulated by socio-legal constraints and it varies greatly with time and place. Consider the legalization of same-sex marriage in France in 2013. That year saw the content-level change in French marriage: a homosexual couple has acquired the right to marry. The key factor behind the content-level change in French marriage is the invariable denotation of French marriage: the socio-legal union between two adults that meets with the public approval of French people. Third and finally, the name of marriage is the string 'marriage'. Notice that the name of a term is significantly different from its content, although the name-level change in a term is often caused by the content-level change in the term. It is not improbable, for example, that the legalization of same-sex marriage will let the French government consider the employment of another name for 'marriage'.

Intuitively understood, the socio-legal constraints that regulate marriage are strongly influenced by the concepts of marriage that are embraced by the people in a particular social and cultural system. This fact justifies the claim that the content of marriage is a kind of *conceptualization*. Additionally, a conceptualization is considered as a kind of representation within the YAMATO ontological framework. For YAMATO, a representation is in nature a 'content-bearing' entity and a conceptualization, i.e. agents' understanding of (part of) the world, essentially has as content a portion of reality. See below for more details on YAMATO's notion of representation.

Therefore, the three types of meanings of marriage presented above are to be elucidated in terms of YAMATO's representational interpretation of conceptualization. Consider a document as the example of representation which is a useful analogy for marriage. Although the name and/or content of a document may change during its repeated revisions, the first version of the document is the 'same' as its third version in some sense. Likewise, by changing its name and/or content (e.g., by removing gender constraints), marriage has a number of 'versions' while maintaining its 'original' (denotation-level) identity. It is important to see that an analogy with a document applies to many other entities than marriage. Consider for instance hypertension. In 1990, Japan employed as the diagnosis criterion of hypertension the value: 160/95 mmHg, whereas in 2017, the Japanese diagnosis criterion of hypertension is the value: 140/90 mmHg. Interpreted from the viewpoint of a representation, the '1990 version' and the '2017 version' of hypertension have as content 160/95 mmHg and 140/90 mmHg, respectively. At its denotation level, however, hypertension refers consistently to the clinically abnormally high blood pressure. Scientific findings are also analyzable in terms of the document analogy, as is supported by the observation that all scientific findings are fundamentally falsifiable hypotheses and the object (denotation) of a scientific investigation remains constant even when a hypothesis (content) of the scientific investigation is falsified.

An overview of YAMATO's theory of representation is as follows. A *representation* is composed of a (*representation*) *form* and the *content* which is constituted by the representation form. Every content is propositional. A representation can be *realized* more than one time, typically in a sequence of characters (*realization*). A representation form of a representation *R* is itself a representation whose content is uniquely denoted by the realization of *R*. For instance, a musical score as a representation is composed of a sequence of musical notes (form) and a piece of music (content). A piece of music is the specification which can be realized by playing actions. A musical score can be realized on a number of papers. A sequence of musical notes is a representation whose content is the symbols that are uniquely denoted by the musical notes, namely the realization of the musical score.

As stated above, a conceptualization is a type of representation. The content of a conceptualization, however, plays such a vital role in determining the essential nature

of the conceptualization that it may well be legitimate to consider a conceptualization either as a virtually ‘formless’ representation or as a special kind of content. In summary, concept change is to be modelled according to three types of meanings of a concept: the denotation, the content, and the name of the concept. There are two kinds of concept change: the content-level change and the name-level change. The content-level concept change occurs when and only when a concept changes its content while preserving its denotation-level identity. The name-level concept change occurs when and only when a concept changes its name while preserving its denotation-level identity. As below a preliminary formalization of concept change could be constructed from a simplified formalization of YAMATO’s theory of representation.

Core formalization of representation

$Representation(x) \rightarrow \exists y, z, t(RepresentationForm(y) \wedge Content(z) \wedge part-of(y, x, t) \wedge part-of(z, x, t) \wedge constituted-by(z, y, t))$

”A representation is composed of a representation form and the content which is constituted by the representation form.”

$RepresentationForm(x) \rightarrow \exists y, t(Content(y) \wedge constituted-by(y, x, t))$

”Every representation form is also a ‘content-bearing’ entity.” ($RepresentationForm(x_1) \wedge Content(y_1) \wedge RepresentationForm(x_2) \wedge Content(y_2) \wedge constituted-by(y_1, x_1, t) \wedge constituted-by(y_2, x_2, t) \wedge y_1 \neq y_2 \rightarrow x_1 \neq x_2$)

”Two representation forms are different when they constitute different contents.”

Preliminary formalization of concept change

$Denotation(x) \rightarrow \exists y, z, t(Name(y) \wedge Conceptualization(z) \wedge denoted-by(x, y, t) \wedge meaning-of(z, x, t))$

$Conceptualization(x) \rightarrow \exists y, t(Content(x) \wedge Representation(y) \wedge Time(t) \wedge part-of(x, y, t) \wedge \exists z(RepresentationForm(z) \wedge part-of(z, y, t) \wedge constituted-by(x, z, t)))$

$Name(x) \rightarrow SemiAbstract(x); Conceptualization(x) \rightarrow SemiAbstract(x)$

$Name-Time(x, y, t) \rightarrow Name(x) \wedge Denotation(y) \wedge Time(t) \wedge denoted-by(y, x, t) \wedge \exists z(Conceptualization(z) \wedge meaning-of(z, y, t))$

$Conceptualization-Time(x, y, t) \rightarrow Conceptualization(x) \wedge Denotation(y) \wedge Time(t) \wedge meaning-of(x, y, t) \wedge \exists z(Name(z) \wedge denoted-by(y, z, t))$

4. Conclusion

We presented an overview of YAMATO and illustrated its theoretical and practical virtues with a concise analysis of the five examples. Further theoretical development of YAMATO includes its fuller axiomatization so that YAMATO will be ontologically and formally comparable to other upper ontologies. The current axiomatization of YAMATO includes, in particular, the axioms of is-a and instance-of relations. This work is currently under review in a journal. In the future we plan to deepen the current formalization of YAMATO and take the step to axiomatize the rest, e.g., regarding the categories of quality/quantity and representation. As for its practical effectiveness, YAMATO has been extensively applied to various domains. Examples include (1) Ontology of diseases based on the River Flow Model (RFM); (2) Development of a learning/instructional theory-aware authoring tool; (3) Reorganization of the grammar of English tense based on the ontology of process and event; (4) Task ontology building of a demolition task of a nuclear power

plant; (5) Ontology building of biomimetics; and (6) Knowhow model of an expert of ferromagnetic materials. Those applications are expected to vindicate, possibly with their future publications, the peerless practicality of YAMATO.

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