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## Towards OntoClean 2.0: A Framework for Rigidity

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## Abstract

The OntoClean methodology was based on a set of formal meta-properties whose semantics were specified in S5 modal logic. One of these metaproperties, Rigidity, has come under more focused scrutiny by the ontology community, and several problems with the formalization have been discussed along with several solutions. In this paper, we attempt to reconcile these results in a larger framework that exposes different kinds of rigidity, as well as two new metaproperties, actuality and permanence, which deal more specifically with the behavior of properties with respect to time and existence.

## 1 Introduction

The notion of rigidity in the OntoClean methodology was originally introduced to account for the conditions under which exemplification of properties by their instances is necessary or essential<sup>1</sup>. Since then, many authors have focused on the analysis of rigidity in various settings, accompanied by claims that the original definition failed to capture key elements such as time and actual existence.

The purpose of this paper is to consolidate work by these authors on the notion of rigidity in OntoClean. We establish a unifying framework that elaborates the dimensions along which the recent proposed accounts of rigidity differ. These dimensions are alethic modality, time, and existence. We apply this framework to develop a range of definitions that, given basic intuitions of how time and existence influences intuitions about rigidity, we claim cover the space of possible definitions.

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<sup>1</sup> In this paper we uniformly use the term “property” to denote unary relations in intension, as was the meaning of the term in the original work on OntoClean done by Guarino and Welty and as is standard usage in philosophical literature. We acknowledge, however, that, in addition, the terms “class”, “kind”, and sometimes “type” are commonly used. When talking about properties that range over properties, we use the term “meta-property”.

A common criticism of OntoClean is that it relies on quantified modal logic (S5) for its expression. While modal logic is required for the expression of the rigidity axioms we present here, many useful theorems derived from them may be used in non-modal settings. For this reason we give the beginnings of a formal ontology of rigidity metaproperties suitable for application with non-modal ontology authoring languages that permit quantification over relations. The main point of this paper is to consolidate subsequent work by many authors on the OntoClean meta-property called Rigidity, and establish a formal framework that exposes differences between them. This work can be seen as a *formal ontology of rigid properties*.

## 2 Background

One of the most often heard criticisms of the OntoClean methodology is that it requires modal logic. The truth is that one does not need modal logic, nor modal logic reasoning, to use OntoClean in ontology-based systems. The formalizations of the OntoClean meta-properties were present to clearly communicate their semantics, much like specifying a model theory for a language, and not with the intention of being used in reasoning systems themselves. The formalization helped to maintain a level of rigor that can, in general, make subtle distinctions clear. Continued analysis of the formalizations themselves has shown that there were more distinctions than originally realized, and will be the subject of this paper.

Modal logic was chosen for the formalization mainly due to the needs of specifying the semantics of rigidity, in particular anti-rigidity. We need to express the fact that some class, e.g. HospitalPatient, is anti-rigid, that any instance of this class must possibly not be an instance. A purely temporal axiomatization would require that every instance does change, which is not true. A person who was a hospital patient for his entire existence should not contradict the anti-rigidity of the class – it was always *possible* for him to become a non-patient, it just never happened.

OntoClean was formalized in S5 modal logic with the Barcan Formula, which gives us a *constant domain* (every ob-

ject exists in every possible world) and *universal accessibility* (every world is accessible from every other world). The domain of quantification is *possibilia*, which when combined with S5+BF introduces a need for an *actual existence* predicate (E), as opposed to logical existence, that indicates some object actually exists in the possible world [Miller, 2002]. The unary existence predicate indicates timeless existence, and the binary predicate indicates existence at a particular time in the possible world.

Given the separate (i.e. non-modal) treatment of time within possible worlds implied by the OntoClean formalizations, we need to clarify the intuition that possible worlds have a time line within them, which we also assume to be totally ordered wrt to a succession relation ( $<$ ) [Artale & Lutz, 2004]. Given the constant domain assumption, times across worlds are *the same*, and we further assume that, in order to be the same, their ordering is maintained across worlds as well:

$$[A1] \quad \forall t_1 t_2 \diamond t_1 < t_2 \rightarrow \Box t_1 < t_2$$

We require a strong notion of subsumption in order to have modal consequences for the meta-properties [Kaplan, 2001]:

$$[A2] \quad \text{subsumes}(\psi, \phi) \leftrightarrow \Box \forall x \phi(x) \rightarrow \psi(x)$$

In order to prevent trivial satisfaction of the axioms, we require that all properties be *exemplifiable* [Andersen & Menzel, 2004], i.e. for any property  $\phi$ :

$$[A3] \quad \diamond \exists x \phi(x)$$

These assumptions may be somewhat controversial in a philosophical setting, however we believe for practical use in ontology engineering, these assumptions are widespread, though often implicit.

### 3 History of Rigidity

Although not the central notion in OntoClean, Rigidity is the simplest and most intuitive, with more obvious immediate utility and applicability across the ontology, conceptual modeling, and domain modeling communities, and this has made it the most carefully studied of the OntoClean metaproperties.

The general intuition of rigidity is that certain properties in an ontology are essential to their instances – an instance cannot change its membership, and was first axiomatized [Guarino & Welty, 2000a] as a property  $\phi$  is rigid iff:

$$[A4] \quad \forall x \phi(x) \rightarrow \Box \phi(x)$$

Kaplan [2001] pointed out that [A4] is not a straightforward extension of Kripke’s *rigid designators* [Kripke, 1982] to universals, and proposed:

$$[A5] \quad \forall x \diamond \phi(x) \rightarrow \Box \phi(x) \quad (\text{basic rigidity})$$

which amounts to saying the extension of a rigid property is the same in all possible worlds. Kaplan also pointed out the inconsistent use of time in the OntoClean axioms, which was present in the accounts of identity and unity, but not rigidity and dependence. To fix these problems, later OntoClean papers treated all the original OntoClean axioms as necessary, and added time [Welty & Guarino, 2001]:

$$[A6] \quad \Box \forall x t \phi(x, t) \rightarrow \Box \forall t' \phi(x, t') \quad (\text{temporal rigidity})$$

which amounts to saying the extension of a temporally rigid property must be the same for all time points and all possible worlds.

Andersen and Menzel [2004] pointed out that [A6] causes problems for non-exemplifiable properties, and does not accurately capture the intuition expressed as, “An instance of a rigid property cannot cease to be an instance of that property, unless it ceases to exist,” [Welty & Guarino, 2001] since [A6] requires an entity to have the property always and in all possible worlds, e.g. if Person is a rigid class, must Aristotle be a person even in a possible world in which he does not exist? To address this, they proposed:

$$[A7] \quad \Box \forall x t \phi(x, t) \rightarrow \Box \forall t' (E(x, t') \rightarrow \phi(x, t')) \quad (\text{temporally existential rigidity})$$

and introduced the constraint (which we have adopted) that  $\phi$  is restricted to only exemplifiable properties.

Citing many of the same problems, Carrera et al [2004] proposed:

$$[A8] \quad \Box \forall x t (E(x, t) \wedge \phi(x, t)) \rightarrow \Box \forall t' (E(x, t') \rightarrow \phi(x, t'))$$

which is similar to [A7], with a slightly stonger restriction on existence.

Both Andersen&Menzel and Carrara et al point out that their accounts of rigidity, by introducing actual existence in the antecedents, say nothing about what happens to entities when they do not exist, leaving open the possibility that an instance of a rigid property could change its membership when it does not exist.

## 4 Kinds of Rigidity

One of the original motivations for specifying the OntoClean meta-properties was to encourage more rigorous analysis of the properties in an ontology in order to make the meaning more clear. This clarity would also help to expose differences in meaning between ontologies that shared terms, e.g. if two ontologies used a class named Person, but it was rigid in one ontology and non-rigid in another, then we would have some indication that the properties mean different things.

The different accounts of rigidity above ([A5]-[A8]) were all intended as corrections on the original formulation, in an effort to come up with the one true formalization of the notion. In this paper, we take a slightly different stance: all of the accounts above are correct, and specify different *kinds of rigidity*. This has encouraged us to clarify these distinctions further, in order to establish a more general framework for rigidity.

We note first that the different “corrections” to rigidity involve invariance over time, across possible worlds, or both. We isolate these aspects in this section, and focus on particular combinations of them that hold meaningful distinctions for ontologies.

### 4.1 Existential Rigidity

The first obvious difference between these accounts of rigidity is the use of the actual existence predicate. Basic rigidity [A5] is independent of existence and time, and axiomatically describes properties that have the same exten-

sion in all possible worlds. In axiom [A7] the intuition was added that rigidity should only apply to entities when they exist. Removing time from that axiom, we get a new kind of rigidity:

$$[\text{A9}] \quad \forall x \diamond \phi(x) \rightarrow \Box(E(x) \rightarrow \phi(x)) \quad (\text{existential rigidity})$$

This tells us that a property  $\phi$  carries existential rigidity when in any possible world that an instance of the property exists, it instantiates the property. This characterization is useful for properties exemplified by abstract entities that arguably exist outside of time (Lowe, 2002), or for so-called “snapshot” ontologies that consider only single states of affairs and treat time, space, possibility, etc., as modalities.

This still tells us nothing about worlds in which the instance does not exist, but by inverting the consequent we find another behavior of a property with respect to existence, though it is not a form of rigidity at all:

$$[\text{A10}] \quad \forall x \diamond \phi(x) \rightarrow \Box(E(x) \leftarrow \phi(x)) \quad (\text{actuality})$$

i.e. the property only holds for actually existing entities. If this holds for all properties in an ontology, we have *strong actualism*, the philosophical position that only actually existing entities can instantiate properties [Menzel, 2003].

We can strengthen these axioms by combining them:

$$[\text{A11}] \quad \forall x \diamond \phi(x) \rightarrow \Box(E(x) \leftrightarrow \phi(x)) \quad (\text{existential actual rigidity})$$

i.e. existentially rigid properties that only hold of actually existing instances.

Considering these new kinds of rigidity clearly begs the question, are these variations useful? Is there any reason *not* to commit to a single definition of rigidity? In this paper, we will not make strong claims either way, our main purpose is to establish the formal framework, and there is limited actual experience applying the framework to applied ontology problems to justify a position scientifically or pragmatically. However, we do believe one aspect of the success of OntoClean has been its relative neutrality with respect to basic ontological choices, and this analysis exposes that, at least formally, variations on the notion of rigidity are possible.

## 4.2 Temporal Rigidity

In addition to behavior with respect to existence, it is also useful to consider the behavior of a property with respect to time. In many cases, we have found that the intuitions people who use OntoClean have regarding rigidity are based on a temporal reading of modality, i.e. rigid properties do not *change* and much of the subsequent analysis of rigidity had that flavor. It is important to note here that the OntoClean formalizations treat time in the domain, rather than as a modality, and therefore a temporal reading of basic rigidity may not be correct. This led to the criticism by Kaplan noted above, and the addition of time to axiomatizations in subsequent papers.

Properties whose extensions change with time are known as *fluents* [McCarthy & Hayes, 1969]. Temporally rigid properties not fluents, but it is useful to consider the behavior of instances of fluents as well. Temporal rigidity in its pure

form (expressed in [A6]), states that instances of these properties remain so for all time and in all possible worlds. If we consider this span of time as a line, infinite in both temporal directions (past and future), then it stands to reason that there are analogous ray and segment-like behaviors:

$$[\text{A12}] \quad \forall xt \diamond \phi(x,t) \rightarrow \Box \exists t_s \forall t' (t' < t_s \rightarrow \neg \phi(x,t')) \wedge (t > t_s \rightarrow \phi(x,t')) \quad (\text{semi temporal rigidity})$$

i.e. when a semi-temporally rigid fluent starts to hold of some instance, it does so from that time forward. An example of such a property is one possible reading of Person – it’s reasonable to conceive of personhood as being rigid but becoming true at some time and continuing thereafter in each possible world. Note that this is a form of *anti-rigidity*, but even stronger, as this states that in every possible world an instance must not be a member of the property at some time, and be a member of the property for some time. One may also consider the property of dead people to have semi-temporal rigidity: once one dies, one is dead forevermore, and all dead people were once not dead. A further discussion of how these properties can be related to existence is given in Section 5.

$$[\text{A13}] \quad \forall xt \diamond \phi(x,t) \rightarrow \Box \exists t_s t_f \forall t' t_s < t_f \wedge (t' < t_s \rightarrow \neg \phi(x,t')) \wedge (t' > t_f \rightarrow \neg \phi(x,t')) \wedge (t_s < t' < t_f \rightarrow \phi(x,t')) \quad (\text{ephemeral rigidity})$$

Instances of necessarily temporary fluents instantiate the property for one finite and continuous period of time (between the starting and finishing times). This is an even stronger form of anti-rigidity, stating that membership in the property must change twice for each instance in every possible world. One may e.g. consider the property of living people to be temporary. More generally, *continuants* could be said to be characterized by ephemeral rigidity as their essential behavior is that they come into and go out of existence.

The problem with both these forms of temporal rigidity is that they require instances of these properties to exhibit the same behavior wrt time in all possible worlds. For example, if we do consider the property of living people to be temporary, then [A13] requires that all possible instances of the property instantiate it for a finite time in all possible worlds. This would mean e.g. that Aristotle is a living person for some time in every possible world. That may well be useful in some applications, but leaves open the obvious need to express something slightly less restrictive.

We could add a myriad of exceptions to these two axioms make them more flexible, however it turns out these possible variations are of limited practical utility, what we need are variations of these forms of temporal rigidity that depend on existence.

## 4.3 Temporal Rigidity and Existence

The most useful varieties of rigidity appear to be those that combine the notions of existence and time, as in [A7]. To begin with, we can extend [A10] with time to get:

[A14]  $\forall xt \diamond \phi(x,t) \rightarrow \Box \forall t' (\phi(x,t') \rightarrow E(x,t'))$   
*(temporal actuality)*

i.e. temporally actual properties only hold for entities at times and worlds where they exist. Note that here it is possible for a given object to exist in a world at a time without ever exemplifying the property in question. This clearly leads to:

[A15]  $\forall xt \diamond \phi(x,t) \rightarrow \Box \forall t' \phi(x,t') \leftrightarrow E(x,t')$   
*(temporally existential actual rigidity)*

i.e. properties holding only of actually existing entities that instantiate the property at all (and only those) times and worlds at which they exist.

Finally, we consider three more variations of temporal rigidity that restrict the line, ray, and segment-like behaviors to possible worlds in which the instances actually exist. Recalling **Error! Reference source not found.**, we have:

[A16]  $\forall xt \diamond \phi(x,t) \rightarrow \Box (E(x) \rightarrow \forall t' \phi(x,t'))$   
*(existential temporal rigidity)*

which is intended to convey the notion that in possible worlds in which an instance of the property exists at any time, it instantiates the property at all times.

[A17]  $\forall xt \diamond \phi(x,t) \rightarrow \Box (E(x) \rightarrow \exists t_s \forall t' (t' < t_s \rightarrow \neg \phi(x,t')) \wedge (t' > t_s \rightarrow \phi(x,t')))$   
*(existential semi temporal rigidity)*

i.e. in possible worlds in which an instance of the property exists, it instantiates the property from some starting time forward. Doing the same for [A13] gives us:

[A18]  $\forall xt \diamond \phi(x,t) \rightarrow \Box (E(x) \rightarrow \exists t_s t_f \forall t' t_s < t_f \wedge (t' < t_s \rightarrow \neg \phi(x,t')) \wedge (t' > t_f \rightarrow \neg \phi(x,t')) \wedge (t_s < t' < t_f \rightarrow \phi(x,t')))$   
*(existential ephemeral rigidity)*

Here, a  $\phi$ -instance that has actual existence at any time in a given world, exemplifies  $\phi$  temporarily, analagous to [A13]. Note that the temporal interval over which a given  $\phi$ -instance does in fact instantiatates  $\phi$  is not required even to include the  $t$  mentioned in the antecedent. Similar observations apply to all of [A16]-[A18].

## 5 Temporal and Modal Issues of Existence

Most of the rigidity axioms rely on the property of actual existence, yet this itself has not been, in practice, well understood. There is a fundamental difference, for example, between existence at a time and existence in a possible world, as expressed in axiom **Error! Reference source not found.** Most intuitions about existence for instances of common biological types like animals, especially persons, is that they do not exist outside their lifetimes. This kind of intuition gives us that there are (possible) worlds in which Aristotle does not exist at all, and worlds in which he does exist but times, within those worlds, that he does not.

Actual existence is a thorny issue and subject to much philosophical debate, and we must be careful in building ontologies to define what we mean by actual existence at all. Intuitively, actual existence in a possible world can be thought of with respect to events that did not happen – for

example the possible world in which Aristotle's parents never met. In that possible world, there is still a rigid designator for Aristotle, however he does not actually exist. Note that it is not a question of being alive or dead – he simply does not exist.

Existence has practical import in designing ontologies for information systems. Understanding and specifying the *existence criteria*, i.e. the manner in which instances of properties in an ontology come into and out of existence, is a critical part of capturing the meaning of those properties. Take our example above regarding Aristotle: we can have two ontologies where what is intended by the Person property may differ only with respect to this distinction, i.e. in one ontology, the Person property carries basic rigidity and in the other the Person property carries strong existential rigidity. Thus, in the first ontology Aristotle is a Person even in worlds in which he does not exist, whereas in the second he is only a Person in worlds in which he exists. The point here is *not* to say that one is correct and the other is not, but rather that they are different, and this difference should be captured somehow.

Rigidity itself cannot help to make the meaning of properties more clear if the issue of existence criteria is left unspecified and at the level of intuitions, which is, unfortunately, the norm. A common problem in common-sense ontologies is precisely this lack of rigor wrt existence. The Person property is quite ubiquitous, however its existence criteria are unclear: do people exist only when they are living, or does a person exist for all time? This lack of precision creates well-known anomalies such as Person being a subclass of Living Being in Cyc<sup>2</sup> and Wordnet, and Aristotle being an instance of Person in both cases.

Intuitively, for classes of biological creatures, many people take existence to be tied to life, i.e. people do not actually exist at times before they are born and after they are dead, and are not people at those times. However in many real information systems, individuals exist in the systems that are instances of Person, even though the persons they denote are dead – take a library system for example. Again, the point here is not to suggest that one of these approaches is incorrect, the point is that they are different.

As an example, let's consider three very reasonable meanings one might intend for instances of the property Person:

- A person exists for all time
- A person exists while alive
- A person exists after being born

The first case is actually the most widespread intended meaning for the Person class found in most common-sense ontologies, as evidenced by the fact that famous dead people are found as instances in many of them. The second class is probably the most common *a priori* intended meaning that human interpreters of an ontology think of. The final class is also quite common in actual applications that deal with people, such as government tax systems or library informa-

<sup>2</sup> This particular example has been fixed in Cyc for a few years.

tion systems – there are typically no records of people before they are born, yet they remain after.

In addition to making an appeal for the importance of understanding, and specifying, existence criteria in ontologies, the point here is to show the difference between rigidity and existence. Note that in the second case, it is still possible to claim that the Person class carries any form of rigidity, including basic or temporal rigidity. A temporally rigid class requires its instances to maintain their membership at all times in all possible worlds, but it makes no claims about existence. Other forms of rigidity place requirements on the instances when they exist, but say nothing about them when they do not.

This appears to give us a new kind of meta-property that captures useful existence criteria. Recalling **Error! Reference source not found.**, we have:

$$[A19] \forall x \diamond \phi(x) \rightarrow \Box(E(x) \rightarrow \forall t E(x,t)) \quad (\textit{permanence})$$

A class carries permanence if its instances exist for all times in worlds in which they exist at all.

$$[A20] \forall x \diamond \phi(x) \rightarrow \Box(E(x) \rightarrow \exists t_c \forall t (t < t_c \rightarrow \neg E(x,t)) \wedge (t > t_c \rightarrow E(x,t))) \quad (\textit{semi-permanence})$$

A class carries semi-permanence if its instances exist from some time forward (the creation time), and do not exist before that time.

$$[A21] \forall x \diamond \phi(x) \rightarrow \Box(E(x) \rightarrow \exists t_c t_d \forall t (t_c < t < t_d \wedge (t < t_c \rightarrow \neg E(x,t)) \wedge (t > t_d \rightarrow \neg E(x,t)) \wedge (t_c < t < t_d \rightarrow E(x,t))) \quad (\textit{ephemerality})$$

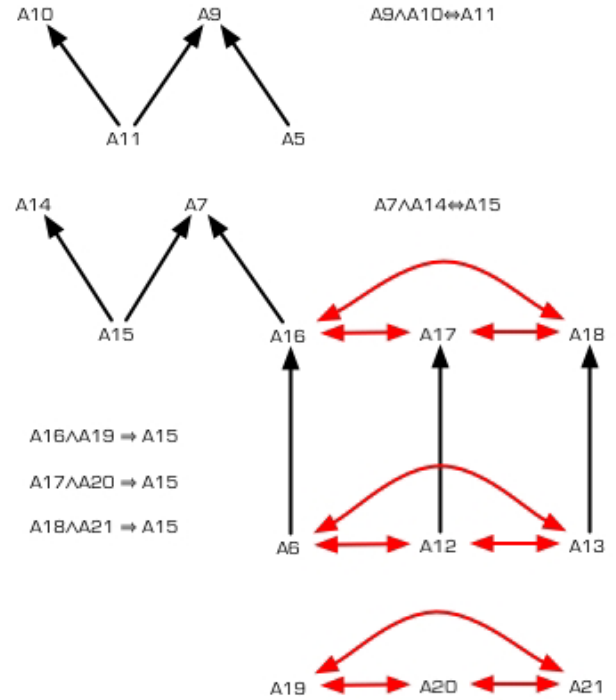
A class carries ephemerality if its instances exist for one finite continuous period (between creation and destruction times), and do not exist outside this period.

It is, of course, possible to consider other variations on permanence, in particular “striped” existence, where entities come in and out of existence in a Cheshire Cat-like way, and of course we can think of variations across possible worlds as well. This deeper analysis we save for future work, for now these three types of permanence seem to cover a lot of common cases.

## 6 Framework

In the previous sections axioms were presented in a historical and rhetorical order. In Table 1 we present the relevant axioms again in a different order to more clearly show the symmetries and relationships they have to each other. We have also refactored several of the axioms based on the fact that, in S5,  $\Box(P \rightarrow \Box Q)$  is equivalent to  $\diamond P \rightarrow \Box Q$ , so that they are all consistently conditioned on the possibility of the predicate being instantiated, in the style of [A5].

The table clearly shows the groupings of the axioms. The first group, which includes basic rigidity, concerns properties whose behaviors do not change with time. These versions of rigidity are useful analysis tools for ontologies that deal with snapshots of the world and do not consider time. This type of ontology is very common in practice, in fact the vast majority of semantic web ontologies do not treat time explicitly.



**Figure 1 Subsumption (black) and Disjointness (red) between MetaProperties.**

The second group consists of forms of rigidity that depend on time but not existence, and includes the line, ray, and segment-like behaviors.

The third group adds temporality to existential rigidity and actuality.

The fourth group takes the line, ray, and segment behaviors and tie them to possible worlds in which the instances actually exist.

Finally the fifth group contains existence metaproperties.

In Figure 1, we show the relationships between the metaproperties, with black arrows indicating subsumption and red indicating disjointness.

## 7 Conclusion and Future Work

We have reviewed the developments concerning the OntoClean metaproperty of Rigidity, and taken the approach that there are different kinds of rigidity that can be used to distinguish subtle semantic differences between properties in an ontology. We presented sixteen metaproperties, that capture distinctions concerning time and existence.

In several cases, we were able to characterize well-known philosophical notions such as strong actualism and continuants using these meta-properties. In future work, we would like to account for more of these philosophical notions, and use more intuitive explanations of the meta-properties to help make the framework more usable to the burgeoning ontology user community.

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Ref	Axiom	Name
[A5]	$\forall x \diamond \phi(x) \rightarrow \Box \phi(x)$	<i>basic rigidity</i>
	$\forall x \diamond \phi(x) \rightarrow \Box (E(x) \rightarrow \phi(x))$	
	$\forall x \diamond \phi(x) \rightarrow \Box (E(x) \leftarrow \phi(x))$	<i>Actuality</i>
	$\forall x \diamond \phi(x) \rightarrow \Box (E(x) \leftrightarrow \phi(x))$	<i>existential actual rigidity</i>
[A6]	$\forall xt \diamond \phi(x,t) \rightarrow \Box \forall t' \phi(x,t')$	<i>temporal rigidity</i>
[A12]	$\forall xt \diamond \phi(x,t) \rightarrow \Box \exists t_s \forall t' (t' < t_s \rightarrow \neg \phi(x,t')) \wedge (t' > t_s \rightarrow \phi(x,t'))$	<i>semi-temporal rigidity</i>
[A13]	$\forall xt \diamond \phi(x,t) \rightarrow \Box \exists t_s t_f t_s < t_f \wedge \forall t' (t' < t_s \rightarrow \neg \phi(x,t')) \wedge (t' > t_f \rightarrow \neg \phi(x,t')) \wedge (t_s < t' < t_f \rightarrow \phi(x,t'))$	<i>ephemeral rigidity</i>
	$\forall xt \diamond \phi(x,t) \rightarrow \Box \forall t' E(x,t') \rightarrow \phi(x,t')$	<i>temporally existential rigidity</i>
[A14]	$\forall xt \diamond \phi(x,t) \rightarrow \Box \forall t' E(x,t') \leftarrow \phi(x,t')$	<i>temporal actuality</i>
	$\forall xt \diamond \phi(x,t) \rightarrow \Box \forall t' E(x,t') \leftrightarrow \phi(x,t')$	
[A16]	$\forall xt \diamond \phi(x,t) \rightarrow \Box (E(x) \rightarrow \forall t' \phi(x,t'))$	<i>existential temporal rigidity</i>
[A17]	$\forall xt \diamond \phi(x,t) \rightarrow \Box (E(x) \rightarrow \exists t_s \forall t' (t' < t_s \rightarrow \neg \phi(x,t')) \wedge (t' > t_s \rightarrow \phi(x,t')))$	<i>existential semi-temporal rigidity</i>
[A18]	$\forall xt \diamond \phi(x,t) \rightarrow \Box (E(x) \rightarrow \exists t_s t_f t_s < t_f \wedge \forall t' (t' < t_s \rightarrow \neg \phi(x,t')) \wedge (t' > t_f \rightarrow \neg \phi(x,t')) \wedge (t_s < t' < t_f \rightarrow \phi(x,t')))$	<i>existential ephemeral rigidity</i>
[A19]	$\forall x \diamond \phi(x) \rightarrow \Box (E(x) \rightarrow \forall t E(x,t))$	<i>permanence</i>
[A20]	$\forall x \diamond \phi(x) \rightarrow \Box (E(x) \rightarrow \exists t_c \forall t (t < t_c \rightarrow \neg E(x,t)) \wedge (t > t_c \rightarrow E(x,t)))$	<i>semi-permanence</i>
[A21]	$\forall x \diamond \phi(x) \rightarrow \Box (E(x) \rightarrow \exists t_c t_d t_c < t_d \wedge \forall t (t < t_c \rightarrow \neg E(x,t)) \wedge (t > t_d \rightarrow \neg E(x,t)) \wedge (t_c < t < t_d \rightarrow E(x,t)))$	<i>ephemerality</i>

Table 1