COMP718: Ontologies and Knowledge Bases

Lecture 11: Temporal Ontologies

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Outline

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Which kind of temporal things?

- Actual dates, time, intervals
- Qualitative temporal relations, such as: before, after, during, while, meet (Allen temporal relations), precedes and immediately precedes (recollect OBO foundry relations)
- More advanced relations; e.g., *transformation_of*, *developed_from*, *derived_from*
- Temporalising classes (cf. 'object migration' in databases); e.g., an active project evolves to completed project
- Temporalising relations; e.g. 'during the lifetime of x, it always has y as part', 'every passenger that boards the plane must have checked in between 24h and 0.5h before the scheduled departure of that flight' [KA10]

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Examples

- Buttery is a transformation of Caterpillar, using both LTL and the phased sortals of OntoClean [Kee09]
- Brain is specific dependent part of Human body, using temporalisation of the parthood relation [AGK08]
- Bypass sometimes comes after the grafting [SSBS09] in SNOMED CT, using CTL then we have E[grafting U bypass]
  - Note shorthand CTL notations: E: exists a path; A: in all paths; F: some time in the future; G: globally in the future; X: next time; and U for p until q
- Brain concussion with loss of consciousness [SSBS09] in SNOMED CT

Reasoning services

- The usual ones (satisfiability, subsumption, etc.)
- Querying temporal knowledge bases
  - "In which year in the previous century was the great flooding disaster (watersnoodramp) in the Netherlands?"
  - "Who was the South African president before Jacob Zuma?"
- Logical implications; e.g. given $B \sqsubseteq A$, then
  - objects active in B must be active in A (e.g., if one is a student (B) then one is also a person (A));
  - objects scheduled to become active in B must exist in A (e.g., an employee (A) is up for promotion to become a manager (B))
- A range of other examples, a.o.:
  - Reasoning with a calendar hierarchy and across calendars
  - Finding a solution satisfying a set of constraints for scheduling the lecture hours of a study programme

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Many issues to investigate

- Temporal logic and modelling issues in ontology development
- Interaction temporal logic and temporal databases
- Temporal logic and verification (formal methods)
- Interaction (temporal) DLs with (temporal) conceptual data modelling
- Computational properties of various fragments of expressive temporal logics
- Linear vs. branching time and endurantism vs. perdurantism in philosophy

Principal models of time

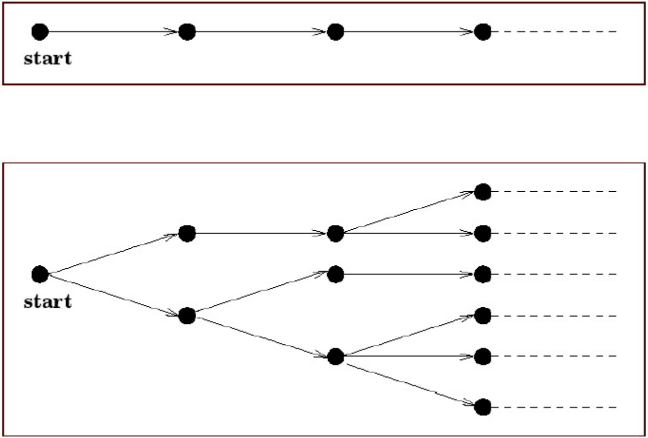

Figure: Top: linear, with corresponding LTLs; Bottom: branching time, with corresponding CTLs to formalise it.

Temporal operators in LTL

- until, ϕ **U** ψ, $\phi \mathcal{U} \psi$, ϕ holds until ψ
- since, ϕ **S** ψ, $\phi \mathcal{S} \psi$, ϕ holds since ψ
- next, **N**ϕ, $\bigcirc\phi$: ϕ has to hold at the next state
- future, **F**ϕ, $\Diamond\phi$: ϕ must hold eventually
- globally **G**ϕ: $\Box\phi$ must hold always (entire subsequent path)
- More precise, e.g.: must have held some time in the past $\Diamond^{-}\phi$, etc.

Intuition of the operators in CTL

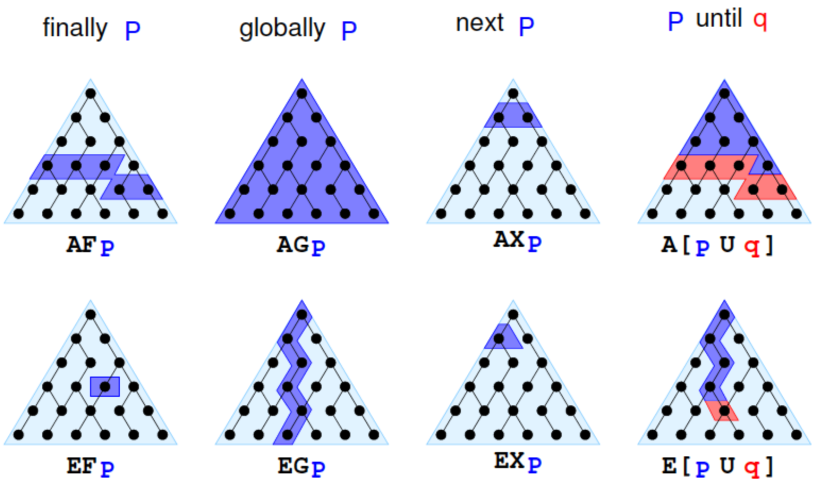

Figure by Artale

Allen temporal relations[1]

Relation	Symbol	Symbol for Inverse	Pictoral Example
X *before* Y	<	>	XXX YYY
X *equal* Y	=	=	XXX YYY
X *meets* Y	m	mi	XXXYYY
X *overlaps* Y	o	oi	XXX YYY
X *during* Y	d	di	XXX YYYYYY
X starts Y	s	si	XXX YYYYY
X finishes Y	f	fi	XXX YYYYY

FIGURE 2. The Thirteen Possible Relationships.

[1] James F. Allen. Maintaining knowledge about temporal intervals. *Communications of the ACM*, 26(11), 1983.

Outline

1. Introduction: why temporal ontologies?
   - Introduction
   - Temporal operators and relations
2. Temporal ontologies
   - Time ontology
   - $\mathcal{DLR}_{\mathcal{US}}$
3. Modelling with temporal ontologies
   - Essential and immutable parts (details in [AGK08])
   - Transforming objects (details in [Kee09])

Overview

- An ontology to describe the temporal content of Web pages and the temporal properties of Web services
- Vocabulary for expressing facts about topological relations among instants and intervals, together with information about durations, and about datetime information
- OWL encoding and a first-order logic axiomatization of the ontology
- It is an ontology to *talk* about time, but **not** to *represent and reason over* temporal knowledge, i.e., a 'workaround'

more info at http://www.w3.org/TR/owl-time/

Core: Topological Temporal Relations

- `TemporalEntity` with two subclasses `Instant` and `Interval`
- `hasBeginning` and `hasEnd` are relations between instants and temporal entities
- `inside` is a relation between an instant and an interval
- `before` relation on temporal entities, which gives directionality to time, but is not enforced in the language
- Interval relations, such as `intervalEquals`, `intervalBefore`, `intervalMeets` etc.

Core: Duration Description

- An interval can have multiple duration descriptions (e.g., 2 days, 48 hours), but can only have one duration
- Different sets of properties for `DateTimeDescription` and `DurationDescription`, because their ranges are different.
    - `year` (in `DateTimeDescription`) has a range of `xsd:gYear`, while `years` (in `DurationDescription`) has a range of`xsd:decimal` so that you can say duration of 2.5 years.
- `durationOf` that takes eight arguments, but split up into 8 binaries
- Other components: Time Zones, DateTime Description

Syntax of $\mathcal{DLR}_{\mathcal{US}}$

- $\mathcal{DLR}_{\mathcal{US}}$ [AFWZ02] combines the PTL with *Since* and *Until* and the DL $\mathcal{DLR}$ [CDG03], i.e., a expressive fragment of $L^{\{\textbf{since, until}\}}$
  - Classes, n-ary relations ($n \geq 2$), role components
  - Binary constructors ($\sqcap, \sqcup, \mathcal{U}, \mathcal{S}$) for relations of the same arity, and all boolean constructors for both class and relation expressions
- For both classes and relations: temporal operators $\Diamond^+$, $\oplus$, and their past counterparts can be defined via $\mathcal{U}$ and $\mathcal{S}$: $\Diamond^+ C \equiv \top\, \mathcal{U}\, C$, $\Diamond^- C \equiv \top\, \mathcal{S}\, C$, $\oplus\, C \equiv \bot\, \mathcal{U}\, C$, etc; $\Box^+$ and $\Box^-$ as $\Box^+ C \equiv \neg \Diamond^+ \neg C$ and $\Box^- C \equiv \neg \Diamond^- \neg C$. $\Diamond^*$ and $\Box^*$ as $\Diamond^* C \equiv C \sqcup \Diamond^+ C \sqcup \Diamond^- C$ and $\Box^* C \equiv C \sqcap \Box^+ C \sqcap \Box^- C$.

$$
\begin{array}{lll}
C & \rightarrow & \top \mid \bot \mid CN \mid \neg C \mid C_1 \sqcap C_2 \mid C_1 \sqcup C_2 \mid \exists^{\lessgtr k}[U_j]R \mid \\
 & & \Diamond^+ C \mid \Diamond^- C \mid \Box^+ C \mid \Box^- C \mid \oplus\, C \mid \ominus\, C \mid C_1\, \mathcal{U}\, C_2 \mid C_1\, \mathcal{S}\, C_2 \\
R & \rightarrow & \top_n \mid RN \mid \neg R \mid R_1 \sqcap R_2 \mid R_1 \sqcup R_2 \mid U_i/n : C \mid \\
 & & \Diamond^+ R \mid \Diamond^- R \mid \Box^+ R \mid \Box^- R \mid \oplus\, R \mid \ominus\, R \mid R_1\, \mathcal{U}\, R_2 \mid R_1\, \mathcal{S}\, R_2
\end{array}
$$

Semantics of $\mathcal{DLR_{US}}$

- Interpreted in *temporal models* over $\mathcal{T}$ (where $\mathcal{T} = \langle \mathcal{T}_p, < \rangle$), which are triples of the form $\mathcal{I} \doteq \langle \mathcal{T}, \Delta, \cdot^{\mathcal{I}(t)} \rangle$, where Δ is the *domain* of $\mathcal{I}$ and $\cdot^{\mathcal{I}(t)}$ an *interpretation function* s.t., for every $t \in \mathcal{T}$, every C, and R, we have $C^{\mathcal{I}(t)} \subseteq \Delta$ and $R^{\mathcal{I}(t)} \subseteq (\Delta)^n$.
- note: $(u, v) = \{w \in \mathcal{T} \mid u < w < v\}$.

Semantics of $\mathcal{DLR}_{\mathcal{US}}$

$$
\begin{aligned}
\top^{\mathcal{I}(t)} &= \Delta^{\mathcal{I}}; \quad \bot^{\mathcal{I}(t)} = \emptyset; \quad CN^{\mathcal{I}(t)} \subseteq \top^{\mathcal{I}(t)}; \quad (\neg C)^{\mathcal{I}(t)} = \top^{\mathcal{I}(t)} \setminus C^{\mathcal{I}(t)}; \\
(C_1 \sqcap C_2)^{\mathcal{I}(t)} &= C_1^{\mathcal{I}(t)} \cap C_2^{\mathcal{I}(t)}; \\
(C_1 \sqcup C_2)^{\mathcal{I}(t)} &= C_1^{\mathcal{I}(t)} \cup C_2^{\mathcal{I}(t)}; \\
(\exists^{\leqslant k}[U_j]R)^{\mathcal{I}(t)} &= \{\, d \in \top^{\mathcal{I}(t)} \mid \sharp\{\langle d_1, \ldots, d_n\rangle \in R^{\mathcal{I}(t)} \mid d_j = d\} \leqslant k\}; \\
(C_1 \,\mathcal{U}\, C_2)^{\mathcal{I}(t)} &= \{\, d \in \top^{\mathcal{I}(t)} \mid \exists v > t.(d \in C_2^{\mathcal{I}(v)} \wedge \forall w \in (t,v).d \in C_1^{\mathcal{I}(w)})\}; \\
(C_1 \,\mathcal{S}\, C_2)^{\mathcal{I}(t)} &= \{\, d \in \top^{\mathcal{I}(t)} \mid \exists v < t.(d \in C_2^{\mathcal{I}(v)} \wedge \forall w \in (v,t).d \in C_1^{\mathcal{I}(w)})\}; \\
(\top_n)^{\mathcal{I}(t)} &\subseteq (\Delta^{\mathcal{I}})^n; \quad RN^{\mathcal{I}(t)} \subseteq (\top_n)^{\mathcal{I}(t)}; \quad (\neg R)^{\mathcal{I}(t)} = (\top_n)^{\mathcal{I}(t)} \setminus R^{\mathcal{I}(t)}; \\
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&\qquad \forall w \in (v,t).\, \langle d_1, \ldots, d_n\rangle \in R_1^{\mathcal{I}(w)})\}; \\
(\Diamond^+ R)^{\mathcal{I}(t)} &= \{\langle d_1, \ldots, d_n\rangle \in (\top_n)^{\mathcal{I}(t)} \mid \exists v > t.\, \langle d_1, \ldots, d_n\rangle \in R^{\mathcal{I}(v)}\}; \\
(\oplus\, R)^{\mathcal{I}(t)} &= \{\langle d_1, \ldots, d_n\rangle \in (\top_n)^{\mathcal{I}(t)} \mid \langle d_1, \ldots, d_n\rangle \in R^{\mathcal{I}(t+1)}\}; \\
(\Diamond^- R)^{\mathcal{I}(t)} &= \{\langle d_1, \ldots, d_n\rangle \in (\top_n)^{\mathcal{I}(t)} \mid \exists v < t.\, \langle d_1, \ldots, d_n\rangle \in R^{\mathcal{I}(v)}\}; \\
(\ominus\, R)^{\mathcal{I}(t)} &= \{\langle d_1, \ldots, d_n\rangle \in (\top_n)^{\mathcal{I}(t)} \mid \langle d_1, \ldots, d_n\rangle \in R^{\mathcal{I}(t-1)}\}.
\end{aligned}
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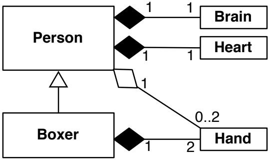
Motivation

- Need to represent difference between essential vs mandatory vs immutable parts and wholes



  - Brain is an essential part of Human
  - Heart is a mandatory part of Human but a heart can be transplanted
  - Hand is an immutable part of Boxer but a human can do without hands
- More generally: the life cycle semantics of parts and wholes

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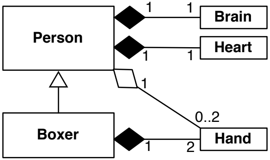

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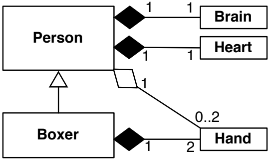

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Defining participation in the relation

- Two criteria: (i) nature of the dependence relationship between the classes and (ii) strength of the participation
  1. Generic Dependence – Mandatory Part. The whole must have a part at each instant of its lifetime. Thus, the presence of the part is mandatory, but it can be replaced over time (e.g., the human heart example).
  2. Unconditional Specific Dependence – Essential Part. The part is mandatory, but it cannot be replaced without destroying the whole (e.g., the human brain example).
  3. Conditional Specific Dependence – Immutable Part (also called *conditionally essential part*). The part is mandatory and cannot be replaced, but only as long as the whole belongs to the class that describes it (e.g., the boxer's hand example).

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$\mathcal{ER}_{VT}$: Temporal EER

- For each $\mathcal{ER}_{VT}$ conceptual data model, there is an equi-satisfiable $\mathcal{DLR}_{\mathcal{US}}$ knowledge base
- Given the set-theoretic semantics for $\mathcal{ER}_{VT}$, modelling notions such as satisfiability, subsumption, and derivation of new constraints have been defined [APS07]
- Textual and a graphical syntax along with a model-theoretic semantics as a temporal extension of the EER semantics [CLN99]
- $\mathcal{ER}_{VT}$ [AFWZ02] supports timestamping for classes, attributes, and relationships
- Status classes [APS07] constrain evolution of an instance's membership in a class along its lifespan

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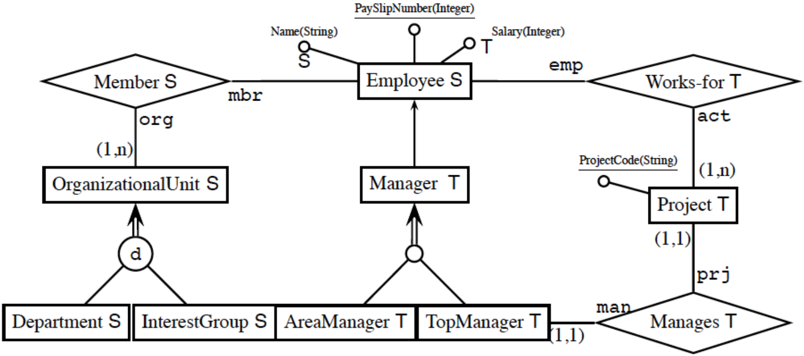
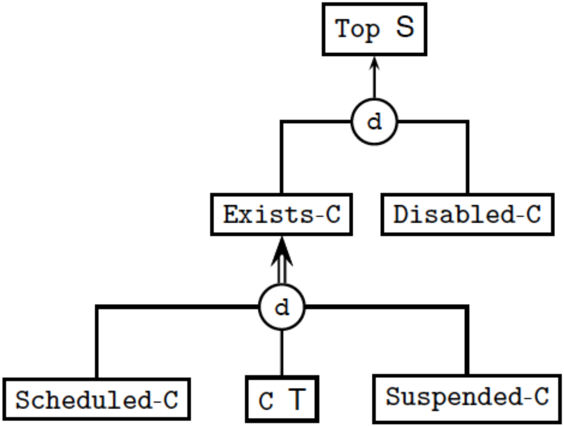
An example



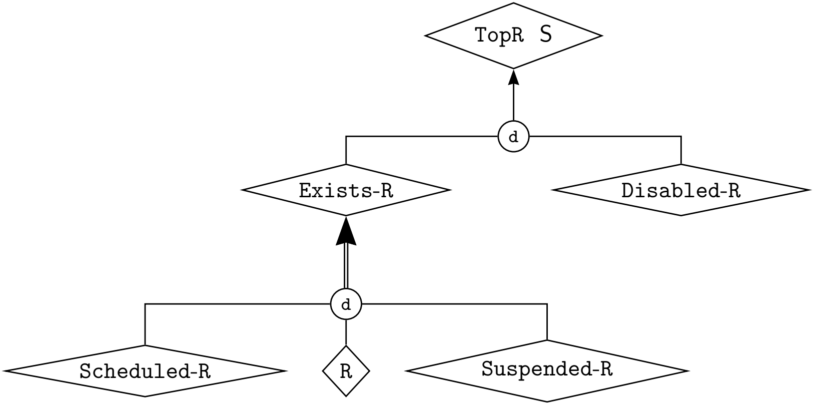
S, snapshot class: $C \sqsubseteq \Box^* C$

T: temporary class: $C \sqsubseteq \Diamond^* \neg C$

Status classes



Status relations



Status relations

- **Scheduled**: a relation is scheduled if its instantiation is known but its membership will only become effective some time later. e.g., a new pillar for the Sagrada Familia's interior is scheduled to become part of that church.
- **Active**: the status of a relation is active if the particular relation fully instantiates the type-level relation and only active classes can participate into an active relation; e.g., the Mont Blanc mountain is part of the Alps mountain range

Extending $\mathcal{ER}_{VT}$ with status relations

- **Suspended**: to capture a temporarily inactive relation; e.g., an instance of a CarEngine is removed from the instance of a Car it is part of for purpose of maintenance.
- **Disabled**: to model expired relations that never again can be used; e.g., to represent the donor of an organ who has donated that organ and one wants to keep track of who donated what to whom.

Essential and immutable parts (details in [AGK08])

(Act) *Active relations involve only active classes.*
$\langle o_1, o_2 \rangle \in \mathtt{R}^{\mathcal{I}(t)} \rightarrow o_1 \in C_1^{\mathcal{I}(t)} \wedge o_2 \in C_2^{\mathcal{I}(t)}$
$\mathtt{R} \sqsubseteq \mathtt{U}_1 : \mathtt{C}_1 \sqcap \mathtt{U}_2 : \mathtt{C}_2$

(RExists) *Existence persists until Disabled.*
$\langle o_1, o_2 \rangle \in \mathtt{Exists\text{-}R}^{\mathcal{I}(t)} \rightarrow \forall t' > t.(\langle o_1, o_2 \rangle \in \mathtt{Exists\text{-}R}^{\mathcal{I}(t')} \vee \langle o_1, o_2 \rangle \in \mathtt{Disabled\text{-}R}^{\mathcal{I}(t')})$
$\mathtt{Exists\text{-}R} \sqsubseteq \Box^{+}(\mathtt{Exists\text{-}R} \sqcup \mathtt{Disabled\text{-}R})$

(RDisab1) *Disabled persists.*
$\langle o_1, o_2 \rangle \in \mathtt{Disabled\text{-}R}^{\mathcal{I}(t)} \rightarrow \forall t' > t.\langle o_1, o_2 \rangle \in \mathtt{Disabled\text{-}R}^{\mathcal{I}(t')}$
$\mathtt{Disabled\text{-}R} \sqsubseteq \Box^{+}\mathtt{Disabled\text{-}R}$

(RDisab2) *Disabled was Active in the past.*
$\langle o_1, o_2 \rangle \in \mathtt{Disabled\text{-}R}^{\mathcal{I}(t)} \rightarrow \exists t' < t.\langle o_1, o_2 \rangle \in \mathtt{R}^{\mathcal{I}(t')}$
$\mathtt{Disabled\text{-}R} \sqsubseteq \Diamond^{-}\mathtt{R}$

(RSusp1) *Suspended was Active in the past.*
$\langle o_1, o_2 \rangle \in \mathtt{Suspended\text{-}R}^{\mathcal{I}(t)} \rightarrow \exists t' < t.\langle o_1, o_2 \rangle \in \mathtt{R}^{\mathcal{I}(t')}$
$\mathtt{Suspended\text{-}R} \sqsubseteq \Diamond^{-}\mathtt{R}$

Essential and immutable parts (details in [AGK08])

(RSusp2) *Suspended involve Active or Suspended Classes.*
$\langle o_1, o_2 \rangle \in \mathtt{Suspended\text{-}R}^{\mathcal{I}(t)} \to o_i \in \mathtt{C_i}^{\mathcal{I}(t)} \vee o_i \in \mathtt{Suspended\text{-}C_i}^{\mathcal{I}(t)},\ i = 1, 2$
$\mathtt{Suspended\text{-}R} \sqsubseteq \mathtt{U_i} : (\mathtt{C_i} \sqcup \mathtt{Suspended\text{-}C_i}),\ i = 1, 2$

(RSch1) *Scheduled will eventually become Active.*
$\langle o_1, o_2 \rangle \in \mathtt{Scheduled\text{-}R}^{\mathcal{I}(t)} \to \exists t' > t. \langle o_1, o_2 \rangle \in \mathtt{R}^{\mathcal{I}(t')}$
$\mathtt{Scheduled\text{-}R} \sqsubseteq \Diamond^{+} \mathtt{R}$

(RSch2) *Scheduled can never follow Active.*
$\langle o_1, o_2 \rangle \in \mathtt{R}^{\mathcal{I}(t)} \to \forall t' > t. \langle o_1, o_2 \rangle \notin \mathtt{Scheduled\text{-}R}^{\mathcal{I}(t')}$
$\mathtt{R} \sqsubseteq \Box^{+} \neg \mathtt{Scheduled\text{-}R}$

Constraints and logical implications

Proposition (Status Relations: Logical Implications)

Given the set of axioms Σ_{st} (REXISTS-RSCH2), an n-ary relation (where $n \geq 2$) $R \sqsubseteq U_1 : C_1 \sqcap \ldots \sqcap U_n : C_n$, the following logical implications hold:

(RACT) *Active will possible evolve into Suspended or Disabled.*
$\Sigma_{st} \models \mathtt{R} \sqsubseteq \Box^{+}(\mathtt{R} \sqcup \mathtt{Suspended\text{-}R} \sqcup \mathtt{Disabled\text{-}R})$

(RDISAB3) *Disabled will never become active anymore.*
$\Sigma_{st} \models \mathtt{Disabled\text{-}R} \sqsubseteq \Box^{+}\neg\mathtt{R}$

(RDISAB4) *Disabled classes can participate only in disabled relations.*
$\Sigma_{st} \models \mathtt{Disabled\text{-}C_i} \sqcap \Diamond^{-}\exists[\mathtt{U_i}]\mathtt{R} \sqsubseteq \exists[\mathtt{U_i}]\mathtt{Disabled\text{-}R}$

Constraints and logical implications

Proposition (Status Relations: Logical Implications–*cont'd*)

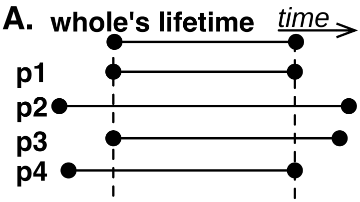
(RDisab5) *Disabled relations involve active, suspended, or disabled classes.*
$\texttt{Disabled-R} \sqsubseteq \texttt{U}_i\!:\!(\texttt{C}_i \sqcup \texttt{Suspended-C}_i \sqcup \texttt{Disabled-C}_i)$, *for all* $i = 1, \ldots, n$.

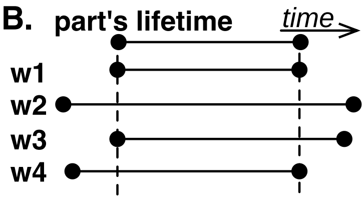
(RSch3) *Scheduled persists until active.*
$\Sigma_{st} \models \texttt{Scheduled-R} \sqsubseteq \texttt{Scheduled-R}\, \mathcal{U}\, \texttt{R}$

(RSch4) *Scheduled cannot evolve directly to Disabled.*
$\Sigma_{st} \models \texttt{Scheduled-R} \sqsubseteq \oplus \neg\texttt{Disabled-R}$

(RSch5) *Scheduled relations do not involve disabled classes.*
$\texttt{Scheduled-R} \sqsubseteq \texttt{U}_\texttt{i} : \neg\texttt{Disabled-C}_\texttt{i}$, *for all* $i = 1, \ldots, n$.

Life cycles


A. whole's lifetime
time
p1
p2
p3
p4


B. part's lifetime
time
w1
w2
w3
w4

Mandatory & Exclusive

(ManP)	$\texttt{W} \sqsubseteq \exists[\texttt{whole}]\texttt{PartWhole}$	*Mandatory Part*
(ManW)	$\texttt{P} \sqsubseteq \exists[\texttt{part}]\texttt{PartWhole}$	*Mandatory Whole*
(ExlP)	$\texttt{P} \sqsubseteq \exists^{\leq 1}[\texttt{part}]\texttt{PartWhole}$	*Exclusive Part*
(ExlW)	$\texttt{W} \sqsubseteq \exists^{\leq 1}[\texttt{whole}]\texttt{PartWhole}$	*Exclusive Whole*

Rigidity

Definition (Rigid (+R))

A *rigid* property ϕ is a property that is essential to *all* its instances, i.e., $\forall x \phi(x) \rightarrow \Box \phi(x)$

Definition (Anti-Rigid (∼R))

An *anti-rigid* property ϕ is a property that is not essential to *all* its instances, i.e., $\forall x \phi(x) \rightarrow \neg \Box \phi(x)$

$$
\begin{array}{ll}
(\textsc{Rigid}) & \mathtt{C} \sqsubseteq \Box^* \mathtt{C} \\
(\textsc{A-Rigid}) & \mathtt{C} \sqsubseteq \Diamond^* \neg \mathtt{C} \\
(\textsc{A-sub-R}) & \mathtt{C_A} \sqsubseteq \mathtt{C_R}
\end{array}
$$

Essential parts and wholes

- *Essential parts* are global properties of rigid wholes that can be formalized in $\mathcal{DLR}_{\mathcal{US}}$ with:

$(\textsc{RigidW})$	$\texttt{W} \sqsubseteq \Box^* \texttt{W}$	*Rigid Whole*
$(\textsc{EssP})$	$\texttt{W} \sqsubseteq \exists[\texttt{whole}]\Box^* \texttt{PartWhole}$	*Essential Part*

- Likewise for *essential whole*

$(\textsc{RigidP})$	$\texttt{P} \sqsubseteq \Box^* \texttt{P}$	*Rigid Part*
$(\textsc{EssW})$	$\texttt{P} \sqsubseteq \exists[\texttt{part}]\Box^* \texttt{PartWhole}$	*Essential Whole*

Additional axioms for Immutable

(SusW) $\texttt{Suspended-PartWhole} \sqsubseteq \texttt{whole} : \texttt{Suspended-W}$
Suspended Whole

(SusP) $\texttt{Suspended-PartWhole} \sqsubseteq \texttt{part} : \texttt{Suspended-P}$
Suspended Part

(DisP) $\texttt{Disabled-PartWhole} \sqsubseteq \texttt{part} : \texttt{Disabled-P}$
Disabled Part

(DisW) $\texttt{Disabled-PartWhole} \sqsubseteq \texttt{whole} : \texttt{Disabled-W}$
Disabled Whole

(SchPW) $\texttt{PartWhole} \sqsubseteq \Diamond^{-}\texttt{Scheduled-PartWhole}$
Scheduled Part-Whole

(SchP) $\texttt{Scheduled-PartWhole} \sqsubseteq \texttt{part} : \texttt{Scheduled-P}$
Scheduled Part

(SchW) $\texttt{Scheduled-PartWhole} \sqsubseteq \texttt{whole} : \texttt{Scheduled-W}$
Scheduled Whole

Immutable part

Theorem (Immutable Parts)

Let $\mathtt{W_R}$ be a rigid class (i.e., $\mathtt{W_R} \sqsubseteq \Box^*\mathtt{W_R}$), $\mathtt{W}$ be an anti-rigid class (i.e., $\mathtt{W} \sqsubseteq \Diamond^*\neg\mathtt{W}$) s.t. $\mathtt{W} \sqsubseteq \mathtt{W_R}$, and $\mathtt{PartWhole} \sqsubseteq \mathtt{part} : \mathtt{P} \sqcap \mathtt{whole} : \mathtt{W}$ be a generic part-whole relation satisfying Σ_{st}. Then, for each whole, o_w, of type $\mathtt{W}$ there exists an immutable part, o_p, of type $\mathtt{P}$ that is temporally related to o_w with the relation:

- $\mathtt{p2}$ *holds if* (ManP), (SusW), (DisW) *hold.*
- $\mathtt{p4}$ *holds if* (ManP), (SusW), (DisW), (DisP) *hold.*
- $\mathtt{p3}$ *holds if* (ManP), (SusW), (DisW), (SchPW), (SchP) *hold.*
- $\mathtt{p1}$ *holds if* (ManP), (SusW), (DisW), (DisP), (SchPW), (SchP) *hold.*

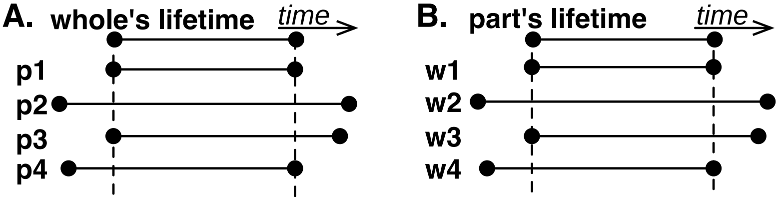
Immutable whole

Theorem (Immutable Wholes)

Let $\mathrm{P_R}$ *be a rigid class (i.e.,* $\mathrm{P_R} \sqsubseteq \Box^* \mathrm{P_R}$*),* $\mathtt{P}$ *be an anti-rigid class (i.e.,* $\mathrm{P} \sqsubseteq \Diamond^* \neg \mathrm{P}$*) s.t.* $\mathrm{P} \sqsubseteq \mathrm{P_R}$*, and* $\mathtt{PartWhole} \sqsubseteq \mathtt{part} : \mathtt{P} \sqcap \mathtt{whole} : \mathtt{W}$ *be a generic part-whole relation satisfying* Σ_{st}*. Then, for each part,* o_p*, of type* $\mathtt{P}$ *there exists an immutable whole,* o_w*, of type* $\mathtt{W}$ *that is temporally related to* o_p *with the relation:*

- `w2` *holds if* (ManW), (SusP), (DisP) *hold.*
- `w4` *holds if* (ManW), (SusP), (DisP), (DisW) *hold.*
- `w3` *holds if* (ManW), (SusP), (DisP), (SchPW), (SchW) *hold.*
- `w1` *holds if* (ManW), (SusP), (DisP), (DisW), (SchPW), (SchW) *hold.*

Life cycles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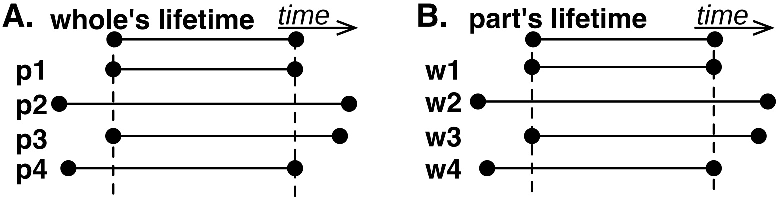
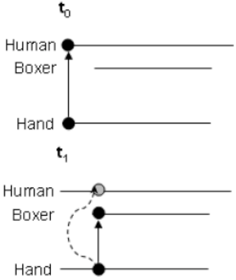


p4 holds if (ManP), (SusW), (DisW), (DisP) hold.

Essential and immutable parts (details in [AGK08])

The Boxer's hand (with p4)



(1)	$\mathtt{Human} \sqsubseteq \Box^* \mathtt{Human}$	(RIGID)
(2)	$\mathtt{HumanHandPW} \sqsubseteq \mathtt{PartWhole}$	
(3)	$\mathtt{HumanHandPW} \sqsubseteq \mathtt{part} : \mathtt{Hand} \sqcap \mathtt{whole} : \mathtt{Human}$	
(4)	$\mathtt{Boxer} \sqsubseteq \Diamond^* \neg \mathtt{Boxer}$	(A-RIGID)
(5)	$\mathtt{Boxer} \sqsubseteq \mathtt{Human}$	(A-SUB-R)
(6)	$\mathtt{Boxer} \sqsubseteq \exists^{=2}[\mathtt{whole}]\mathtt{HumanHandPW}$	(MANP)
(7)	$\mathtt{Suspended\text{-}HumanHandPW} \sqsubseteq \mathtt{whole} : \mathtt{Suspended\text{-}Boxer}$	(SUSW)
(8)	$\mathtt{Disabled\text{-}HumanHandPW} \sqsubseteq \mathtt{part} : \mathtt{Disabled\text{-}Hand}$	(DISP)
(9)	$\mathtt{Disabled\text{-}HumanHandPW} \sqsubseteq \mathtt{whole} : \mathtt{Disabled\text{-}Boxer}$	(DISW)
(10)	$\Sigma_{st} \models \mathtt{R} \sqsubseteq \Box^+(\mathtt{R} \sqcup \mathtt{Suspended\text{-}R} \sqcup \mathtt{Disabled\text{-}R})$	(RACT)
(11)	$\Sigma_{st} \models \mathtt{Disabled\text{-}C_i} \sqcap \Diamond^- \exists[\mathtt{U_i}]\mathtt{R} \sqsubseteq \exists[\mathtt{U_i}]\mathtt{Disabled\text{-}R}$	(RDISAB4)

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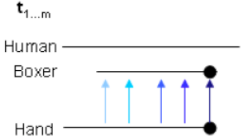

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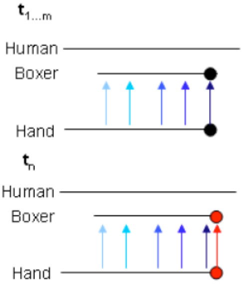

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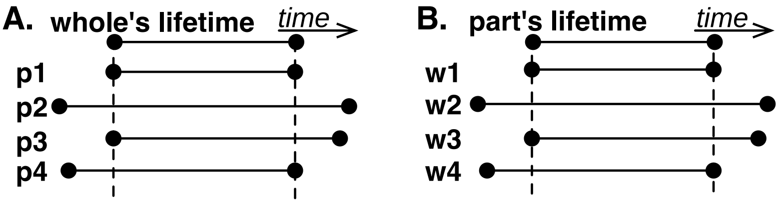

p2 holds if (MANP), (SUSW), (DISW) hold.

Conclusions and current work

- Solution to the modeling problem of representing mandatory, immutable, and essential parts and wholes
- $\mathcal{ER}_{VT}$ augmented with *status relations* and its formalization into the temporal DL $\mathcal{DLR}_{\mathcal{US}}$

- Suspension
- TDL-Lite [AKL+07] (re temporal: with only $\mathcal{U}$ and $\oplus$; other variations recently investigated)
- Interaction with types of part-whole relations [KA08]
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Motivation

- Preliminary categorizations and vocabularies of biological entities, focus on endurants
- With the maturing of (bio-)ontologies, scope is broadening to temporal aspects
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Motivation

- Example definition for *transformation_of* relation in the Relation Ontology [SCK+05]:
  "*C transformation_of C_1 = [definition] C and C_1 for all c, t, if Cct, then there is some t_1 such that C_1ct_1, and t_1 earlier t, and there is no t_2 such that Cct_2 and C_1ct_2.*"
- Two issues:
  - ignorant of the distinction between unidirectional transformations vs. where some instance of C_1 may, after transforming into C, transform back into C_1
  - does not say how the entities undergoing transformation are able to change and yet keep their identity;
- This under-specification can lead to unintended models of the theory

Preliminary definition

- Let a instantiate C_s and C_t at the two different times, with *s*ource and *t*arget the source is transformed into
- 'enough' properties are shared by $a \in C_s$ and $a \in C_t$ for identification as the same individual ($a_s =_i a_t$)
- other properties $\pi_1 \dots \pi_n$ of a are lost or gained so that a instantiates a different universal after transformation

Definition (C_t transformation_of C_s)

Let C_t be the target and C_s the source universal, x, y range over instances and $t_0, \dots, t_n$ range over points in time, then $C_t(x)$ *transformation_of* $C_s(y)$ iff for all x, there exist y, $t_0, \dots t_n$, if $C_t(x, t_0)$, then there is some t_1 such that $C_s(y, t_1)$, $t_1 < t_0$, C_s and C_t have the same identity criterion ($C_s =_i C_t$), x and y differ in at least one other property π_i, and there does not exist a t_2 such that $C_t(x, t_2)$ and $C_s(y, t_2)$.

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OntoClean

- Uses the metaproperties of properties (unary predicates) to categorise types of entities [GW00a, GW00b]
- Rigidity, Identity, Unity, Dependence
- For instance, being a *Patient* and being a *Caterpillar* are $\sim$R and being a *Person* and being a *Herbivore* are $+$R that may subsume *Patient* and *Caterpillar*

Definition (+R)

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- *diachronic* identity (cf. synchronic identity)
- identity criteria (IC), which are both necessary and sufficient for identity
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A property that is not rigid *carries* an IC Γ iff it is subsumed by a rigid property carrying Γ.

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Properties and their metaproperties

<table>
<tr><td rowspan="2">+O</td><td rowspan="2">+I</td><td rowspan="2">+R</td><td>+D</td><td rowspan="2">Type</td><td rowspan="8">Sortal</td></tr>
<tr><td>-D</td></tr>
<tr><td rowspan="2">-O</td><td rowspan="2">+I</td><td rowspan="2">+R</td><td>+D</td><td rowspan="2">Quasi-Type</td></tr>
<tr><td>-D</td></tr>
<tr><td>-O</td><td>+I</td><td>~R</td><td>+D</td><td>Material role</td></tr>
<tr><td>-O</td><td>+I</td><td>~R</td><td>-D</td><td>Phased sortal</td></tr>
<tr><td rowspan="2">-O</td><td rowspan="2">+I</td><td rowspan="2">¬R</td><td>+D</td><td rowspan="2">Mixin</td></tr>
<tr><td>-D</td></tr>
<tr><td rowspan="2">-O</td><td rowspan="2">-I</td><td rowspan="2">+R</td><td>+D</td><td rowspan="2">Category</td><td rowspan="6">Non-Sortal</td></tr>
<tr><td>-D</td></tr>
<tr><td>-O</td><td>-I</td><td>~R</td><td>+D</td><td>Formal role</td></tr>
<tr><td rowspan="3">-O</td><td rowspan="3">-I</td><td>~R</td><td>-D</td><td rowspan="3">Attribution</td></tr>
<tr><td rowspan="2">¬R</td><td>+D</td></tr>
<tr><td>-D</td></tr>
</table>

Characterising the transforming entities

(CT1) A phased sortal does *not* supply an IC, i.e., -O

(CT2) A phased sortal *must* be subsumed by C_p that has +O

(CT3) A phased sortal carries an IC, i.e., +I

(CT4) A phased sortal is a sortal

(CT5) A phased sortal is anti-rigid, i.e., ~R

if C_t and C_s of the transformation_of relation are both categorised as phased sortals, then:

(CT6) C_t and C_s both must be subsumed by C_p

Characterising the transforming entities

(CT7) C_p must be a type (+O+I+R)

(CT8) Each type that subsumes phased sortals, which are related through the *transformation_of* relation, must subsume *at least two* phased sortals

if C_t transformation_of C_s and C_t and C_s are categorised as states, then the following constraints must hold:

(CT9) C_t and C_s must carry identity (+I)

(CT10) If C_t is a transformation of C_s, then it is possible, but not necessary, that at a later point in time C_t transforms back into C_s

(CT11) C_t and C_s have meta-properties that are either ∼R or +R

Characterising the transforming entities

(CT12) If C_t and C_s are categorised as states, they are neither both types nor both roles

(CT13) If C_t is a transformation of C_s, C_t and C_s are phased sortals, then it is *not* possible that at a later point in time C_t is a transformation of C_s, i.e., C_t does not transform back

Thus, based on foundational notions of Ontology, CT1-CT13 offers a more precise catergorisation for the relata of the *transformation_of*, as well as their position in a taxonomy.

Temporal conceptual data modelling

- [APS07] have formalised the well-known core elements of temporal databases in $\mathcal{DLR}_{\mathcal{US}}$ with corresponding $\mathcal{ER}_{VT}$ that extends EER
- Does not take into account the kind of classes like phased sortal, but has *evolution constraints* and status classes
- *Status* is associated to a class to log the evolving status of membership of each object in the class and the relation between the statuses
  - E.g., when at t_0 object $o \in$ *Caterpillar* (and $o \in$ *Scheduled-Butterfly*) starts transforming into an instance of *Butterfly*, then we have at the next time transformation at t_1 (with $t_0 < t_1$) that $o \in$ *Disabled-Caterpillar* and $o \in$ *Butterfly*

Temporal conceptual data modelling

- [APS07] have formalised the well-known core elements of temporal databases in $\mathcal{DLR}_{\mathcal{US}}$ with corresponding $\mathcal{ER}_{VT}$ that extends EER
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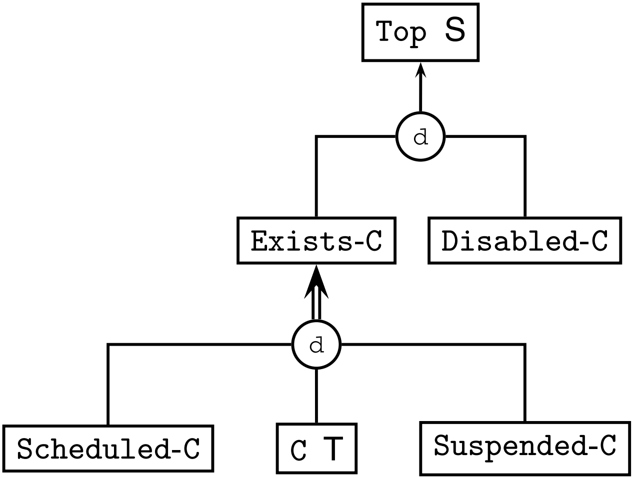
Status classes



Status property S

Definition (+S)

A property ϕ has status *active* at time t iff $\phi(x)$ holds at time t.

Definition (-S)

If a property ϕ has status *scheduled* at time t then $\phi(x)$ holds at some time t_0, for $t_0 > t$.

Definition ($\sim$S)

If a property ϕ has status *suspended* at time t then $\phi(x)$ holds at some time t_0, with $t_0 < t$.

Definition ($\neg$S)

A property ϕ has status *disabled* at time t iff ϕ holds at some time t_0, with $t_0 < t$, and for all t', such that $t' \geq t$, $\phi(x)$ does not hold.

Status property S

When the instance *cannot* transform back:

(CT14) C_s has $+$S at the time of transformation and $\neg$S after transformation

(CT15) C_t has -S at the time of transformation and $+$S after transformation

If the entity *can* transform back, then CT14 and CT15 have to be replaced with:

(CT14′) C_s has $+$S at the time of transformation and either $\neg$S or $\sim$S after transformation

(CT15′) C_t has either -S or $\sim$S at the time of transformation and $+$S after transformation

Status property S: position of classes in the taxonomy—transformation back possible

$$\phi^+ \rightarrow \psi^+ \quad (1)$$
$$\phi^\sim \rightarrow \psi^\sim \vee \psi^+ \quad (2)$$
$$\phi^\neg \rightarrow \psi^\neg \vee \psi^\sim \vee \psi^+ \quad (3)$$
$$\phi^- \rightarrow \neg\psi^\neg \quad (4)$$
$$\psi^\neg \wedge \diamond\phi^+ \rightarrow \phi^\neg \quad (5)$$

.

Status property S: position of classes in the taxonomy—no transformation back

$\phi^+ \rightarrow \psi^+$ (1)	$\phi^- \rightarrow \neg\psi^\neg$ (4)
–	$\psi^\neg \wedge \diamond\phi^+ \rightarrow \phi^\neg$ (5)
–	$\phi^\neg \rightarrow \psi^\neg \vee \psi^+$ (6)

- (1) & (4), CT6, CT14 & CT15 imply C_p^+, because always one of the phased sortals subsumed by C_p is active.
- Permitting suspension, $\sim$S, then C_p^+ is also implied, because of (1), (2), (4), CT14′ & CT15′

Status property S: position of classes in the taxonomy—no transformation back

$\phi^{+} \rightarrow \psi^{+}$	(1)	$\phi^{-} \rightarrow \neg\psi^{\neg}$	(4)
	–	$\psi^{\neg} \wedge \diamond\phi^{+} \rightarrow \phi^{\neg}$	(5)
	–	$\phi^{\neg} \rightarrow \psi^{\neg} \vee \psi^{+}$	(6)

- (1) & (4), CT6, CT14 & CT15 imply C_p^{+}, because always one of the phased sortals subsumed by C_p is active.
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Reassessment of modelling choices

- Transformations like caterpillar and butterfly (phased sortals)
- Monocyte/macrophage transformation
  - Option 1: as phased sortals (known proposal); with CT14, CT15, but violating CT6, CT7, and CT8 (no suitable C_p)
  - Option 2: as states (like in Physiome); CT1, CT3, CT5, CT9, CT10, CT11, CT12, CT14 & CT15
  - Option 3: somewhere in the taxonomy (FMA); cannot guarantee diachronic identity
- Transforming healthy and pathological entities
  - "Canonical" anatomy assumes healthy: C_p?
  - Non-curable diseases: CT9-CT12, CT14, CT15
  - Curable diseases: CT9-CT12, CT14′, CT15′

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Recurring combinations

i. Phased sortals, unidirectional transformation: CT1-CT8, CT13, CT14, CT15;
ii. States (including quasi-types), unidirectional transformation: CT1-CT9, CT11-CT15;
iii. States (including quasi-types), transformation back is possible: CT1-CT13, CT14′, CT15′;
iv. Pathological transformations, terminal disease: see constraints point ii, permit status change from -S directly into ¬S;
v. Pathological transformations, reversal possible: see constraints point iii, permit status change from -S directly into ¬S.

Conclusions and future directions

- Represent changing entities more precisely
- Kind of the participating entities and proposed, based on core ideas of the OntoClean approach
- Status property, generalised from temporal conceptual data modeling
- 17 constraints for transforming entities and its relation
- Assessment on applicability to bio-ontologies

- Implications of the interactions between OntoClean's property kinds, the status property, and temporal constraints in $\mathcal{DLR}_{\mathcal{US}}$ or the simpler TDL-Lite

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Summary

1. Introduction: why temporal ontologies?
   - Introduction
   - Temporal operators and relations
2. Temporal ontologies
   - Time ontology
   - $\mathcal{DLR}_{\mathcal{US}}$
3. Modelling with temporal ontologies
   - Essential and immutable parts (details in [AGK08])
   - Transforming objects (details in [Kee09])

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