

Megamodel-driven Traceability Recovery of Correspondence & Conformance Links

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vorgelegt von

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Zusammenfassung

TBD.

Abstract

TBD.

Acknowledgements

TBD.

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Chapter 1

Introduction

TBD.

Chapter 2

Related Work

TBD.

Chapter 3

Background

This chapter summarizes the necessary background topics of the thesis. Each topic is introduced as independent as possible, interrelation is done during synthesis of hypotheses for this thesis in chapter 4. However, some of the following sections are sorted in a way that one may be based on its predecessor. In particular sections on the necessary mathematical background share definitions. Introducing them repeatedly would be redundant.

3.1 Predicate Logic

3.2 Relations

This section introduces the necessary aspects of mathematical relations for this thesis. The concept of relations is a generalization of semantic dependencies between two or more mathematical objects. This section is based on [12].

Relations are based on set-theory. We also introduce the necessary constructs of set-theory in order to clarify terminology and notation. A set is a collection of well distinguishable mathematical objects. Objects in a set are called elements of the set. A set does not contain two or more identical elements. The notation $x \in X$ denotes that x is an element of the set X . The symbol \emptyset denotes the *empty set*, which contains no elements. The symbol Ω denotes the universal set, which contains all elements.

Definition 1 (Inclusion) Let X and Y be a sets. Y includes X if and only if:

$$X \subset Y :\Leftrightarrow \forall x[x \in X \rightarrow x \in Y] \Leftrightarrow \forall x[x \notin X \vee x \in Y] \quad (3.1)$$

Then X is called subset of Y and Y is called superset of X . For an arbitrary set $Z \neq \emptyset$, the statement $\emptyset \subset Z$ is always true, respectively $Z \subset \emptyset$ is always false.

We also define the opposite property: Y does not include X if and only if:

$$X \not\subset Y :\Leftrightarrow \exists x[x \in X \wedge x \notin Y] \quad (3.2)$$

Definition 2 (Union) Let X and Y be a sets.

$$X \cup Y := \{x|x \in X \vee x \in Y\} \quad (3.3)$$

$X \cup Y$ is called union of X and Y .

Definition 3 (Intersection) Let X and Y be a sets.

$$X \cap Y := \{x|x \in X \wedge x \in Y\} \quad (3.4)$$

$X \cap Y$ is called intersection of X and Y .

Definition 4 (Power-Set) Let X be a set, then the power-set of X is defined as:

$$\mathcal{P}(X) := \{Y|Y \subset X\} \quad (3.5)$$

The definition of inclusion provides an order for power-sets. So we may compare two sets A and B in the sense of *smaller* and *larger*, i.e.:

$$A \text{ is smaller than } B \Leftrightarrow A \subset B \quad (3.6)$$

$$A \text{ is larger than } B \Leftrightarrow B \subset A \quad (3.7)$$

$$A \text{ is the smallest subset of } B \Leftrightarrow \forall C \in \mathcal{P}(B) : A \subset C \quad (3.8)$$

$$A \text{ is the largest subset of } B \Leftrightarrow \forall C \in \mathcal{P}(B) : C \subset A \quad (3.9)$$

Definition 5 (Upper & Lower Bound) Let Ω be a universe, $X \in \mathcal{P}(\Omega)$ be a set in the universe and $A \subset \mathcal{P}(\Omega)$, $A \neq \emptyset$, non-empty subsets in the universe.

$$X \text{ is an upper bound for } A :\Leftrightarrow \forall Y \in A : Y \subset X \quad (3.10)$$

$$X \text{ is a lower bound for } A :\Leftrightarrow \forall Y \in A : X \subset Y \quad (3.11)$$

We also define:

$$\mathbf{U}_A := \{U \in \mathcal{P}(\Omega) | \forall Y \in A : Y \subset U\} \quad (3.12)$$

$$\mathbf{L}_A := \{L \in \mathcal{P}(\Omega) | \forall Y \in A : L \subset Y\} \quad (3.13)$$

as sets of all upper/lower bounds for A .

Because our definition of upper and lower bounds is based on power-sets, existence is guaranteed: Given an arbitrary set S , the S and \emptyset are always elements of $\mathcal{P}(S)$. For each element Y of a non-empty selection $A \subset \mathcal{P}(S)$ of the power-set, $Y \subset S$ and $\emptyset \subset Y$ holds. So S is an upper and \emptyset is a lower bound for A .

Definition 6 (Supremum & Infimum) Let Ω be a universe, $X \in \mathcal{P}(\Omega)$ be sets in the universe and $A \subset \mathcal{P}(\Omega)$, $A \neq \emptyset$ a non-empty selection of sets in the universe. If

$$X = \sup A := \bigcup_{Y \in A} Y :\Leftrightarrow X \in \mathbf{U}_A \wedge \forall U \in \mathbf{U}_A : X \subset U \quad (3.14)$$

$$X = \inf A := \bigcap_{Y \in A} Y :\Leftrightarrow X \in \mathbf{L}_A \wedge \forall L \in \mathbf{L}_A : L \subset X \quad (3.15)$$

then X is called supremum/infimum for A .

Existence for supremum and infimum is guaranteed, because upper and lower bounds exist as shown above. Thus, for any non-empty selection $A \subset \mathcal{P}(S)$ of a power-set, \mathbf{U}_A and \mathbf{L}_A are not empty. So we need to proof, that $X = \bigcup_{Y \in A} Y$ respectively $X = \bigcap_{Y \in A} Y$ are in fact the smallest upper and the largest lower bound. Or in other words: Does another bound $X' \in \mathbf{U}_A$ respectively $X' \in \mathbf{L}_A$ exist with $X' \neq X$ and $X' \subset X$ respectively $X \subset X'$?

1. Supremum: We assume $X' \in \mathbf{U}_A$ with $X' \neq X$ and $X' \subset X$ for $X = \bigcup_{Y \in A} Y$ exists, then an element $x \in X$ exists, which is not element of X' . Because X

is the union of all sets in selection A , x must be element of at least one of its sets. However, then X' cannot include sets containing x . Thus, X' cannot be an upper bound for A and $X = \sup A$.

2. Infimum: We assume $X' \in \mathbf{L}_A$ with $X' \neq X$ and $X \subset X'$ for $X = \bigcap_{Y \in A} Y$ exists, then an element $x \in X'$ exists, which is not element of X . Because X is the intersection of all sets in selection A , x cannot be element of at least one of its sets. However, then X' must include sets containing x . Thus, X' cannot be a lower bound for A and $X = \inf A$.

Supremum and Infimum are unique for any non-empty selection of sets in a universe and can be obtained by its union respectively its intersection. [12]

Definition 7 (Cartesian Product) Let U be a universe and $X_n \in \mathcal{P}(U)$ sets with $i = 1 \dots n, n \in \mathbb{N}$, then:

$$X_1 \times \dots \times X_n := \{(x_1, \dots, x_n)\} \quad (3.16)$$

is called Cartesian product.

Definition 8 (Relation) A relation is a subset of a Cartesian product:

$$R \subset X_1 \times \dots \times X_n \quad (3.17)$$

The relation of only two sets is called binary relation. Instead of writing $(x, y) \in R$ we may also use the shorter notation xRy .

An arbitrary relation $R \subset A \times B$ is called *homogeneous* if $A = B$, otherwise it is called *heterogeneous*. However, an arbitrary relation $R \subset A \times B$ is also homogeneous in the sense of $R \subset A \times B \subset (A \cup B) \times (A \cup B)$. For the remainder of this section we focus on homogeneous relations unless noted otherwise.

In order to clarify our notation, when we are specifically working with relations instead of ordinary sets, we use the symbols \sqsubset for inclusion, $\not\sqsubset$ for non-inclusion, \sqcup for union and \sqcap for intersection, i.e.:

$$R \sqsubset S :\Leftrightarrow \forall x, y [(x, y) \in R \rightarrow (x, y) \in S] \quad (3.18)$$

$$R \not\sqsubset S :\Leftrightarrow \exists x, y [(x, y) \in R \wedge (x, y) \notin S] \quad (3.19)$$

$$R \sqcup S := \{(x, y) | (x, y) \in R \vee (x, y) \in S\} \quad (3.20)$$

$$R \sqcap S := \{(x, y) | (x, y) \in R \wedge (x, y) \in S\} \quad (3.21)$$

Furthermore, we use $\mathcal{R}(A)$ to denote the set of all homogeneous relations in set A and the symbols \mathcal{O} and \mathcal{A} to denote the empty relation and the universal relation:

$$\mathcal{R}(A) := \{R | R \subset A \times A\} \quad (3.22)$$

$$(\mathcal{O} := \emptyset) \subset A \times A \quad \Leftrightarrow \forall R \in \mathcal{R}(A) [\mathcal{O} \sqsubset R] \quad (3.23)$$

$$(\mathcal{A} := A \times A) \subset A \times A \quad \Leftrightarrow \forall R \in \mathcal{R}(A) [R \sqsubset \mathcal{A}] \quad (3.24)$$

Definition 9 (Composition of Binary Relations) Let $R, S \in \mathcal{R}(A)$. Then $R \circ S \in \mathcal{R}(A)$ is defined

$$R \circ S = RS := \{(r, s) \in A \times A | \exists x \in A : (r, x) \in R \wedge (x, s) \in S\} \quad (3.25)$$

and called composition or multiplication of R and S . Instead of writing $R \circ S$ we also write simply RS .

In conjunction with \sqsubset composition is monotone:

$$\forall P, Q, R \in \mathcal{R}(A) : P \sqsubset Q \rightarrow R \circ P \sqsubset R \circ Q \quad (3.26)$$

$$\forall P, Q, R \in \mathcal{R}(A) : P \sqsubset Q \rightarrow P \circ R \sqsubset Q \circ R \quad (3.27)$$

- (\Rightarrow) Following the definition of composition, it can easily be observed, if Q includes P , all elements of P are also in Q :

$$\forall x, y : (x, y) \in R \circ P \quad (3.28)$$

$$\rightarrow \exists z : (x, z) \in R \wedge (z, y) \in P \xrightarrow{P \sqsubset Q} \exists z : (x, z) \in R \wedge (z, y) \in Q \quad (3.29)$$

$$\rightarrow (x, y) \in R \circ Q \quad (3.30)$$

An analogous deduction can be shown for the right hand side composition of R .

- (\Leftarrow) The opposite direction can be proven indirectly, assuming $R \circ P \sqsubset R \circ Q$ holds, but $P \sqsubset Q$ does not:

Definition 10 (Identity Relation) *The relation $\mathcal{I} \in \mathcal{R}(A)$*

$$\mathcal{I} := \{(a, b) \in A \times A \mid a = b\} = \{(a, a) \mid a \in A\} \subset A \times A \quad (3.31)$$

is called identity relation.

$(\mathcal{R}(A), \circ, \mathcal{I})$ is a monoid, i.e. for all relations in $\mathcal{R}(A)$ composition is associative and \mathcal{I} serves as it's identity element:

$$(Q \circ R) \circ S = Q \circ (R \circ S) \quad (3.32)$$

$$R \circ \mathcal{I} = \mathcal{I} \circ R = R \quad (3.33)$$

Also, \mathcal{O} serves as absorbing element for composition:

$$R \circ \mathcal{O} = \mathcal{O} \circ R = \mathcal{O} \quad (3.34)$$

Because $(\mathcal{R}(A), \circ, \mathcal{I})$ is a monoid, we can define exponentiation:

Definition 11 (Exponentiation of Relations) *Let $R \in \mathcal{R}(A)$ and $n \in \mathbb{N}$.*

$$R^0 := \mathcal{I} \quad (3.35)$$

$$R^n := R \circ R^{n-1} \quad (3.36)$$

Consider the following example:

$$A = \{a, b, c, d\} \quad (3.37)$$

$$R = \{(a, b), (a, c), (c, d)\} \quad (3.38)$$

$$R^0 = \{(a, a), (b, b), (c, c), (d, d)\} \quad (3.39)$$

$$R^1 = R \circ R^0 = R \circ \mathcal{I} = \{(a, b), (a, c), (c, d)\} \quad (3.40)$$

$$R^2 = R \circ R^1 = R \circ R = \{(a, d)\} \quad (3.41)$$

$$R^3 = R \circ R^2 = \mathcal{O} \quad (3.42)$$

$$R^4 = R^5 = R^6 = \dots = R \circ \mathcal{O} = \mathcal{O} \quad (3.43)$$

Definition 12 (Reflexivity) A relation $R \in \mathcal{R}(A)$ is called:

$$\text{reflexive} :\Leftrightarrow \forall a \in A : (a, a) \in R \quad (3.44)$$

$$\text{irreflexive} :\Leftrightarrow \forall a \in A : (a, a) \notin R \quad (3.45)$$

Definition 13 (Reflexive Closure) Let $R \in \mathcal{R}(A)$. Then

$$R^\circ := \inf\{S \mid R \sqsubset S \wedge S \text{ reflexive}\} = R \sqcup \mathcal{I} \quad (3.46)$$

is called reflexive closure of R .

The reflexive closure of a homogeneous relation R is the infimum or largest lower bound of the set $A = \{S \mid R \sqsubset S \wedge S \text{ reflexive}\}$ containing all reflexive relations, which include R . The smallest reflexive relation is \mathcal{I} . The smallest relation including R is R itself. So, for an arbitrary relation $R' \in A$ the inclusions $R \sqsubset R'$, $\mathcal{I} \sqsubset R'$ and $(R \sqcup \mathcal{I}) \sqsubset R'$ hold. Thus $R \sqcup \mathcal{I}$ is a lower bound for A and $(R \sqcup \mathcal{I}) \sqsubset \inf A$ holds. Vice versa, $R \sqcup \mathcal{I}$ is an element of A and any relation $R'' \sqsubset (R \sqcup \mathcal{I})$ does either not include R or is not reflexive. Thus $R \sqcup \mathcal{I}$ is also the smallest relation in A and $\inf A \sqsubset (R \sqcup \mathcal{I})$. From $(R \sqcup \mathcal{I}) \sqsubset \inf A$ and $\inf A \sqsubset (R \sqcup \mathcal{I})$ follows $\inf A = (R \sqcup \mathcal{I})$. [12]

Definition 14 (Symmetry) A relation $R \in \mathcal{R}(A)$ is called:

$$\text{symmetric} :\Leftrightarrow \forall a, b \in A : (a, b) \in R \Rightarrow (b, a) \in R \quad (3.47)$$

$$\text{asymmetric} :\Leftrightarrow \forall a, b \in A : (a, b) \in R \Rightarrow (b, a) \notin R \quad (3.48)$$

$$\text{antisymmetric} :\Leftrightarrow \forall a, b \in A : (a, b) \in R \wedge (b, a) \in R \Rightarrow a = b \quad (3.49)$$

Definition 15 (Transitivity) A relation $R \in \mathcal{R}(A)$ is called:

$$\text{transitive} :\Leftrightarrow R^2 \sqsubset R \quad (3.50)$$

$$:\Leftrightarrow \forall a, b, c \in A : (a, b) \in R \wedge (b, c) \in R \rightarrow (a, c) \in R \quad (3.51)$$

$$\text{intransitive} :\Leftrightarrow R^2 \not\sqsubset R \quad (3.52)$$

$$:\Leftrightarrow \forall a, b, c \in A : (a, b) \in R \wedge (b, c) \in R \rightarrow (a, c) \notin R \quad (3.53)$$

The equivalent characterization of transitivity is $R^2 \sqsubset R$ is easily obtained:

$$\forall a, b, c \in A : (a, b) \in R \wedge (b, c) \in R \Rightarrow (a, c) \in R \quad (3.54)$$

$$\Leftrightarrow \forall a, c \in A : (a, c) \in RR \rightarrow (a, c) \in R \quad (3.55)$$

$$\Leftrightarrow \forall a, c \in A : (a, c) \in R^2 \rightarrow (a, c) \in R \quad (3.56)$$

$$\Leftrightarrow R^2 \sqsubset R \quad (3.57)$$

If $\mathcal{T}(A) := \{R \in \mathcal{R}(A) | R^2 \sqsubset R\}$ is the set over all transitive relations of set A , it's infimum $I := \inf \mathcal{T}(A)$ is also transitive. Assuming it is not, at least one element exists, which is in I^2 , but not in I . Because I is the infimum of $\mathcal{T}(A)$, all transitive relations R must include it. Thus the same element is in R^2 , but not in R . However, this is a contradiction, because R is transitive and all elements in R^2 must be in R .

$$\neg(I^2 \sqsubset I) \Leftrightarrow \forall x, y : \neg[(x, y) \in I^2 \rightarrow (x, y) \in I] \quad (3.58)$$

$$\Leftrightarrow \forall x, y : (x, y) \in I^2 \wedge (x, y) \notin I \quad (3.59)$$

$$\Leftrightarrow \forall x, y \exists z : (x, z) \in I \wedge (z, y) \in I \wedge (x, y) \notin I \quad (3.60)$$

$$\Leftrightarrow \forall x, y \exists z : (x, z) \in R \wedge (z, y) \in R \wedge (x, y) \notin R \quad (3.61)$$

$$\Leftrightarrow \forall x, y : (x, y) \in R^2 \wedge (x, y) \notin R \quad (3.62)$$

$$\Leftrightarrow \forall x, y : \neg[(x, y) \in R^2 \rightarrow (x, y) \in R] \quad (3.63)$$

$$\Leftrightarrow \neg(R^2 \sqsubset R) \quad (3.64)$$

Definition 16 (Transitive Closure) Let $R \in \mathcal{R}(A)$ and $i \in \mathbb{N}$. Then

$$R^+ := \inf\{S | R \sqsubset S \wedge S \text{ transitive}\} = \sup\{R^i | i \geq 1\} \quad (3.65)$$

is called transitive closure of R .

The transitive closure of a relation is the infimum or greatest lower bound of the set $A = \{S | R \sqsubset S \wedge S \text{ transitive}\}$ containing all transitive relations, which include R . Because A contains only transitive relations, its infimum $I = \inf A$ is also transitive.

Definition 17 (Transitive-Reflexive Closure) $R^* := R^+ \cup I$ is called reflexive-transitive closure

Definition 18 (Order Relation) content...

3.3 Mereology

Mereology is the logical study on the semantics of parthood. *"As a formal theory, mereology is simply an attempt to set out the general principles underlying the relationships between a whole and its constituent parts [...]"* [15]. Achille C. Varzi describes a collection of formal theories, i.e. sets of distinct axioms, of mereology in [15], which will be summarized in this section.

ToDo: add SEP reference [14]

ToDo: add paragraph with applications of mereology in computer science [11]

The first part of this section will just introduce the axioms of mereology. Then, at the end of this section, we will use these axiom to build some of the theories described in [15]. Note, that the terms relation, relationship and predicate may be used synonymously throughout this section.

3.3.1 Parthood

First we define the intuitive notion of the parthood relationship:

Definition 19 (partOf) *Let x and y objects of interest. We define:*

$$x \text{ partOf } y :\Leftrightarrow x \text{ is a constituent part of } y \quad (3.66)$$

We further assume, that **partOf** satisfies the following properties:

$$(P1) \quad x \text{ partOf } x \quad (\text{Reflexivity}) \quad (3.67)$$

$$(P2) \quad x \text{ partOf } y \wedge y \text{ partOf } x \rightarrow x = y \quad (\text{Antisymmetry}) \quad (3.68)$$

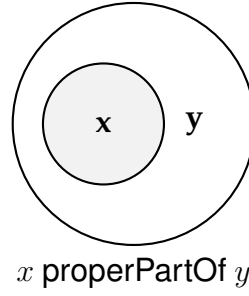
$$(P3) \quad x \text{ partOf } y \wedge y \text{ partOf } z \rightarrow x \text{ partOf } z \quad (\text{Transitivity}) \quad (3.69)$$

Thus, **partOf** induces a partial order of things.

However, since the reflexive parthood may be to weak for some cases, we also define a stricter, irreflexive parthood relationship as follows:

$$x \text{ properPartOf } y :\Leftrightarrow x \text{ partOf } y \wedge \neg(y \text{ partOf } x) \quad (\text{Proper Part}) \quad (3.70)$$

Proper parthood induces a strict partial order of things. Figure 3.1 shows a schematic illustration of proper parts.



This Venn-style diagram depicts a schematic illustration of Proper Part: x is certainly a part of y , however y is not a part of x .

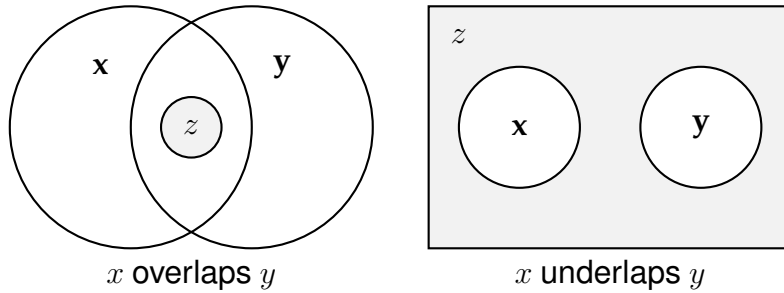
Figure 3.1 A schematic depiction of Proper Part

In addition to the relationships above we introduce the following predicates in order to provide a more concise notation:

$$x \text{ overlaps } y :\Leftrightarrow \exists z : z \text{ partOf } x \wedge z \text{ partOf } y \quad (\text{Overlap}) \quad (3.71)$$

$$x \text{ underlaps } y :\Leftrightarrow \exists z : x \text{ partOf } z \wedge y \text{ partOf } z \quad (\text{Underlap}) \quad (3.72)$$

Overlap models situations, where two things share at least on distinct part. Underlap models situations, where two things are part of the same distinct thing. Figure 3.2 illustrates both in a schematic fashion.



These Venn-style diagrams depict schematic illustrations of Overlap & Underlap:

- $x \text{ overlaps } y$: x and y share a distinct part z , which is emphasized as gray area.
- $x \text{ underlaps } y$: x and y are both parts of z , which is emphasized as gray area.

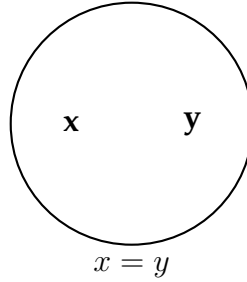
Figure 3.2 A schematic depiction of Overlap & Underlap

ToDo: Define and outline Identity/Equality. Note seems to be some problems with mereological equality of words, see [14]

In axiom 3.68 (P2) we already used identity/equality "=" to describe antisymmetry. So we used first order logic *with* identity/equality to define parthood. However, it is worthwhile noting, that parthood itself also allows for defining identity/equality [14]:

$$x = y :\Leftrightarrow x \text{ partOf } y \wedge y \text{ partOf } x \quad (\text{Identity/Equality}) \quad (3.73)$$

Note that identity and equality cannot be distinguished in the mereological context. Figure 3.3 shows a schematic depiction of identity/equality.



This Venn-style diagram depicts a schematic illustration of Identity/Equality.

Figure 3.3 A schematic depiction of Identity/Equality

In any case, the right hand side of 3.73 defines an equivalence relation due to *partOf* being a partial order.

Proof 1 Let \prec be a partial order (reflexive, antisymmetric, transitive) and

$$x \approx y :\Leftrightarrow x \prec y \wedge y \prec x$$

then \approx is an equivalence relation (reflexive, symmetric, transitive). If \approx is not an equivalence relation, then it is not reflexive, not symmetric or not transitive. However:

1. if \approx is not reflexive:

$$\neg(x \approx x) \Leftrightarrow \neg(x \prec x \wedge x \prec x) \Leftrightarrow \neg(x \prec x) \quad \text{?}$$

2. *if \approx is not symmetric:*

$$\begin{aligned}
 & \neg(x \approx y \rightarrow y \approx x) \\
 & \Leftrightarrow x \approx y \wedge \neg(y \approx x) \\
 & \Leftrightarrow (x \prec y \wedge y \prec x) \wedge \neg(y \prec x \wedge x \prec y) \\
 & \Leftrightarrow (x \prec y \wedge y \prec x) \wedge \neg(x \prec y \wedge y \prec x) \\
 & \Leftrightarrow (x \prec x) \wedge \neg(x \prec x) \quad \text{⚡}
 \end{aligned}$$

3. *if \approx is not transitive:*

$$\begin{aligned}
 & \neg(x \approx z \wedge z \approx y \rightarrow x \approx y) \\
 & \Leftrightarrow x \approx z \wedge z \approx y \wedge \neg(x \approx y) \\
 & \Leftrightarrow (x \prec z \wedge z \prec x) \wedge (z \prec y \wedge y \prec z) \wedge \neg(x \prec y \wedge y \prec x) \\
 & \Leftrightarrow (x \prec z \wedge z \prec y \wedge y \prec z \wedge z \prec x) \wedge \neg(x \prec y \wedge y \prec x) \\
 & \Leftrightarrow (x \prec y \wedge y \prec x) \wedge \neg(x \prec y \wedge y \prec x) \\
 & \Leftrightarrow (x \prec x) \wedge \neg(x \prec x) \quad \text{⚡}
 \end{aligned}$$

We shall later see that identity/equality can also be extensionally determined:

$$x = y \Leftrightarrow \forall z(z \text{ partOf } x \leftrightarrow z \text{ partOf } y) \quad (3.74)$$

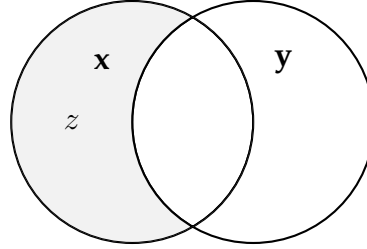
i.e. two things x and y identical or equal if and only if all parts of x are parts of y and vice versa.

3.3.2 Supplementation

The fourth axiom, which can be assumed in an universe described by means of mereology, is the supplementation axiom. It models the effects of situations more precisely, where one thing is not part of another. Namely, if this is the case, a third thing may exist, which is part of the former but not part of the latter.

$$(P4) \quad \neg(x \text{ partOf } y) \rightarrow \exists z(z \text{ partOf } x \wedge \neg(z \text{ overlaps } y)) \quad (3.75)$$

The supplementation axiom reads: If a thing x is not part of another thing y , then at least one part of x does not share further parts with y . Figure 3.4 depicts a schematic example of the supplementation axiom.



This Venn-style diagram exemplifies the supplementation axiom: x is not part of y . z is emphasized as gray area. x contains z , but z shares no further parts with y .

Figure 3.4 A schematic example of the Supplementation Axiom

ToDo: add paragraph explaining "strong" and "weak" supplementation

One can also observe from figure 3.4, that the supplementation axiom can be interpreted as analogue to set-theoretic difference.

3.3.3 Sum, Product & Difference

The next three axioms allow for the notions of sum, product and difference in a mereological context.

3.3.3.1 Sum

The fifth axiom, which can be assumed in an universe described by means of mereology, is the sum axiom. It models the intuitive notion, where all parts of one thing and all parts of another thing are exactly the constituent parts of a third thing.

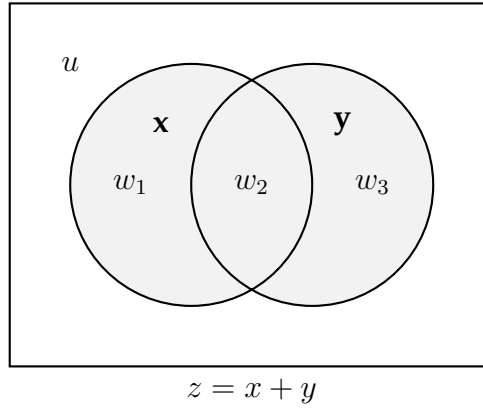
$$\begin{aligned}
 \text{(P5)} \quad & x \text{ underlaps } y \\
 & \rightarrow \exists z \forall w (w \text{ overlaps } z \leftrightarrow (w \text{ overlaps } x \vee w \text{ overlaps } y))
 \end{aligned}
 \tag{3.76}$$

The sum axiom reads: If things x and y are two parts of the same thing, then another thing z exist, which only shares parts with things, which in turn share

parts with x or y . Then z can be interpreted as the sum of x and y . This notion is captured by following definition of the term $z = x + y$:

$$z = x + y :\Leftrightarrow \forall w (w \text{ overlaps } z \leftrightarrow (w \text{ overlaps } x \vee w \text{ overlaps } y)) \quad (3.77)$$

Figure 3.5 depicts a schematic example of the sum axiom.



This Venn-style diagram exemplifies the sum axiom: x and y are part of u . $z = x + y$ is emphasized as gray area. All w_i share parts with z , if and only if they share parts with x or y .

Figure 3.5 A schematic example of the Sum Axiom

One can also observe similarities between the sum axiom and set-theoretic union from figure 3.5 and the definition 3.77.

3.3.3.2 Product

The sixth axiom, which can be assumed in an universe described by means of mereology, is the product axiom. It models the intuitive notion, where all things, which are parts of two things at the same time, are exactly the constituent parts of a third thing.

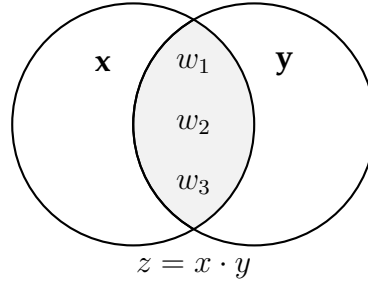
$$(P6) \quad \begin{aligned} & x \text{ overlaps } y \\ & \rightarrow \exists z \forall w (w \text{ partOf } z \leftrightarrow (w \text{ partOf } x \wedge w \text{ partOf } y)) \end{aligned} \quad (3.78)$$

The sum axiom reads: If things x and y share at least one part, then another thing z exists, which only consists of parts, which in turn are parts of x and y at the

same time. Then z can be interpreted as the product of x and y . This notion is captured by the following definition of the term $z = x \cdot y$:

$$z = x \cdot y :\Leftrightarrow \forall w (w \text{ partOf } z \leftrightarrow (w \text{ partOf } x \wedge w \text{ partOf } y)) \quad (3.79)$$

Figure 3.6 depicts a schematic example of the product axiom.



This Venn-style diagram exemplifies the product axiom: x and y share arts. $z = x \cdot y$ is emphasized as gray area. All w_i are part of z , if and only if they are part of x and y .

Figure 3.6 A schematic example of the Product Axiom

One can also observe similarities between the sum axiom and set-theoretic intersection from figure 3.6 and the definition 3.79.

3.3.3.3 Difference

The seventh axiom, which can be assumed in an universe described by means of mereology, is the difference axiom. It models the intuitive notion, where things may be split, so that their constituent parts are regrouped into disjoint things, which share no parts.

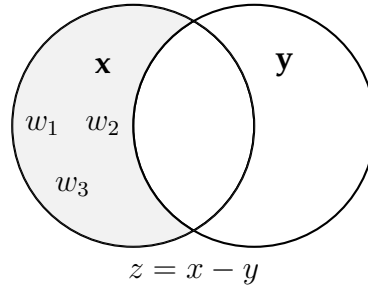
$$\begin{aligned} (P7) \quad & \exists z (z \text{ partOf } x \wedge \neg(z \text{ overlaps } y)) \\ & \rightarrow \exists z \forall w (w \text{ partOf } z \leftrightarrow (w \text{ partOf } x \wedge \neg(w \text{ overlaps } y))) \end{aligned} \quad (3.80)$$

The difference axiom reads: If for things x and y a supplementary thing exists, which is part of x , but shares no parts with y , then another thing z exists, consisting of parts, which are also part of x , but share no parts with y . Then z can

be interpreted as the difference between x and y , in that order. This notion is captured by the following definition of the term $z = x - y$:

$$z = x - y :\Leftrightarrow \forall w (w \text{ partOf } z \leftrightarrow (w \text{ partOf } x \wedge \neg(w \text{ overlaps } y))) \quad (3.81)$$

Figure 3.7 depicts a schematic example of the difference axiom.



This Venn-style diagram exemplifies the difference axiom: x is not part of y and parts of x exists, which do not share parts with y . $z = x - y$ is emphasized as gray area. All w_i are part of z , if and only if they are part of x and do not share further parts with y .

Figure 3.7 A schematic example of the Difference Axiom

One can also observe again similarities between the sum axiom and set-theoretic difference from figure 3.7 and the definition 3.81.

ToDo: Outline dependencies with supplementation axiom

3.3.4 Universal Top, Complement & Bottom

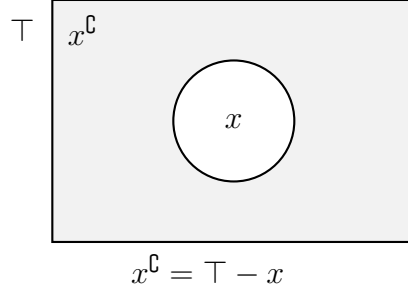
The sum axiom (P5) at 3.76 gives immediate rise to the idea, that all things can be summed up to an universal thing and all things are part of it. This notion is captured by the top axiom:

$$\exists \top \forall x (x \text{ partOf } \top) \quad (\text{Top}) \quad (3.82)$$

Having an universe also facilitates the definition of a universal or absolute complement:

$$x^c := \top - x \quad (\text{Complement}) \quad (3.83)$$

Figure 3.8 depicts a schematic illustration of an universal top and a complement.



This Venn-style diagram illustrates universal top and a complement: Top \top is the rectangle containing everything. The complement x^c of x is emphasized as gray area.

Figure 3.8 A schematic illustration of Universal Top & Complement

An universal top renders the underlap relationship as defined at 3.72 trivially true, thus the mereological sum of two things as defined at 3.77 can never be undefined. In an algebraic sense, an universal top also provides an absorbing element for mereological sum and a neutral element for the mereological product as defined at 3.79:

$$\top = \top + x = x + \top \quad (3.84)$$

$$x = \top \cdot x = x \cdot \top \quad (3.85)$$

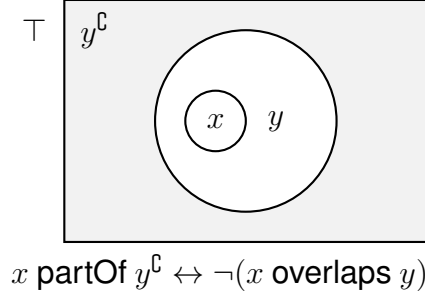
Properties of the mereological complement can in part be observed from figure 3.8. Obviously, in addition to the definition of complements, the following identity also holds:

$$x = \top - x^c \quad (3.86)$$

Less obvious properties may be the following equivalences incorporating complement, parthood and overlap:

$$\begin{aligned} \forall x \forall y (x \text{ partOf } y^c &\leftrightarrow \neg(x \text{ overlaps } y)) \\ \forall x \forall y (x \text{ partOf } y &\leftrightarrow \neg(x \text{ overlaps } y^c)) \end{aligned} \quad (3.87)$$

Figure 3.9 shows a schematic illustration of this equivalence. Both equations fol-



This Venn-style diagram illustrates the equivalence incorporating complement, parthood and overlap: Top \top is the rectangle containing everything. x is a proper part of y . The complement y^c of y is emphasized as gray area. x shares no parts with y^c .

Figure 3.9 A schematic illustration the equivalence incorporating Complement, Parthood & Overlap

low directly from the definition of mereological difference by simple deduction, since $x \text{ partOf } \top$ is always true:

$$\begin{aligned}
 x^c = \top - x &\Leftrightarrow \forall y (y \text{ partOf } x^c \leftrightarrow x \text{ partOf } \top \wedge \neg(y \text{ overlaps } x)) \\
 &\Leftrightarrow \forall y (y \text{ partOf } x^c \leftrightarrow \text{true} \wedge \neg(y \text{ overlaps } x)) \\
 &\Leftrightarrow \forall y (y \text{ partOf } x^c \leftrightarrow \neg(y \text{ overlaps } x))
 \end{aligned} \tag{3.88}$$

$$\begin{aligned}
 x = \top - x^c &\Leftrightarrow \forall y (y \text{ partOf } x \leftrightarrow x \text{ partOf } \top \wedge \neg(y \text{ overlaps } x^c)) \\
 &\Leftrightarrow \forall y (y \text{ partOf } x \leftrightarrow \text{true} \wedge \neg(y \text{ overlaps } x^c)) \\
 &\Leftrightarrow \forall y (y \text{ partOf } x \leftrightarrow \neg(y \text{ overlaps } x^c))
 \end{aligned} \tag{3.89}$$

A direct corollary is the identity of complement involution:

$$(x^c)^c = x \tag{3.90}$$

This identity is deduced by substitution of the equivalence above at 3.88 and 3.89:

$$\begin{aligned}
 (x^c)^c = \top - x^c &\Leftrightarrow \forall y (y \text{ partOf } (x^c)^c \leftrightarrow \neg(y \text{ overlaps } x^c)) \\
 &\Leftrightarrow \forall y (y \text{ partOf } (x^c)^c \leftrightarrow y \text{ partOf } x) \\
 &\Leftrightarrow (x^c)^c = x
 \end{aligned} \tag{3.91}$$

This property allows for a refinement of the definition for mereological difference, which again shows another similarity with set-theoretic difference:

$$z = x - y = x \cdot y^{\complement} \quad (3.92)$$

The proof is the same simple deduction as above:

$$\begin{aligned} z = x - y &\Leftrightarrow \forall w (w \text{ partOf } z \leftrightarrow w \text{ partOf } x \wedge \neg(w \text{ overlaps } y)) \\ &\Leftrightarrow \forall w (w \text{ partOf } z \leftrightarrow w \text{ partOf } x \wedge w \text{ partOf } y^{\complement}) \\ &\Leftrightarrow z = x \cdot y^{\complement} \end{aligned} \quad (3.93)$$

The notion of an universal top gives immediate rise to the question, whether a converse thing, an universal bottom, exists. The universal bottom for parthood satisfies:

$$\exists \perp \forall x (\perp \text{ partOf } x) \quad (\text{Bottom}) \quad (3.94)$$

An universal bottom renders the overlap relationship as defined at 3.71 trivially true, thus the mereological product of two things can never be undefined. In an algebraic sense, an universal bottom provides an absorbing element for the mereological product and a neutral element for the mereological sum:

$$\perp = \perp \cdot x = x \cdot \perp \quad (3.95)$$

$$x = \perp + x = x + \perp \quad (3.96)$$

Moreover, it makes mereological difference sound. With an universal bottom the difference $x - x$ of only one thing is now possible:

$$\begin{aligned} z = x - x &\Leftrightarrow z = x \cdot x^{\complement} \\ &\Leftrightarrow \forall y (y \text{ partOf } z \leftrightarrow y \text{ partOf } x \wedge y \text{ partOf } x^{\complement}) \\ &\Leftrightarrow z = \perp \end{aligned} \quad (3.97)$$

The only thing, which is part of x and its complement at the same time, is the universal bottom. Given this fact, now complements of top and bottom can also be determined:

$$\top^c = \top - \top = \perp \quad (3.98)$$

$$\perp^c = \top - \perp = \top - \top^c = \top \cdot (\top^c)^c = \top \cdot \top = \top \quad (3.99)$$

However, the notion of an universal bottom or null thing is more controversial than the notion of an universal top [15].

ToDo: Outline why bottom is disputed. Perhaps, if bottom and atoms are assumed, bottom would be the only "real" atom.

3.3.5 Unrestricted Fusion

3.3.6 Atomic Parts

3.3.7 Mereology Theories

3.4 Formal Languages & Grammars

[13]

3.4.1 Context-Free Languages & Grammars

3.5 Traceability

[16] [4] [7] TBD.

3.5.1 Traceability Relationship

3.5.2 Traceability Link

3.5.3 Traceability Recovery

3.5.4 Traceability Exploration

3.6 Ontologies

TBD. [5]

3.7 Megamodeling

TBD. [1] [3]

3.7.1 MegaL

[9] [2] [8]

3.7.1.1 MegaL/Xtext

[6]

3.8 Program Analysis

TBD.

3.9 XML Data Binding

TBD.

3.9.1 Java Architecture for XML Binding (JAXB)

3.10 Object Relational Mapping

TBD.

3.10.1 Java Persistence API (JPA)

3.10.2 Hibernate

3.11 Another Tool For Language Recognition (ANTLR)

[10]

Chapter 4

Hypotheses

This chapter introduces the hypotheses this thesis is based upon. TBD.

4.1 Fragments

The Oxford English Dictionary defines fragment¹ as “[...] *isolated or incomplete part of something* [...]”. Regarding natural languages, sentence fragments are incomplete sentences lacking one or more grammatical elements. **ToDo: Lacks citation for "sentence fragment"!**

The intuitive notion of a fragment when working with and/or talking over computer programs is, that it is a piece of code containing a functionality of momentary interest. In that regard, we exclusively use the word fragment referring to isolated or incomplete parts of things having a textual representation, e.g. computer programs. However, computer science knows different levels of organization in text, which effects the semantics of textual fragments.

The most basic level of textual organization is no organization at all. Random text is only restricted by its alphabet, which allows us to specify fragmentation solely in terms of concatenation.

¹<https://en.oxforddictionaries.com/definition/fragment> (retrieved 08/28/2017)

Definition 20 (Fragments over Alphabets) Let Σ be an alphabet and $x, y \in \Sigma^*$ be two words over that alphabet. x is a fragment of y , if and only if there is a concatenation containing x and resulting in y :

$$\text{fragmentOf} : \Sigma^* \times \Sigma^* \quad (4.1)$$

$$x \text{ fragmentOf } y :\Leftrightarrow \exists u, v \in \Sigma^* (uxv = y) \quad (4.2)$$

We can also observe from definition 20 that textual fragmentation shares similarities with mereological parthood, i.e. the `fragmentOf` definition is also reflexive, antisymmetric and transitive:

1. Reflexivity: $x \text{ fragmentOf } x$
 $x \text{ fragmentOf } x$ holds for all x since $u = v = \epsilon \in \Sigma^*$.
2. Antisymmetry: $x \text{ fragmentOf } y \wedge y \text{ fragmentOf } x \rightarrow x = y$
 $x \text{ fragmentOf } y \wedge y \text{ fragmentOf } x$ is equivalent to $axb = y \wedge cyd = x$, from which follows $caxbd = x$ and then $a = b = c = d = \epsilon$, thus $x = y$ follows eventually
3. Transitivity: $x \text{ fragmentOf } y \wedge y \text{ fragmentOf } z \rightarrow x \text{ fragmentOf } z$
 $x \text{ fragmentOf } y \wedge y \text{ fragmentOf } z$ is equivalent to $axb = y \wedge cyd = z$, from which follows $caxbd = z$, which is in turn equivalent to $uxv = z$ with $u = ca$ and $v = bd$, thus $x \text{ fragmentOf } z$ follows eventually

There is a universal bottom element, which is fragment of all words:

$$\forall x \in \Sigma^* (\epsilon \text{ fragmentOf } x) \quad (4.3)$$

and there is a universal top element, all words are fragments of:

$$\begin{aligned} \forall x \in \Sigma^* (x \text{ fragmentOf } W) \\ W := w_1 w_2 w_3 \dots \quad w_i \in \Sigma^* \setminus \{\epsilon\}, i \in \mathbb{N} \end{aligned} \quad (4.4)$$

where W is the concatenation of all words in Σ^* and thus is an infinite word. $W \in \Sigma^\omega$ is interpreted as mapping $\mathbb{N} \rightarrow \Sigma$, giving a symbol from the alphabet for its position in the word. **ToDo: citation for infinite words, Handbook on Formal languages**

We can now easily agree upon, that `fragmentOf` is `partOf` for texts. Thus both are logically equivalent relations:

$$\text{fragmentOf} \equiv \text{partOf} \quad (4.5)$$

ToDo: refer to philosophical problems from SEP

A higher level of textual organization are formal languages, i.e. subsets of Σ^* for any alphabet Σ [13]. Given any language specified with set-builder notation:

$$L := \{w \in \Sigma^* \mid \Phi(w)\} \subseteq \Sigma^* \quad (4.6)$$

where $\Phi(w)$ is an arbitrary restriction on w , we can still observe the same behavior regarding fragments, e.g.:

$$L = \{a^n b^n \mid n \in \mathbb{N} : n \geq 2\} \subseteq \{a, b\}^* = \{aabb, aaabbb, aaaabbbb, \dots\}$$

...

ab `fragmentOf` *aabb*

aaabbb `fragmentOf` *aaaabbbb*

aaaabbbb `fragmentOf` *aaaabbbb*

...

However, we can only observe the behavior partly for `fragmentOf` : $\Sigma^* \times \Sigma^*$ and `fragmentOf` : $\Sigma^* \times L$, but not for `fragmentOf` : $L \times L$. In other words, the fragments of words in formal languages are not necessarily words of that language itself. This becomes even more apparent if we consider fragments and languages generated by formal grammars.

Definition 21 (Fragments generated by Grammars) *Let $G = (V, \Sigma, P, S)$ be a grammar and $x, y \in \Sigma^*$ be two words over its terminal symbols. x is a fragment of y generated by G , if and only if there is a derivation from a concatenation containing x to y :*

$$x \text{ fragmentOf}_G y \Leftrightarrow \exists u, v \in (V \cup \Sigma)^* (S \Rightarrow_G^* u x v \Rightarrow_G^* y) \quad (4.7)$$

4.1.1 Fragment Languages

4.2 Correspondence

The Oxford English Dictionary defines correspondence² as “[...] *close similarity, connection, or equivalence* [...]”. [8]

Definition 22 (Correspondence) Let $R \subseteq L_1 \times L_2$ be a relation between two languages L_1 and L_2 . Two artifacts a_1 and a_2 recursively correspond to each other in the sense of R if both artifacts contain parts, which correspond in the same fashion to exactly one part of the other artifact:

$$\begin{aligned}
 &(a_1, a_2) \in R \\
 &\wedge \forall b_1 \in L_1 \exists! b_2 \in L_2 (b_1 \text{ partOf } a_1 \rightarrow (b_2 \text{ partOf } a_2 \wedge b_1 \text{ correspondsTo}_R b_2)) \\
 &\wedge \forall b_2 \in L_2 \exists! b_1 \in L_1 (b_2 \text{ partOf } a_2 \rightarrow (b_1 \text{ partOf } a_1 \wedge b_2 \text{ correspondsTo}_R b_1)) \\
 &\Rightarrow a_1 \text{ correspondsTo}_R a_2
 \end{aligned} \tag{4.8}$$

4.3 Conformance

The Oxford English Dictionary defines conformance³ as synonym for conformity⁴ and thus in turn as “*Compliance with standards, rules, or laws*”.

[8]

Definition 23 (Conformance) Let $L \subseteq \text{Any}$ be a language, $\text{Def}_L \subseteq \text{Any}$ the definition language of L and $\text{def}_L \in \text{Def}_L$ the actual definition artifact of L . An arbitrary artifact conforms to the definition artifact of L , if and only if it is an element of L :

$$\forall x \in \text{Any} (x \text{ conformsTo } \text{def}_L \Leftrightarrow x \in L) \tag{4.9}$$

²<https://en.oxforddictionaries.com/definition/correspondence> (retrieved 08/28/2017)

³<https://en.oxforddictionaries.com/definition/conformance> (retrieved 08/28/2017)

⁴<https://en.oxforddictionaries.com/definition/conformity> (retrieved 08/28/2017)

Chapter 5

Methodology

This chapter summarizes the methodology used to develop the recovery system for this thesis. In short, the recovery system is developed example-driven using the model of a fictional Human Resource Management System used by the 101wiki¹ for its contributions.

5.1 The 101HRMS Model

The 101 Human Resource Management System² (101HRMS) provides a simple model of a company with many departments and employees. Figure 5.1 shows an UML class diagram of a variant of the model where each entity also has an ID attribute.

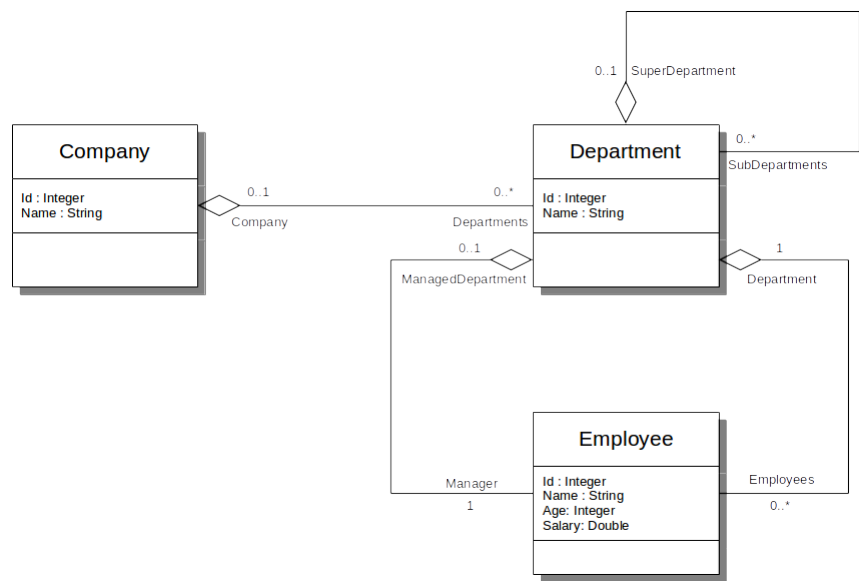
The 101HRMS model consists of companies attributed with a name. Each company accumulates departments. Each department is also attributed with a name, aggregates employees and has one employee acting as manager. Departments can further be refined into sub-departments. Each employee is attributed with a name, an age and a salary.

5.2 The 101HRMS Example Corpus

The actual

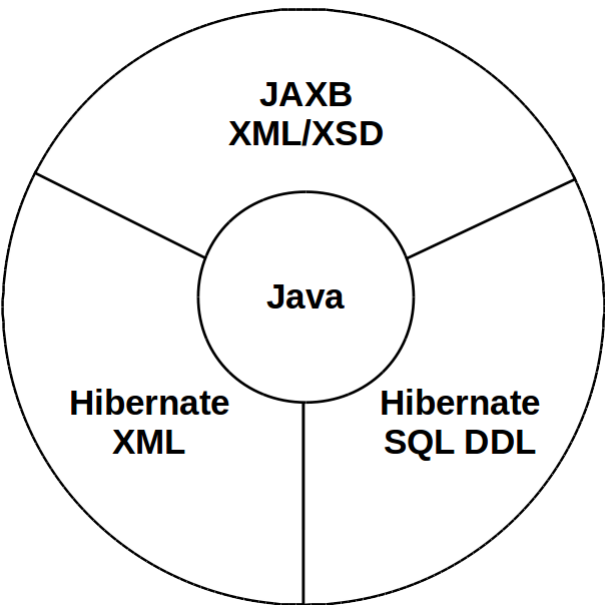
¹<https://101wiki.softlang.org/> (retrieved 12th November, 2017)

²<https://101wiki.softlang.org/101:@system> (retrieved 12th November, 2017)



This UML class diagram depicts the model of the 101 Human Resource Management System. It consists of simple companies with nested departments and employees mapped to the latter.

Figure 5.1 The 101 Human Resource Management System Model



This UML class diagram depicts the model of the 101 Human Resource Management System. It consists of simple companies with nested departments and employees mapped to the latter.

Figure 5.2 Example Java O/R/X Domains

Chapter 6

Requirements

This chapter summarizes functional requirements for the recovery system developed as part of this thesis.

R1 The recovery system must be capable of recovering parthood links, i.e. links capturing the relation between syntactically well-formed software artifacts and their fragments.

R2 The recovery system must be capable of recovering correspondences links, i.e. links capturing the relation between fragments of software artifacts denoting a predefined similarity among them and their fragments.

ToDo: refer to a correspondence definition

R3 The recovery system must be capable of recovering conformance links, i.e. links capturing the relation between a software artifacts or fragments denoting that one defines the other.

ToDo: refer to a conformance definition

R4 The recovery system must be capable of running within the MegaL/Xtext environment, i.e. the implementations of requirements R1, R2 and R3 must be compatible with the MegaL/Xtext plug-in-system.

Chapter 7

Design

TBD.

Chapter 8

Implementation

TBD.

8.1 Recovery

TBD.

8.1.1 CFG Fragmentation with ANTLR

Context-Free Grammar Fragmentation with ANTLR

TBD.

8.1.2 Similarity Heuristics

8.1.2.1 Name Similarity Heuristic

Heuristics are quick and "simple" methods for finding good approximate solutions for complex problems. The Name Correspondence Heuristic determines correspondence between artifacts simply by finding similarities of names in those artifacts.

TBD.

8.1.2.2 Annotation Similarity Heuristic

TBD.

8.2 Exploration

TBD.

Chapter 9

Results

TBD.

Chapter 10

Conclusion

TBD.

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