Ontology Alignment

Ontology Alignment

- Ontology alignment
- Ontology alignment strategies
- Evaluation of ontology alignment strategies
- Ontology alignment challenges

Ontologies in biomedical research

- many biomedical ontologies

  e.g. GO, OBO, SNOMED-CT

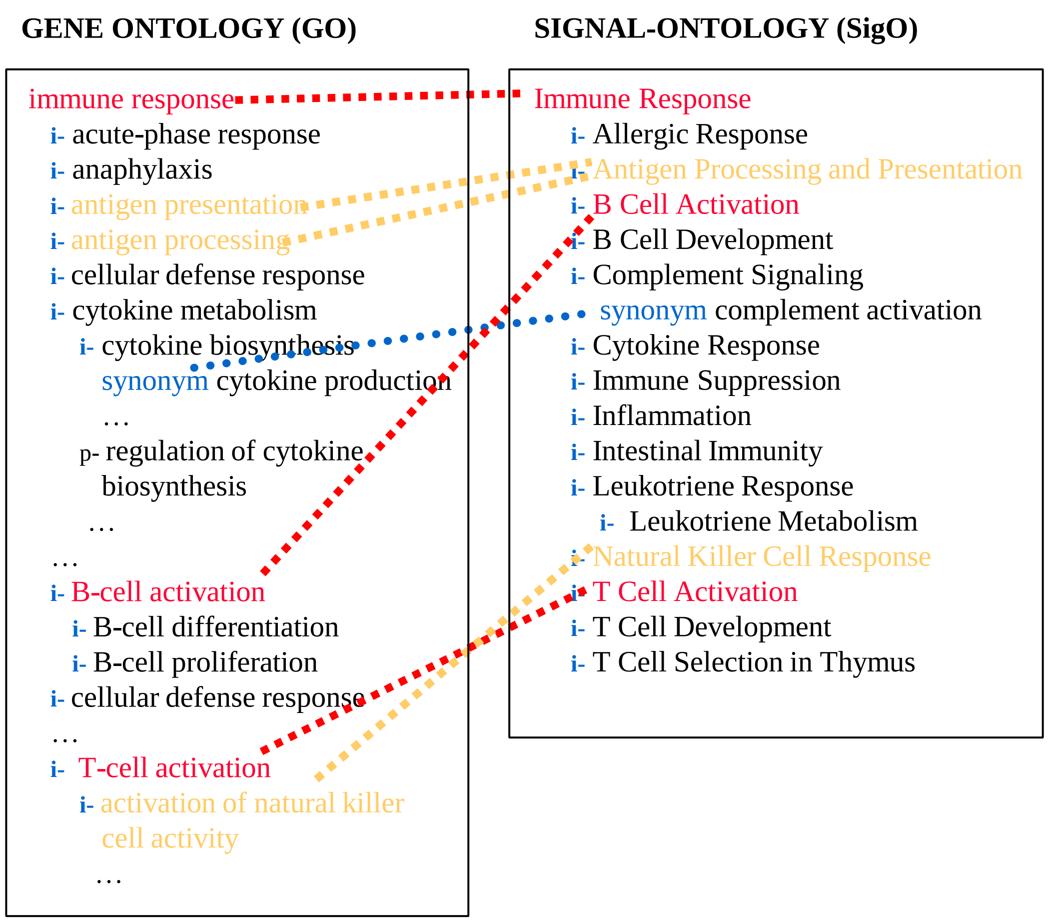
- practical use of biomedical ontologies

  e.g. databases annotated with GO

GENE ONTOLOGY (GO)

immune response
  i- acute-phase response
  i- anaphylaxis
  i- antigen presentation
  i- antigen processing
  i- cellular defense response
  i- cytokine metabolism
    i- cytokine biosynthesis
      synonym cytokine production
      …
    p- regulation of cytokine biosynthesis
    …
  …
  i- B-cell activation
    i- B-cell differentiation
    i- B-cell proliferation
  i- cellular defense response
  …
  i- T-cell activation
    i- activation of natural killer cell activity
    …

Ontologies with overlapping information



Ontologies with overlapping information

- Use of multiple ontologies
  - custom-specific ontology + standard ontology
  - different views over same domain
  - overlapping domains
- Bottom-up creation of ontologies

  experts can focus on their domain of expertise

→ important to know the inter-ontology relationships

GENE ONTOLOGY (GO)

immune response
- i- acute-phase response
- i- anaphylaxis
- i- antigen presentation
- i- antigen processing
- i- cellular defense response
- i- cytokine metabolism
  - i- cytokine biosynthesis
    synonym cytokine production
    …
  - p- regulation of cytokine biosynthesis
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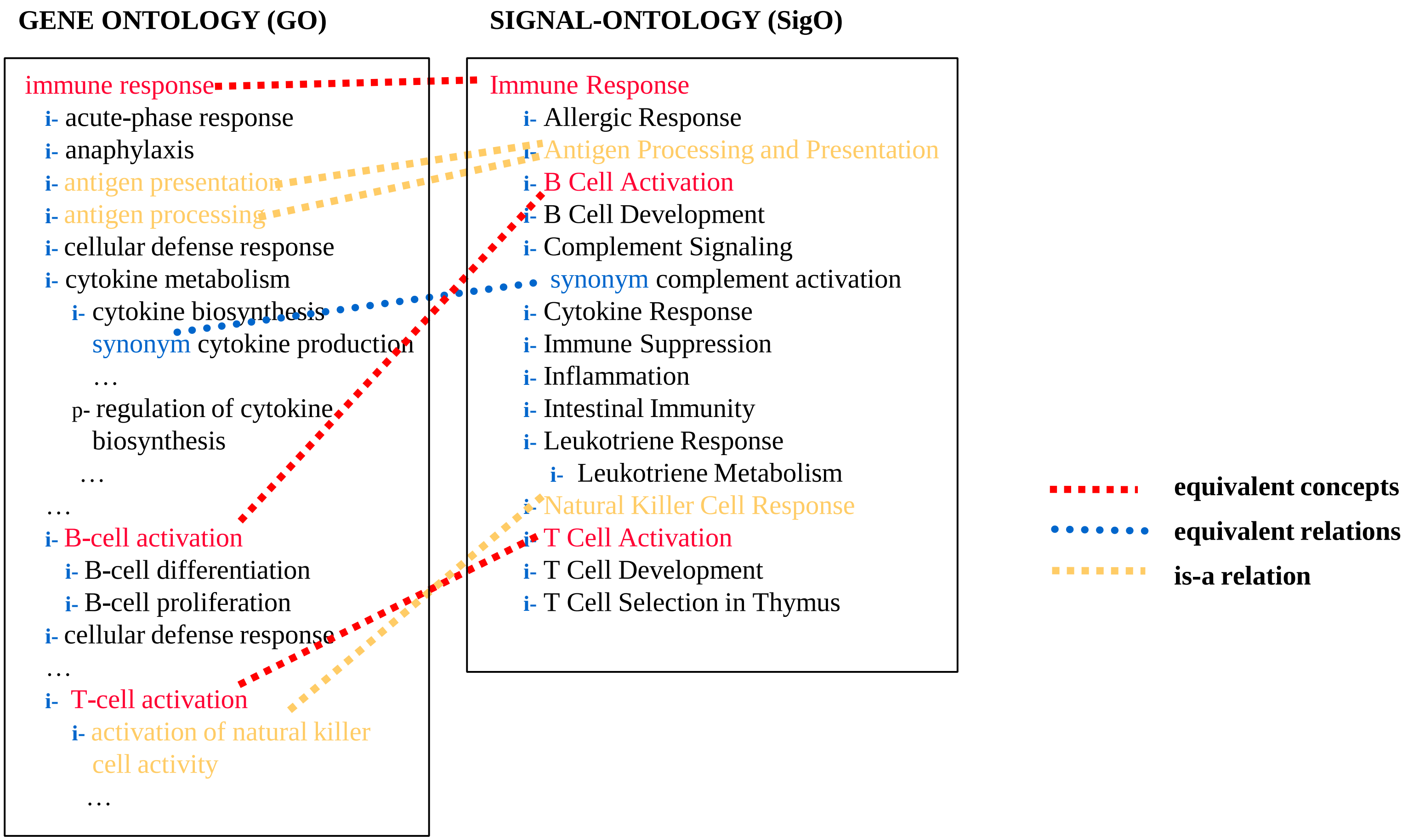
- …
- i- B-cell activation
  - i- B-cell differentiation
  - i- B-cell proliferation
- i- cellular defense response
- …
- i- T-cell activation
  - i- activation of natural killer cell activity
  - …

SIGNAL-ONTOLOGY (SigO)

Immune Response
- i- Allergic Response
- i- Antigen Processing and Presentation
- i- B Cell Activation
- i- B Cell Development
- i- Complement Signaling
  synonym complement activation
- i- Cytokine Response
- i- Immune Suppression
- i- Inflammation
- i- Intestinal Immunity
- i- Leukotriene Response
  - i- Leukotriene Metabolism
- i- Natural Killer Cell Response
- i- T Cell Activation
- i- T Cell Development
- i- T Cell Selection in Thymus

Ontology Alignment



Defining the relations between the terms in different ontologies

Ontology Alignment

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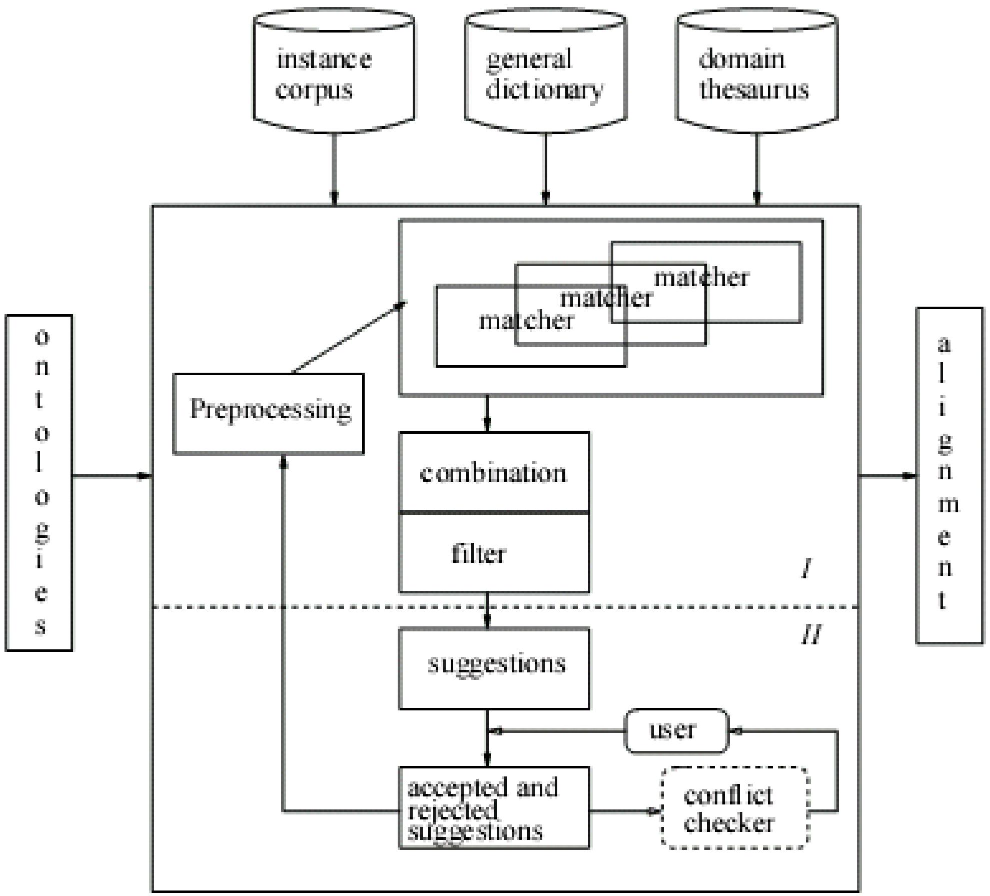
- Evaluation of ontology alignment strategies
- Ontology alignment challenges

An Alignment Framework



Preprocessing

Preprocessing

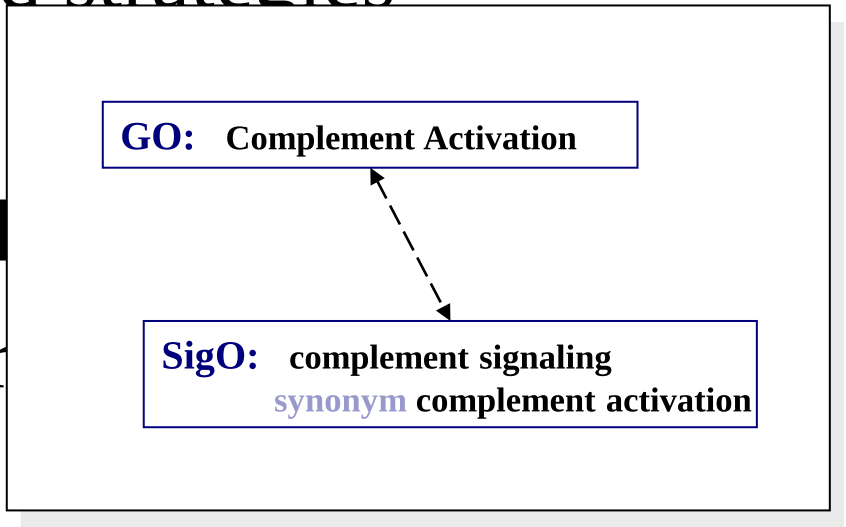
For example,

- Selection of features
- Selection of search space

Matchers

Matcher Strategies

- Strategies based on linguistic matching
- Structure-based strategies
- Constraint-bas
- Instance-based
- Use of auxiliar

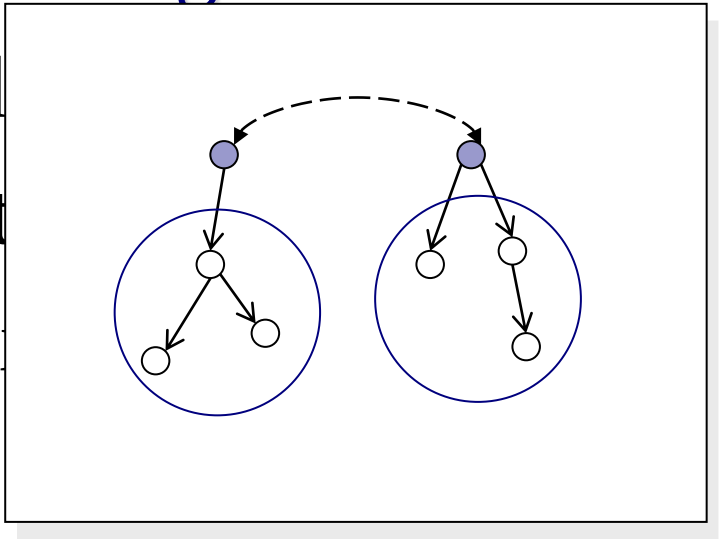


Example matchers

- Edit distance
  - Number of deletions, insertions, substitutions required to transform one string into another
  - aaaa → baab: edit distance 2
- N-gram
  - N-gram : N consecutive characters in a string
  - Similarity based on set comparison of n-grams
  - aaaa : {aa, aa, aa};   baab : {ba, aa, ab}

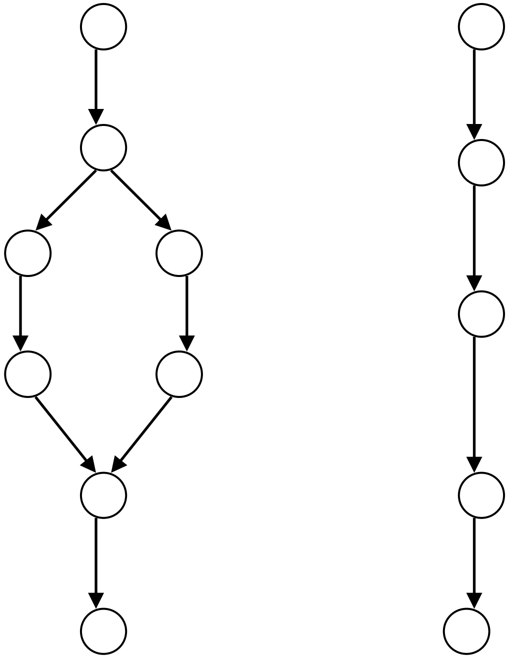
Matcher Strategies

- Strategies based on linguistic matching
- Structure-based strategies
- Constraint-based
- Instance-based st
- Use of auxiliary



Example matchers

- Propagation of similarity values
- Anchored matching



Example matchers

- Propagation of similarity values
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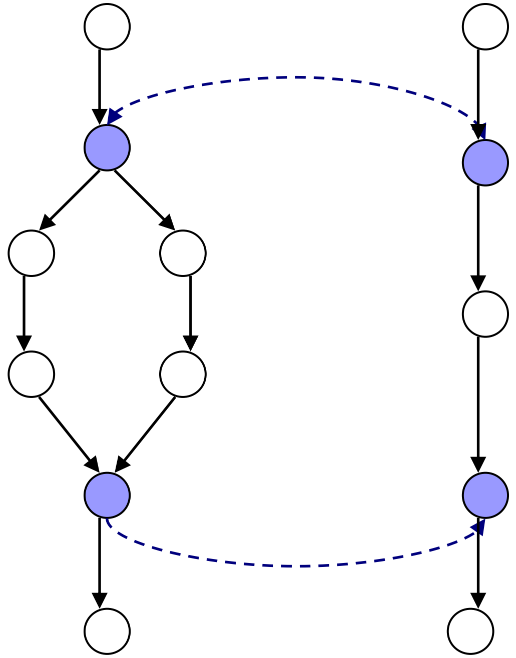

Example matchers

- Propagation of similarity values
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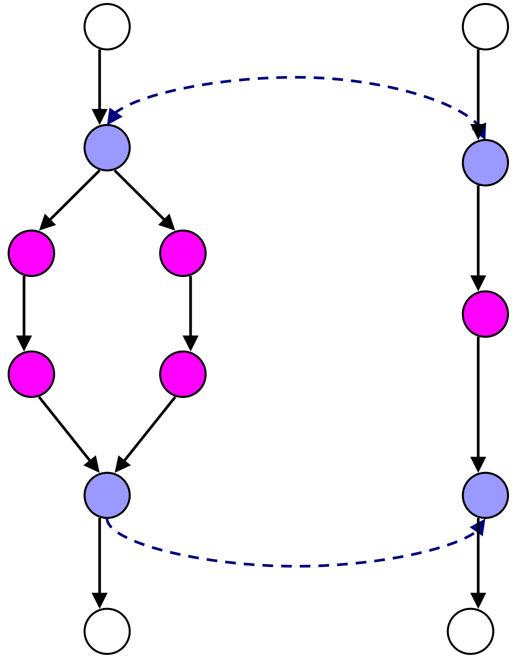

Matcher Strategies

- Strategies based on linguistic matching
- Structure-based strategies
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- Instance-based s
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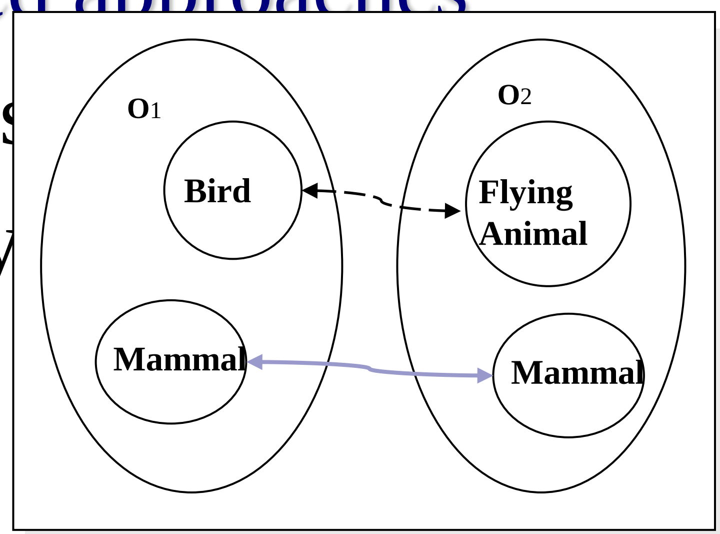

Matcher Strategies

- Strategies based on linguistic matching
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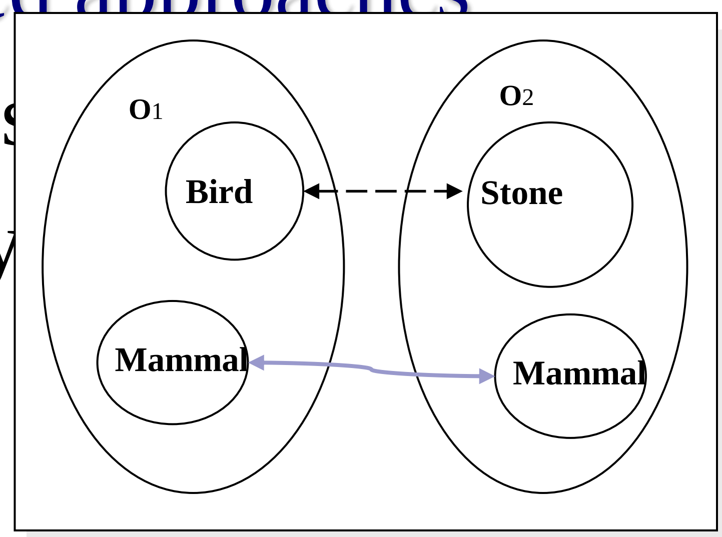
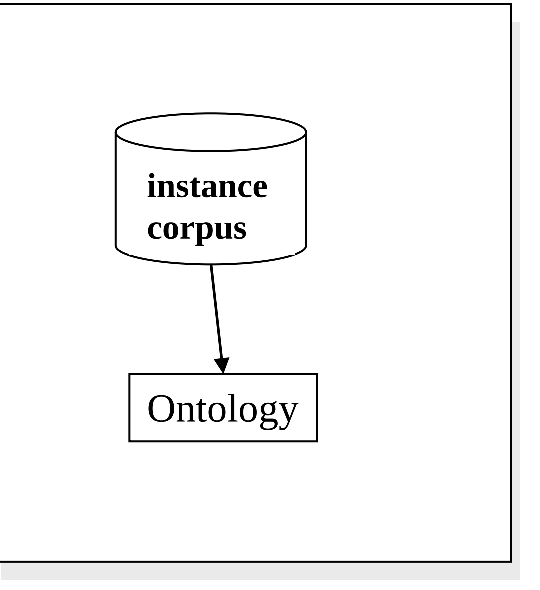


Example matchers

- Similarities between data types
- Similarities based on cardinalities

Matcher Strategies

- Strategies based on linguisti
- Structure-based strategies
- Constraint-based approache
- Instance-based strategies
- Use of auxiliary information



Example matchers

- Instance-based
- Use life science literature as instances

Learning matchers – instance-based strategies

- Basic intuition

  A similarity measure between concepts can be computed based on the probability that documents about one concept are also about the other concept and vice versa.

Learning matchers - steps

- Generate corpora
  - Use concept as query term in PubMed
  - Retrieve most recent PubMed abstracts
- Generate text classifiers
  - One classifier per ontology / One classifier per concept
- Classification
  - Abstracts related to one ontology are classified by the other ontology's classifier(s) and vice versa
- Calculate similarities

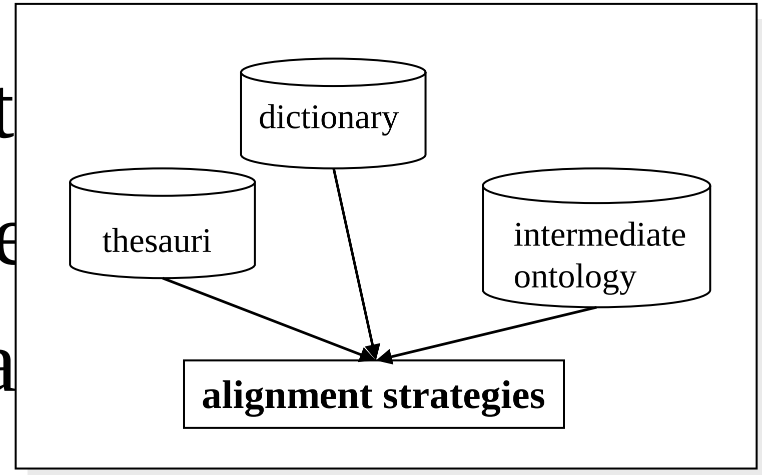
Basic Naïve Bayes matcher

- Generate corpora
- Generate classifiers
  - Naive Bayes classifiers, one per ontology
- Classification
  - Abstracts related to one ontology are classified to the concept in the other ontology with highest posterior probability P(C|d)
- Calculate similarities

$$sim(C_1, C_2) = \frac{n_{NBC2}(C_1, C_2) + n_{NBC1}(C_2, C_1)}{n_D(C_1) + n_D(C_2)}$$

Matcher Strategies

- Strategies based linguist
- Structure-based strategie
- Constraint-based approa
- Instance-based strategies
- Use of auxiliary information



Example matchers

- Use of WordNet
  - Use WordNet to find synonyms
  - Use WordNet to find ancestors and descendants in the is-a hierarchy
- Use of Unified Medical Language System (UMLS)
  - Includes many ontologies
  - Includes many alignments (not complete)
  - Use UMLS alignments in the computation of the similarity values

Table 7 Matching Strategies in the participating systems - 1

System	String-based strategies	Structure-based strategies	Constraint-based strategies	Instance-based strategies
AgreementMaker	SubString, Edit-Distance, TF-IDF	✓	✓	✓
ALIN	SimMetrics API[a] , WS4J API[b]	✓	-	-
AML	Jaccard, I-Sub	✓	✓	✓
Anchor-Flood	Jaro-Winkler	✓	-	✓
AOAS	Jaro-Winkler	✓	-	-
AOT, AOTL	Edit-Distance, Block-Distance, SLIM-Winkler, Jaro-Winkler, Smith-Winkler, Needleman-Wunsch	-	-	-
AROMA	Jaro-Winkler	✓	✓	-
ASMOV	Edit-Distance	✓	✓	✓
BLOOMS	Jaccard, Exact Match, Lin, Jaro-Winkler	-	-	-
CIDER-CL	Soft TF-IDF, Jaro-Winkler	✓	-	-
CODI	Edit-Distance, Jaro-Winkler, Cosine, Smith-Waterman, Jaccard, Overlap coefficient	✓	✓	✓
COMMAND	UMBC similarity Model	✓	-	-
CroMatcher	N-Gram, TF-IDF	✓	✓	✓
CSA	Edit-Distance, Wu-Palmer, TF-IDF	✓	-	✓
DKP-AOM, DKP-AOM-Lite	SimMetrics API[a]	✓	✓	-
DSSim	Jaccard, Jaro-Winkler	✓	-	-
Eff2Match	Exact Match, TF-IDF	✓	-	-
Falcon-AO	I-Sub, TF-IDF	✓	-	-
FCA-Map	Exact Match	✓	-	-
GeRoMeSuite+SMB	Edit-Distance, Jaro-Winkler, I-Sub, Soft TF-IDF, SecondString Library[c]	✓	-	✓
GMap	Edit-Distance, TF-IDF	✓	-	-
GOMMA, GOMMA-bk	Exact Match, N-gram	✓	-	✓
Hertuda	Damerau-Levenshtein[d]	-	-	-
HotMatch	Damerau-Levenshtein[d]	✓	✓	✓
IAMA	Edit-Distance	-	-	✓

Dragisic Z, Ivanova V, Li H, Lambrix P,
Experiences from the Anatomy track in the Ontology Alignment Evaluation Initiative,
Journal of Biomedical Semantics 8:56, 2017

Table 8 Matching strategies in the participating systems - 2

System	String-based strategies	Structure-based strategies	Constraint-based strategies	Instance-based strategies
JarvisOM	Cosine, WuPalmer, Lin, N-gram	-	-	-
KOSIMap	SimMetrics APP, Degree of commonality coefficient	✓	✓	-
Lily	Edit-Distance	✓	✓	✓
LogMap	I-Sub	✓	-	✓
LPHOM	I-Sub, Mongue-Elkan, 3-Gram, Jaccard, Lin	-	-	-
LYAM++	SOFT TF-IDF, Jaccard	✓	-	-
MaasMatch	Cosine, Edit-Distance, Jaccard, 3-Gram, Longest Common Substring	✓	-	✓
MapSSS	Edit-Distance, Choice based on [10]	✓	✓	-
NBJLM	Set of words-level	✓	-	-
ODGOMS	Longest Common Subsequence, SMOA, TF-IDF	✓	-	-
Optima+	Lin, Smith-Waterman, Needleman-Wunsch, Inverse Edit-Distance	✓	-	-
Prior+	Edit-Distance	✓	-	-
RiMOM	Edit-Distance, Cosine	✓	-	✓
RSDLWB	Jaccard, Substring	✓	✓	-
SAMBO, SAMBOdtf	Edit-Distance, 3-Gram	✓	-	✓
ServOMap	Edit-Distance, I-Sub, Q-Gram, TF-IDF, Monge-Elkan, Jaccard	✓	-	-
SOBOM	I-Sub	✓	-	-
StringsAuto	Choice based on [10]	-	-	-
TaxoMap	Lin, 3-gram, Degree of commonality coefficient	✓	✓	-
TOAST	✓[b]	✓	-	-
WeSeE	Edit-Distance, TF-IDF	-	-	-
WikiMatch	Jaccard	-	-	-
X-SOM	Edit-Distance, Jaro	✓	-	✓
XMap	Edit distance, Jaro-Winkler, N-gram, Jaccard, Cosine	✓	✓	-
YAM++	Tversky[c], TF-IDF	✓	-	✓

Table 9 Use of auxiliary information by the participating systems

System	Background knowledge						
	UMLS	Uberon	BioPortal	MeSH	FMA	WordNet	Other
AgreementMaker	✓	✓	-	-	-	✓	-
ALIN	-	-	-	-	-	✓	-
AML	✓	✓		✓		✓	-
Anchor-Flood	-	-	-	-	-	✓	-
AOAS	✓	-	-	-	✓	-	-
AOT, **AOTL**	-	-	-	-	-	✓	-
ASMOV	✓	-	-	-	-	✓	-
COMMAND	✓	-	-	-	-	✓	-
CroMatcher	-	✓	-	-	-	✓	-
CSA	-	-	-	-	-	✓	-
DKP-AOM	-	-	-	-	-	✓	-
DSSim	-	-	-	-	-	✓	-
Eff2Match	-	-	-	-	-	✓	-
GOMMA	✓	✓	-	-	✓	-	-
GeRoMeSuite+SMB	-	-	-	-	-	✓	-
Hotmatch	-	-	-	-	-	-	API lanes[a], WikiPedia, Big Huge Thesaurus[b]
JarvisOM	-	-	-	-	-	✓	Apache Lucene[c]
IAMA	-	-	-	-	-	-	Apache Lucene[c]
Lily	-	-	-	-	-	-	Web search (Google)
LogMapBio	-	-	✓	-	-	-	-
LYAM++	-	✓	-	-	-	-	BabelNet[d]
MaasMatch	-	-	-	-	-	✓	-
MapSSS	-	-	-	-	-	-	Google
NBJLM	-	-	-	-	-	✓	-
Optima+	-	-	-	-	-	✓	-
RiMOM	✓	-	-	-	-	✓	Wiki Pages
RSDLWB	-	-	-	-	-	✓	DBpedia[e]
SAMBO	✓	-	-	-	-	✓	-
ServOMap	-	-	-	-	-	✓	Apache Lucene[c]
TaxoMap	-	-	-	-	-	✓	-
TOAST	-	-	-	-	-	✓	-
WeSeE	-	-	-	-	-	-	Microsoft Bing Search JFreeWebSearch[f]
WikiMatch	-	-	-	-	-	-	WikiPedia
XMap	✓		-	-	-	✓	-
X-SOM	-	-	-	-	-	✓	Google
YAM++	-	-	-	-	-	-	Apache Lucene[c]

Combinations

Combination Strategies

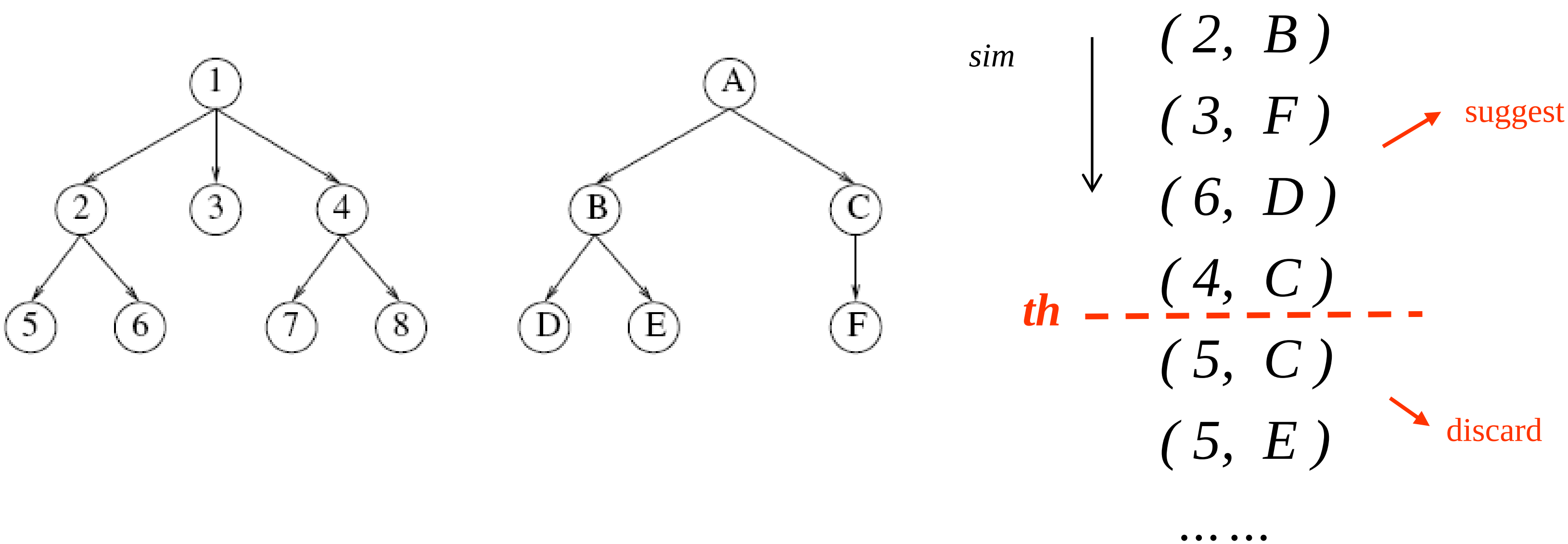
- Usually weighted sum of similarity values of different matchers
- Maximum of similarity values of different matchers

Filtering

Filtering techniques

- Threshold filtering

  Pairs of concepts with similarity higher or equal than threshold are alignment suggestions

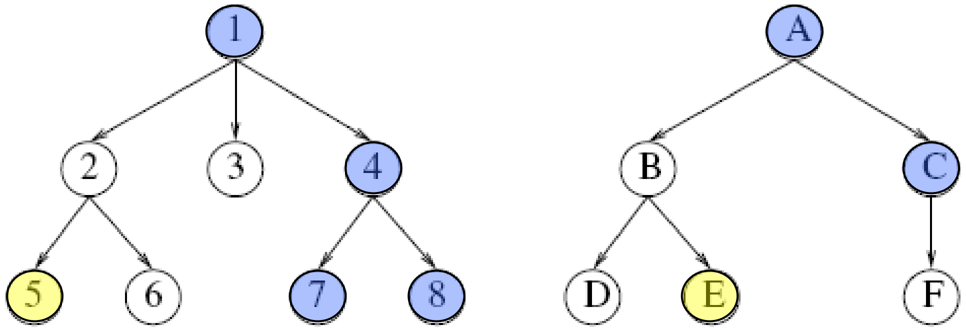


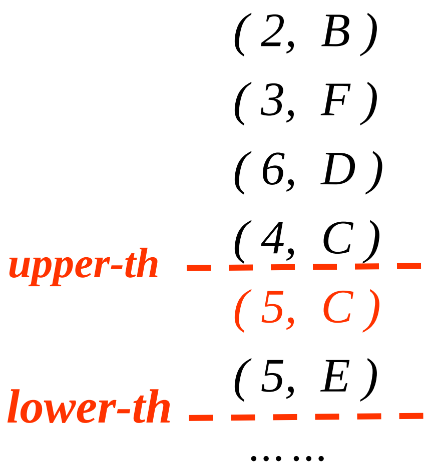
Filtering techniques

- Double threshold filtering

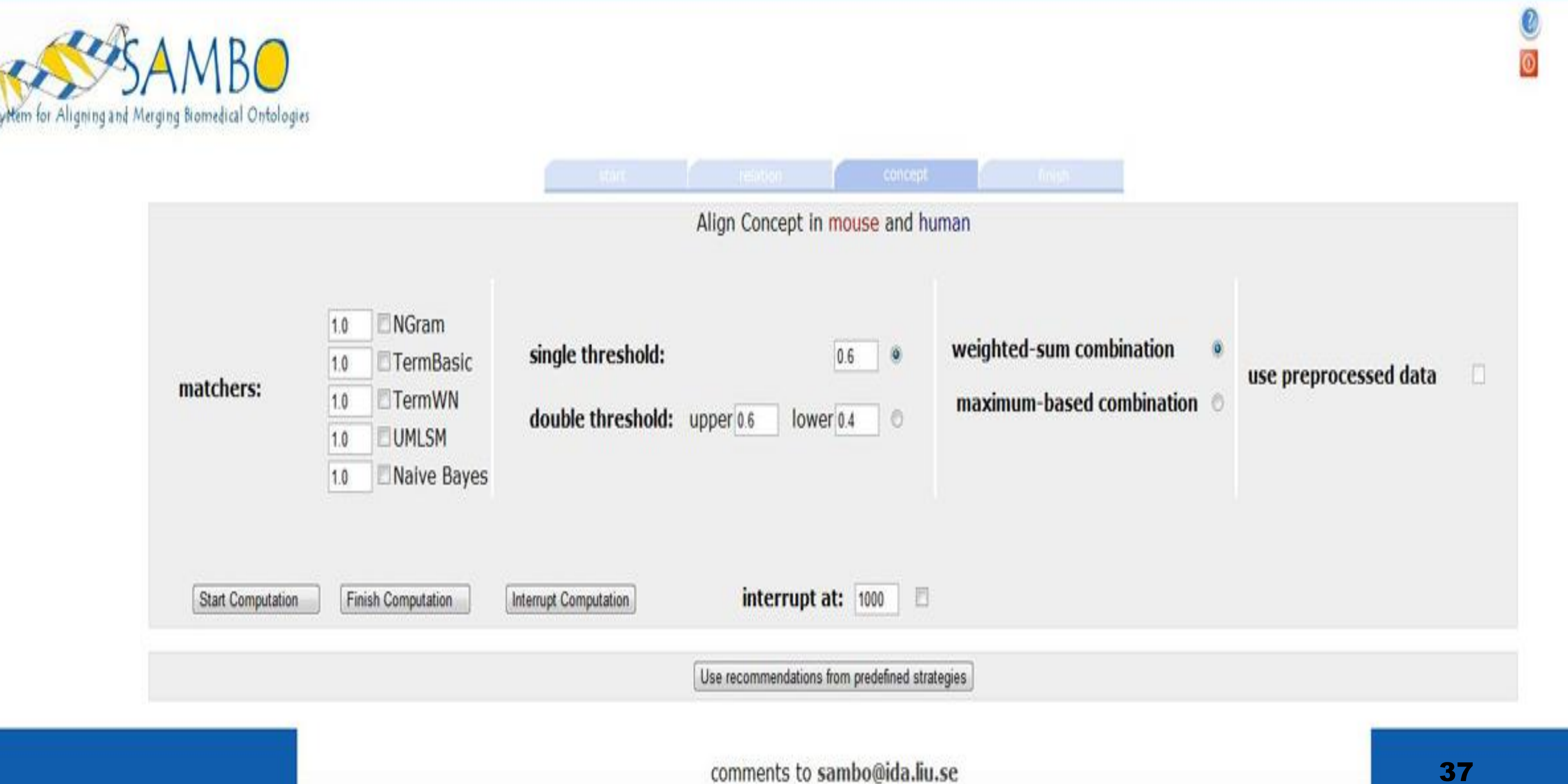
  (1) Pairs of concepts with similarity higher than or equal to **upper** threshold are alignment suggestions

  (2) Pairs of concepts with similarity between **lower** and **upper** thresholds are alignment suggestions if they make sense with respect to the structure of the ontologies and the suggestions according to (1)





Example alignment system SAMBO – matchers, combination, filter



Example alignment system SAMBO – suggestion mode

Table 6 Analysis of the components of the participating systems

Systems	Basic processes					
	Preprocessing[D/R]	Matching	Combination	Filtering	Debugging	User interaction[*]
AgreementMaker	-	✓	✓	✓	-	✓[#]
ALIN	-	✓	✓	✓	-	✓
AML, AML_bk	D	✓	✓	✓	✓	✓[#]
Anchor-Flood	D	✓	✓	✓	-	-
AOAS	-	✓	✓	✓	-	-
AOT, AOTL	-	✓	✓	✓	-	-
AROMA	D	✓	✓	✓	-	-
ASMOV	-	✓	✓	✓	✓	✓
BLOOMS	D	✓	✓	✓	-	-
CIDER-CL	D	✓	✓	✓	-	-
CODI	D	✓	✓	✓	✓	-
COMMAND	-	✓	✓	✓	-	-
CroMatcher	D	✓	✓	✓	-	-
CSA	D	✓	✓	✓	-	-
DKP-AOM, DKP-AOM-Lite	D	✓	✓	✓	✓	-
DSSim	R	✓	✓	✓	-	-
Eff2Match	D	✓	✓	✓	-	-
Falcon-AO	R	✓	✓	✓	-	✓[#]
FCA-Map	D	✓	-	-	✓	-
GeRoMeSuite+SMB	-	✓	✓	✓	✓	✓[#]
GMap	-	✓	✓	✓	-	-
GOMMA, GOMMAbk	R	✓	✓	✓	✓	✓(#)[1]
Hertuda	D	✓	-	✓	-	✓
HotMatch	D	✓	✓	✓	-	-
IAMA	D	✓	✓	✓	-	-

Dragisic Z, Ivanova V, Li H, Lambrix P,
Experiences from the Anatomy track in the Ontology Alignment Evaluation Initiative,
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JarvisOM	D	✓	✓	✓	-	✓
KOSIMap	D	✓	✓	✓	✓	-
Lily	D	✓	✓	✓	✓	✓*
LogMap, LogMapBio, LogMapC, LogMapLite	D,R	✓	✓	✓	✓	✓*
LPHOM	D	✓	✓	✓	-	-
LYAM++	D	✓	-	✓	-	-
MaasMatch	D	✓	✓	✓	-	-
MapSSS	-	✓	✓	✓	-	-
NBJLM	-	✓	✓	✓	-	-
ODGOMS	D	✓	✓	✓	-	-
Optima+	-	✓	✓	✓	-	-
Prior+	D	✓	✓	✓	-	-
RiMOM	D	✓	✓	✓	-	-
RSDLWB	D	✓	✓	-	-	✓*
SAMBO, SAMBOdtf	-	✓	✓	✓	✓	✓*
ServOMap(L), ServOMBI	D	✓	✓	✓	✓	✓
SOBOM	-	✓	✓	✓	-	-
StringsAuto	-	✓	✓	✓	-	-
TaxoMap	D,R	✓	✓	✓	-	-
TOAST	-	✓	-	-	-	-
WeSeE	D	✓	-	✓	-	✓
WikiMatch	D	✓	-	✓	-	-
X-SOM	-	✓	✓	✓	✓	-
XMap, XMAPGen, XMAPSig	-	✓	✓	✓	-	✓
YAM++	D	✓	✓	✓	✓	-

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Evaluation measures

- Precision:

$$\frac{\text{\# correct mapping suggestions}}{\text{\# mapping suggestions}}$$

- Recall:

$$\frac{\text{\# correct mapping suggestions}}{\text{\# correct mappings}}$$

- F-measure: combination of precision and recall

Ontology Alignment Evaluation Initiative

http://oaei.ontologymatching.org/

OAEI

- Since 2004, Evaluation of *systems*
- Different tracks (2020)
  - Ontologies
    - Anatomy, conference, large biomedical ontologies, disease and phenotype, biodiversity and ecology
    - Multilingual: multifarm (9 languages)
    - Complex
    - Interactive
  - Instance matching and link discovery
  - Knowledge graphs

OAEI

- Evaluation measures
  - Precision/recall/f-measure
  - recall of non-trivial mappings

  - full / partial golden standard

OAEI 2019

- 12 systems
- Anatomy:
  - best system f=0.943, p=0.95, r=0.936, r+=0.832, 76 seconds (42s in 2018)
  - 4 systems produce coherent mappings (5 in 2018)

OAEI Anatomy Track 2007-2016*

- Components
  - Almost all systems implement preprocessing, matchers, combination, filtering components
  - Debugging component and GUI rarely implemented
- Matching strategies
  - Variety of string-based strategies
  - Most often string and structured-based strategies
- Use of background knowledge
  - Almost all systems use sources of background knowledge

* Dragisic Z, Ivanova V, Li H, Lambrix P, Experiences from the Anatomy track in the Ontology Alignment Evaluation Initiative, *Journal of Biomedical Semantics* 8:56, 2017.

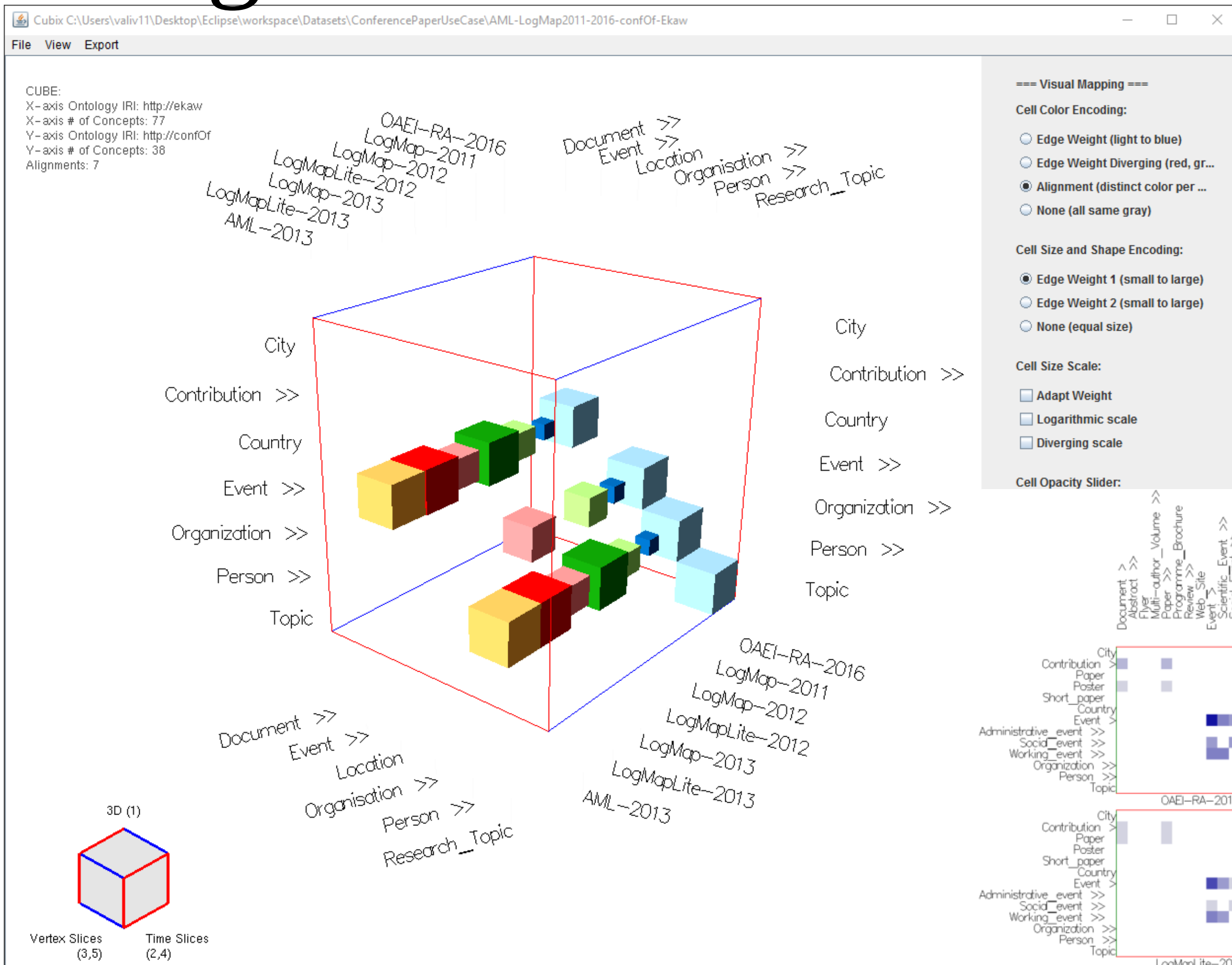
Complementary evaluation

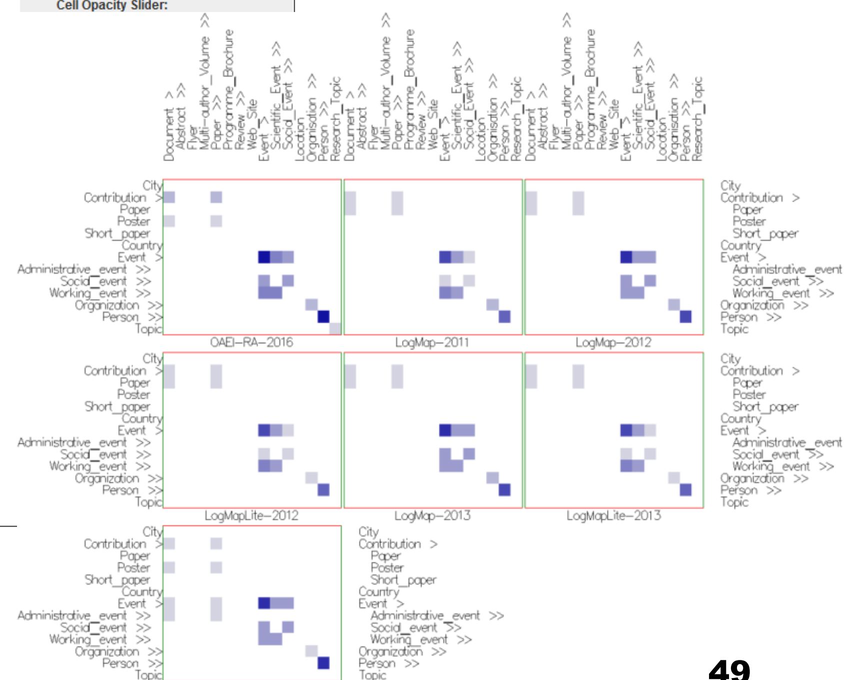
Alignment cubes

- Interactive visualization of alignments
- Region-level, mapping level
- Missing mappings
- Often found mappings

- http://www.ida.liu.se/~patla00/research/AlignmentCubes/

Alignment cubes





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Challenges

- Large-scale matching evaluation
- Efficiency of matching techniques
  - parallellization
  - distribution of computation
  - approximation of matching results (not complete)
  - modularization of ontologies
  - optimization of matching methods

Challenges

- Matching with background knowledge
  - partial alignments
  - reuse of previous matches
  - use of domain-specific corpora
  - use of domain-specific ontologies

- Matcher selection, combination and tuning
  - recommendation of algorithms and settings

Challenges

- User involvement
  - visualization
  - user feedback

- Explanation of matching results
- Social and collaborative matching
- Alignment management: infrastructure and support

Further reading

Starting points for further studies

Further reading ontology alignment

- http://www.ontologymatching.org
(plenty of references to articles and systems)

- Ontology alignment evaluation initiative: http://oaei.ontologymatching.org
(home page of the initiative)

- Euzenat, Shvaiko, *Ontology Matching*, Springer, 2007.

- Shvaiko, Euzenat, Ontology Matching: state of the art and future challenges, *IEEE Transactions on Knowledge and Data Engineering* 25(1):158-176, 2013.

- Dragisic Z, Ivanova V, Li H, Lambrix P, Experiences from the Anatomy track in the Ontology Alignment Evaluation Initiative, *Journal of Biomedical Semantics* 8:56, 2017.

Further reading ontology alignment

Systems at LiU / IDA / ADIT

- Lambrix, Tan, SAMBO – a system for aligning and merging biomedical ontologies, *Journal of Web Semantics*, 4(3):196-206, 2006.

(description of the SAMBO tool and overview of evaluations of different matchers)

- Lambrix, Tan, A tool for evaluating ontology alignment strategies, *Journal on Data Semantics*, VIII:182-202, 2007.

(description of the KitAMO tool for evaluating matchers)

- Lambrix P, Kaliyaperumal R, A Session-based Ontology Alignment Approach enabling User Involvement, *Semantic Web Journal* 8(2):225-251, 2017.

- Ivanova V, Bach B, Pietriga E, Lambrix P, Alignment Cubes: Towards Interactive Visual Exploration and Evaluation of Multiple Ontology Alignments, 16th International Semantic Web Conference, 400-417, 2017.

Further reading ontology alignment

- Chen, Tan, Lambrix, Structure-based filtering for ontology alignment,*IEEE WETICE workshop on semantic technologies in collaborative applications*, 364-369, 2006.

(double threshold filtering technique)

- Tan, Lambrix, A method for recommending ontology alignment strategies, *International Semantic Web Conference*, 494-507, 2007.

  Ehrig, Staab, Sure, Bootstrapping ontology alignment methods with APFEL, *International Semantic Web Conference*, 186-200, 2005.

  Mochol, Jentzsch, Euzenat, Applying an analytic method for matching approach selection, *International Workshop on Ontology Matching*, 2006.

(recommendation of alignment strategies)

- Lambrix, Liu, Using partial reference alignments to align ontologies, *European Semantic Web Conference*, 188-202, 2009.

(use of partial alignments in ontology alignment)

Further reading ontology alignment

User Involvement

- Li H, Dragisic Z, Faria D, Ivanova V, Jimenez-Ruiz E, Lambrix P, Pesquita C, User validation in ontology alignment: functional assessment and impact, *The Knowledge Engineering Review*, 2019.

- Ivanova V, Lambrix P, Åberg J, Requirements for and Evaluation of User Support for Large-Scale Ontology Alignment, *12th Extended Semantic Web Conference - ESWC 2015*, LNCS 9088, 3-20, 2015.

Ontology Completion and Debugging

Defects in ontologies

- Syntactic defects
  - E.g. wrong tags or incorrect format
- Semantic defects
  - E.g. unsatisfiable concepts, incoherent and inconsistent ontologies
- Modeling defects
  - E.g. wrong or missing relations

Example - incoherent ontology

- Example: DICE ontology
  - Brain $\sqsubseteq$ CentralNervousSystem $\sqcap$ BodyPart $\sqcap$ $\exists$systempart.NervousSystem $\sqcap$ $\exists$ region.HeadAndNeck $\sqcap$ $\forall$region.HeadAndNeck

    A brain is a central nervous system and a body part which has a system part that is a nervous system and that is in the head and neck region.

  - CentralNervousSystem $\sqsubseteq$ NervousSystem

    A central nervous system is a nervous system.

  - BodyPart $\sqsubseteq \neg$NervousSystem

Nothing can be at the same time a body part and a nervous system.

Slide from G. Qi

Example - inconsistent ontology

- **Example from Foaf:**
  - **Person(timbl)**
  - **Homepage(timbl, http://w3.org/)**
  - **Homepage(w3c, http://w3.org/)**
  - **Organization(w3c)**
  - **InverseFunctionalProperty(Homepage)**
  - **DisjointWith(Organization, Person)**
- **Example from OpenCyc:**
  - **ArtifactualFeatureType(PopulatedPlace)**
  - **ExistingStuffType(PopulatedPlace)**
  - **DisjointWith(ExistingObjectType,ExistingStuffType)**
  - **ArtifactualFeatureType $\sqsubseteq$ ExistingObjectType**

Slide from G. Qi

Example - missing is-a relations

- In 2008 Ontology Alignment Evaluation Initiative (OAEI) Anatomy track, task 4
  - Ontology MA : Adult Mouse Anatomy Dictionary (2744 concepts)
  - Ontology NCI-A : NCI Thesaurus - anatomy (3304 concepts)
  - 988 mappings between MA and NCI-A
    - 121 missing is-a relations in MA
    - 83 missing is-a relations in NCI-A

Influence of missing structure

- Ontology-based querying.

Medical Subject Headings (MeSH)

All MeSH Categories
- **Diseases Category**
  - **Eye Diseases**
    - **Scleral Diseases**
      - **Scleritis**

...

return 1617 articles

Influence of missing structure

- Incomplete results from ontology-based queries

Medical Subject Headings (MeSH)

All MeSH Categories

Diseases Category

Eye Diseases

Scleral Diseases

Scleritis

...

return 1617 articles

return 695 articles

57% results are missed !

Defects in ontologies and ontology networks

- Ontologies and ontology networks with defects, although often useful, also lead to problems when used in semantically-enabled applications.

→ Wrong conclusions may be derived or valid conclusions may be missed.

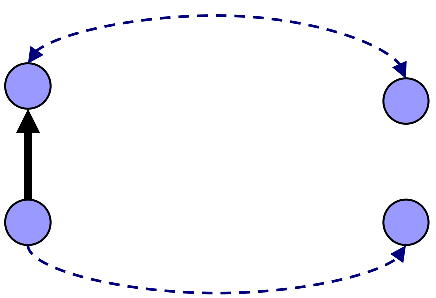
Completion and debugging process

- Detection (find candidate defects)
- Validation (real defects)
- Repair (remove wrong, add correct)

Detection

Many approaches

- inspection
- ontology learning or evolution
- using linguistic and logical patterns
  - animals *such as* dogs and cats
- by using knowledge intrinsic to an ontology network



- by using machine learning and statistical methods

Repairing

Definition 1 *(Repair) Let* T *be a TBox and* C *be the set of all atomic concepts in* T. *Let* M *and* W *be finite sets of TBox axioms. Let* Or *be an oracle that given a TBox axiom returns true or false. A repair for Complete-Debug-Problem CDP*(T, C, Or, M, W) *is any pair of finite sets of TBox axioms* (A, D) *such that*
(i) $\forall\ \psi_a \in A$: $Or(\psi_a) = true$;
(ii) $\forall\ \psi_d \in D$: $Or(\psi_d) = false$;
(iii) $(T \cup A) \setminus D$ *is consistent;*
(iv) $\forall\ \psi_m \in M$: $(T \cup A) \setminus D \models \psi_m$;
(v) $\forall\ \psi_w \in W$: $(T \cup A) \setminus D \not\models \psi_w$.

Current work usually focuses on debugging or completion, but not both.
Most work on debugging.

Ontology Debugging

Example : an Incoherent Ontology

Consider the following TBox $\mathcal{T}^*$, where A, B and C are primitive and $A_1, \ldots, A_7$ defined concept names:

$ax_1: A_1 \dot{\sqsubseteq} \neg A \sqcap A_2 \sqcap A_3$	$ax_2: A_2 \dot{\sqsubseteq} A \sqcap A_4$
$ax_3: A_3 \dot{\sqsubseteq} A_4 \sqcap A_5$	$ax_4: A_4 \dot{\sqsubseteq} \forall s.B \sqcap C$
$ax_5: A_5 \dot{\sqsubseteq} \exists s.\neg B$	$ax_6: A_6 \dot{\sqsubseteq} A_1 \sqcup \exists r.(A_3 \sqcap \neg C \sqcap A_4)$
$ax_7: A_7 \dot{\sqsubseteq} A_4 \sqcap \exists s.\neg B$	

⇓

DL Reasoner ⇒ The ontology is incoherent!
The set of unsatisfiable concepts are : $\{A_1, A_3, A_6, A_7\}$.

What are the root causes of these defects?

Explain the Semantic Defects

- We need to identify the sets of axioms which are necessary for causing the logic contradictions.

$ax_1: A_1 \dot{\sqsubseteq} \neg A \sqcap A_2 \sqcap A_3$	$ax_2: A_2 \dot{\sqsubseteq} A \sqcap A_4$
$ax_3: A_3 \dot{\sqsubseteq} A_4 \sqcap A_5$	$ax_4: A_4 \dot{\sqsubseteq} \forall s.B \sqcap C$
$ax_5: A_5 \dot{\sqsubseteq} \exists s.\neg B$	$ax_6: A_6 \dot{\sqsubseteq} A_1 \sqcup \exists r.(A_3 \sqcap \neg C \sqcap A_4)$
$ax_7: A_7 \dot{\sqsubseteq} A_4 \sqcap \exists s.\neg B$	

  - For example, for the unsatisfiable concept "*A₁*", there are two sets of axioms.

$ax_1: A_1 \dot{\sqsubseteq} \underline{\neg A} \sqcap A_2 \sqcap A_3$
$ax_2: A_2 \dot{\sqsubseteq} \underline{A} \sqcap A_4$

$ax_1: A_1 \dot{\sqsubseteq} \neg A \sqcap A_2 \sqcap \underline{A_3}$
$ax_3: A_3 \dot{\sqsubseteq} \underline{A_4 \sqcap A_5}$
$ax_4: A_4 \dot{\sqsubseteq} \underline{\forall s.B} \sqcap C$
$ax_5: A_5 \dot{\sqsubseteq} \underline{\exists s.\neg B}$

Minimal Unsatisfiability Preserving Sub-TBoxes (MUPS)

Definition 1 Let A be a concept which is unsatisfiable in a TBox $\mathcal{T}$. A set $\mathcal{T}' \subseteq \mathcal{T}$ is a *minimal unsatisfiability-preserving sub-TBox (MUPS)* of $\mathcal{T}$ if

- A is unsatisfiable in $\mathcal{T}'$, and
- A is satisfiable in every sub-TBox $\mathcal{T}'' \subset \mathcal{T}'$.

We will abbreviate the set of MUPS of $\mathcal{T}$ and A by $mups(\mathcal{T}, A)$.

$$mups(\mathcal{T}^*, A_1) = \{\{ax_1, ax_2\}, \{ax_1, ax_3, ax_4, ax_5\}\}$$

- The MUPS of an unsatisfiable concept imply the solutions for repairing.

  → Remove at least one axiom from each axiom set in the MUPS

Example

$$
\begin{aligned}
mups(\mathcal{T}^*, A_1) &= \{\{\cancel{ax_1}, ax_2\}, \{\cancel{ax_1}, \cancel{ax_3}, \cancel{ax_4}, ax_5\}\} \\
mups(\mathcal{T}^*, A_3) &= \{\{\cancel{ax_3}, \cancel{ax_4}, ax_5\}\} \\
mups(\mathcal{T}^*, A_6) &= \{\{\cancel{ax_1}, ax_2, \cancel{ax_4}, ax_6\}, \\
&\quad\ \{\cancel{ax_1}, \cancel{ax_3}, \cancel{ax_4}, ax_5, ax_6\}\} \\
mups(\mathcal{T}^*, A_7) &= \{\{\cancel{ax_4}, ax_7\}\}
\end{aligned}
$$

- Possible ways of repairing all the unsatisfiable concepts in the ontology:

$$\{ax_1, ax_3, ax_4\}$$

How to represent all these possibilities?

Minimal Incoherence Preserving Sub-TBox (MIPS)

Definition 2 Let $\mathcal{T}$ be an incoherent TBox. A TBox $\mathcal{T}' \subseteq \mathcal{T}$ is a *minimal incoherence-preserving sub-TBox (MIPS) of* $\mathcal{T}$ if

- $\mathcal{T}'$ is incoherent, and
- every sub-TBox $\mathcal{T}'' \subset \mathcal{T}'$ is coherent.

$$mups(\mathcal{T}^*, A_1) = \{\{ax_1, \cancel{ax_2}\}, \{ax_1, ax_3, \cancel{ax_4}, ax_5\}\}$$
$$mups(\mathcal{T}^*, A_3) = \{\{ax_3, \cancel{ax_4}, ax_5\}\}$$
$$mups(\mathcal{T}^*, A_6) = \{\{ax_1, \cancel{ax_2}, \cancel{ax_4}, ax_6\}, \{ax_1, ax_3, \cancel{ax_4}, ax_5, ax_6\}\}$$
$$mups(\mathcal{T}^*, A_7) = \{\{\cancel{ax_4}, \cancel{ax_7}\}\}$$

We will abbreviate the set of MIPS of $\mathcal{T}$ by $mips(\mathcal{T})$. For $\mathcal{T}^*$ we get three MIPS:

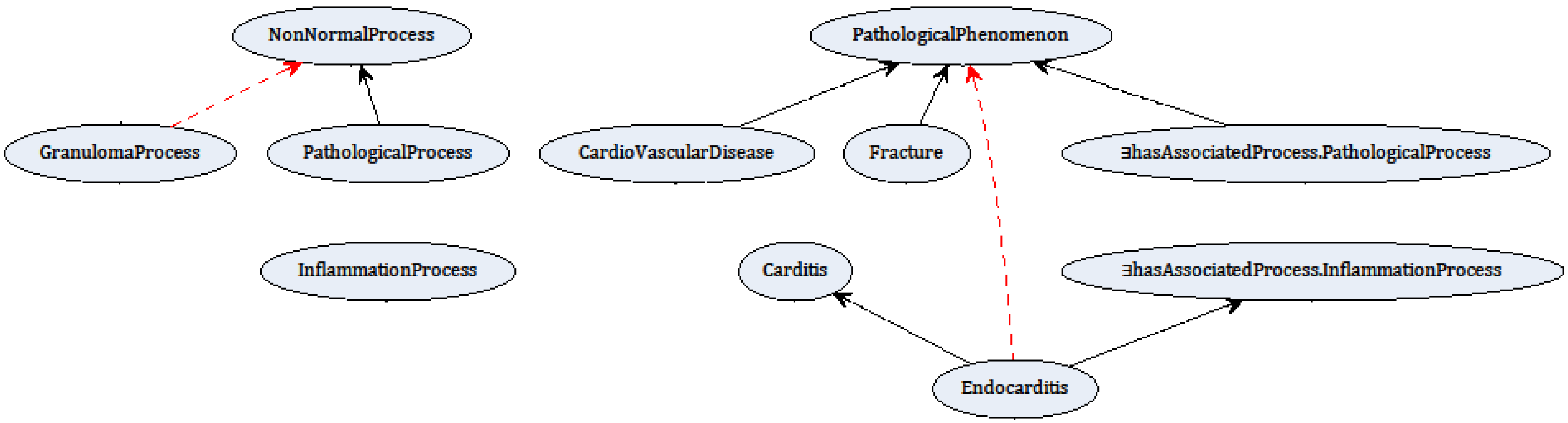
$$mips(\mathcal{T}^*) = \{\{ax_1, ax_2\}, \{ax_3, ax_4, ax_5\}, \{ax_4, ax_7\}\}$$

A possible repairing is $\{ax_i\} \cup \{ax_j\} \cup \{ax_k\}$, where

- $ax_i \in \{ax_1, \cancel{ax_2}\}$
- $ax_j \in \{ax_3, \cancel{ax_4}, ax_5\}$
- $ax_k \in \{ax_4, \cancel{ax_7}\}$

Completing the is-a structure of ontologies

Example



Repairing actions:

$\{\text{Endocarditis} \dot{\sqsubseteq} \text{PathologicalPhenomenon}, \text{GranulomaProcess} \dot{\sqsubseteq} \text{NonNormalProcess}\}$

$\{\text{Carditis} \dot{\sqsubseteq} \text{CardioVascularDisease}, \text{GranulomaProcess} \dot{\sqsubseteq} \text{PathologicalProcess}\}$

$\{\text{Carditis} \dot{\sqsubseteq} \text{Fracture}, \text{GranulomaProcess} \dot{\sqsubseteq} \text{NonNormalProcess}\}$

Description logic EL

- Concepts

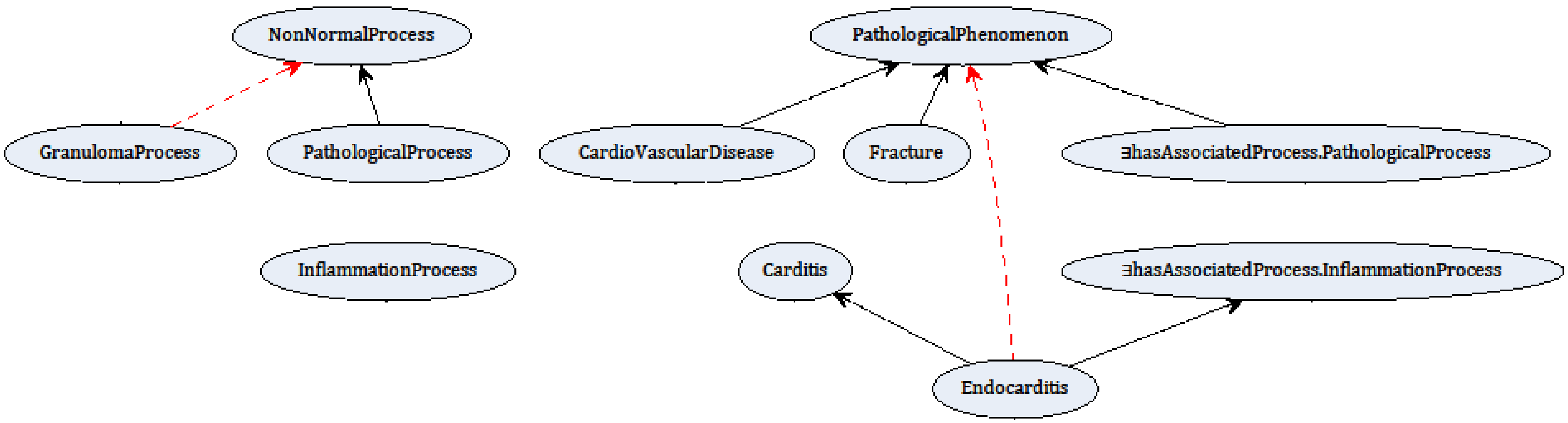
Atomic concept	A
Universal concept	$\top$
Intersection of concepts	$C \sqcap D$
Existential restriction	$\exists r.C$

- Terminological axioms: equivalence and subsumption

Generalized Tbox Abduction Problem – GTAP(**T**,**C**,Or,M)

- Given
  - **T**- a Tbox in EL
  - **C**- a set of atomic concepts in **T**
  - M = $\{A_i \subseteq B_i\}_{i=1..n}$ and $\forall$ i:1..n: A_i, $B_i \in$ **C**
  - Or: $\{C_i \subseteq D_i \mid C_i, D_i \in$ **C**$\} \rightarrow$ {true, false}
- Find
  - S = $\{E_i \subseteq F_i\}_{i=1..k}$ such that
    $\forall$ i:1..k: E_i, $F_i \in$ **C** and Or($E_i \subseteq F_i$) = true
    and T U S is consistent and T U S |= M

GTAP - example



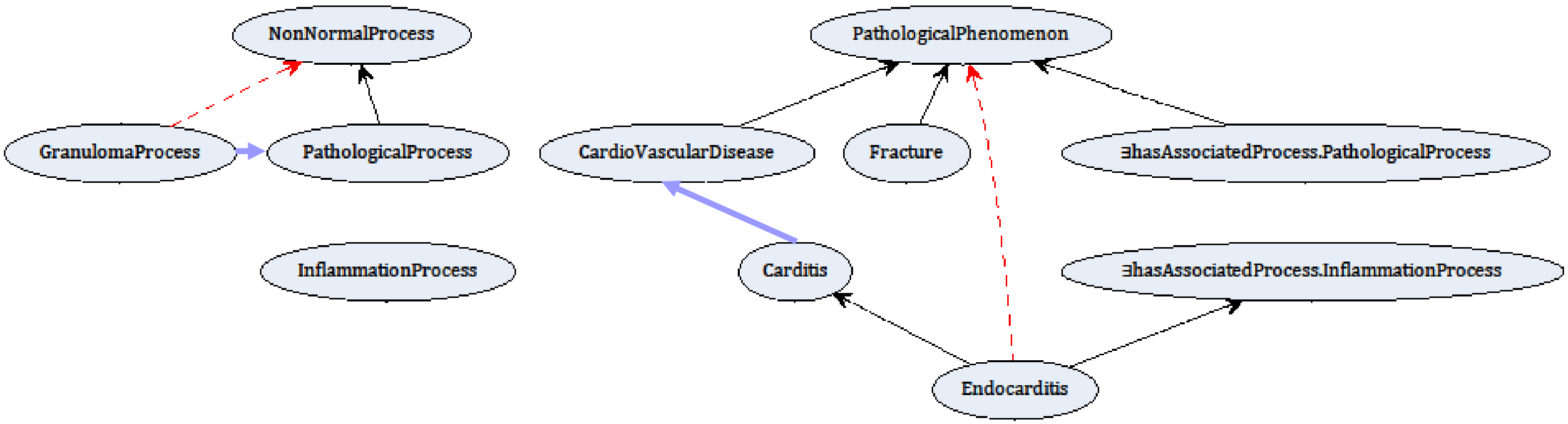
C = { GranulomaProcess, CardioVascularDisease, PathologicalPhenomenon, Fracture, Endocarditis, Carditis, InflammationProcess, PathologicalProcess, NonNormalProcess}

T = { GranulomaProcess $\dot{\sqsubseteq}$ $\top$, hasAssociatedProcess $\dot{\sqsubseteq}$ $\top \times \top$,
CardioVascularDisease $\dot{\sqsubseteq}$ PathologicalPhenomenon, Fracture $\dot{\sqsubseteq}$ PathologicalPhenomenon,
∃hasAssociatedProcess.PathologicalProcess $\dot{\sqsubseteq}$ PathologicalPhenomenon,
Endocarditis $\dot{\sqsubseteq}$ Carditis, Endocarditis $\dot{\sqsubseteq}$ ∃hasAssociatedProcess.InflammationProcess,
PathologicalProcess $\dot{\sqsubseteq}$ NonNormalProcess }

M = { Endocarditis $\dot{\sqsubseteq}$ PathologicalPhenomenon, GranulomaProcess $\dot{\sqsubseteq}$ NonNormalProcess }

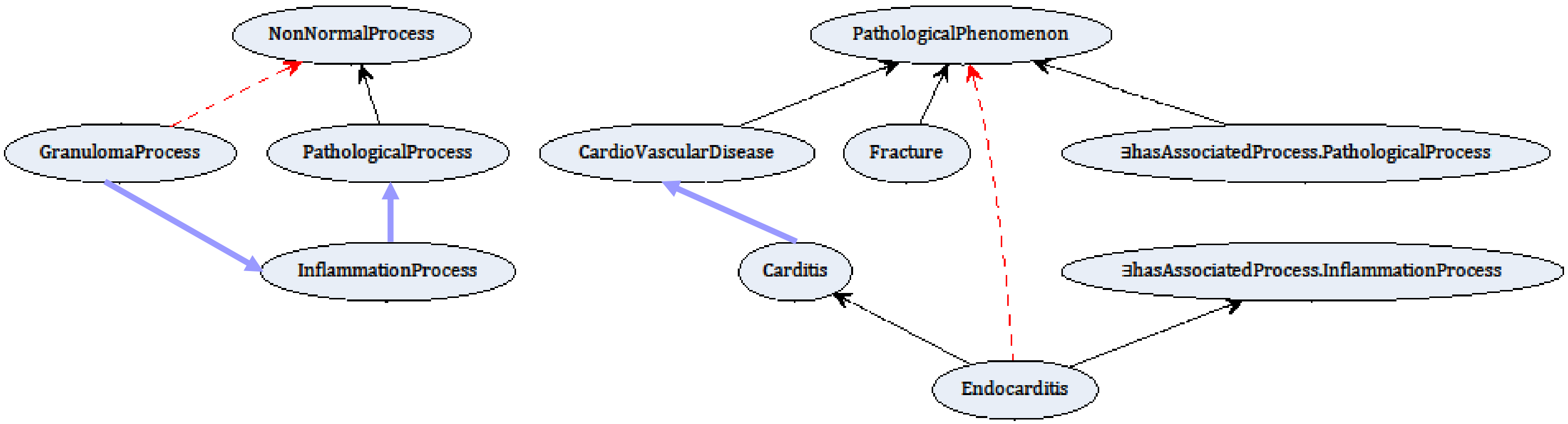
Preference criteria

- There can be many solutions for GTAP



Preference criteria

- There can be many solutions for GTAP



Not all are equally interesting.

More informative

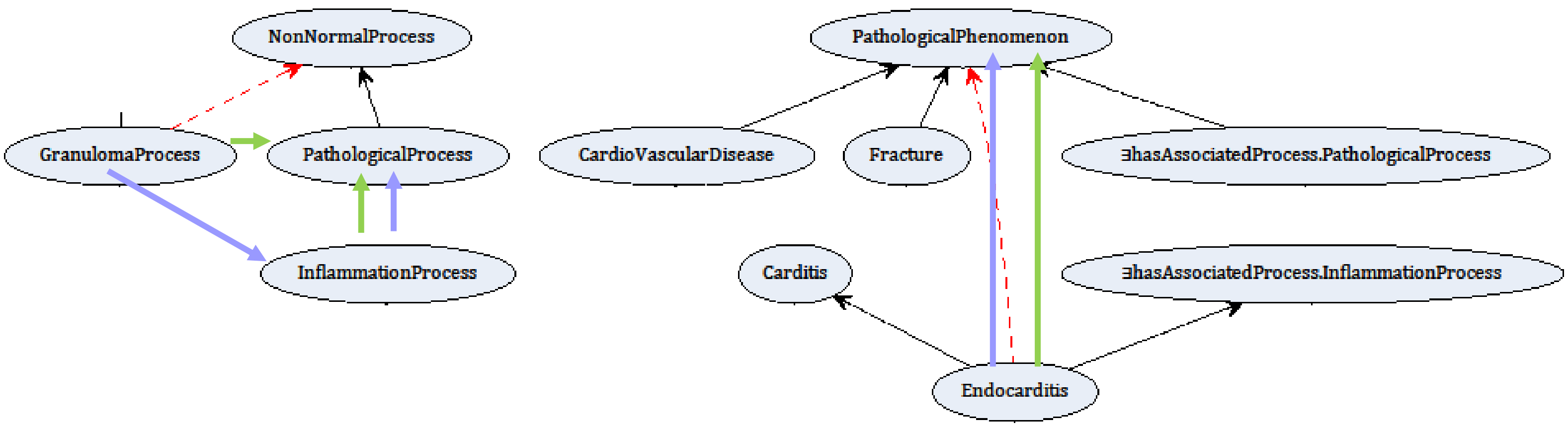
- Let *S* and *S'* be two solutions to GTAP(**T**,**C**,Or,M). Then,

 - *S* is more informative than *S'*
iff **T** U *S* |= *S'* but not **T** U *S'* |= *S*

 - *S* is equally informative as *S'*
iff **T** U *S* |= *S'* and **T** U *S'* |= *S*

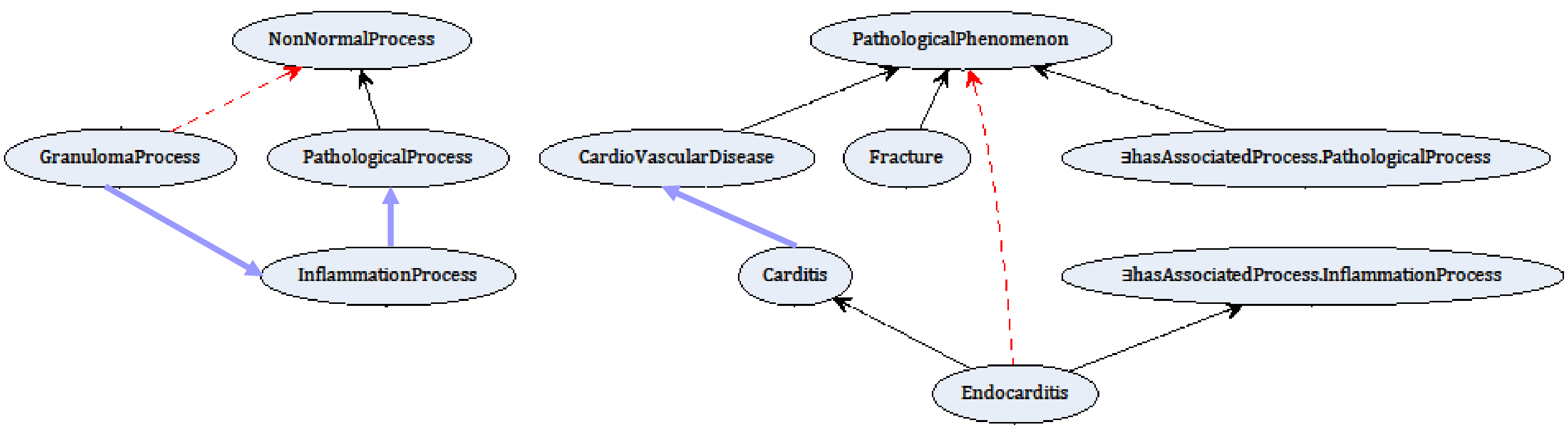
More informative

- ’Blue’ solution is more informative than ’green’ solution



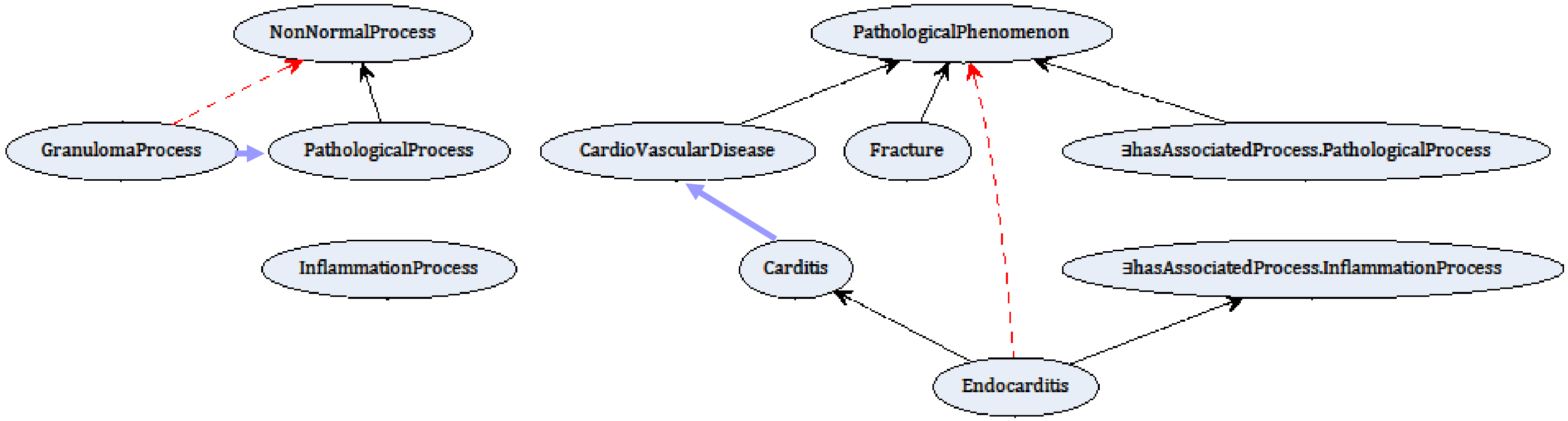
Semantic maximality

- A solution *S* to GTAP(**T**,**C**,Or,M) is semantically maximal iff there is no solution *S*' which is more informative than *S*.



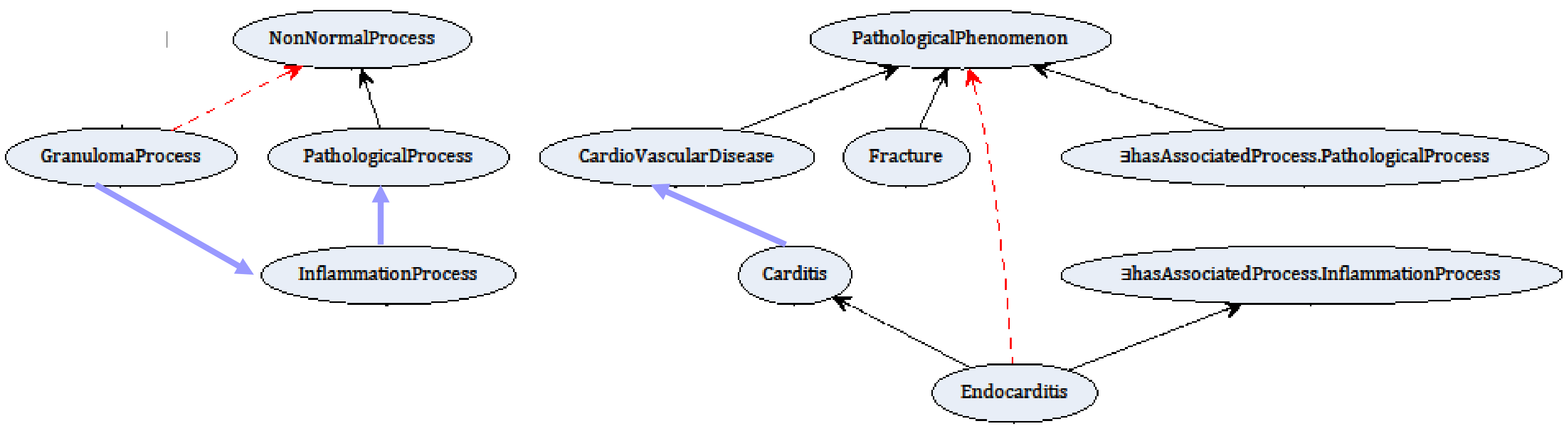
Subset minimality

- A solution *S* to GTAP(**T**,**C**,Or,M) is subset minimal iff there is no proper subset *S*' of *S* that is a solution.



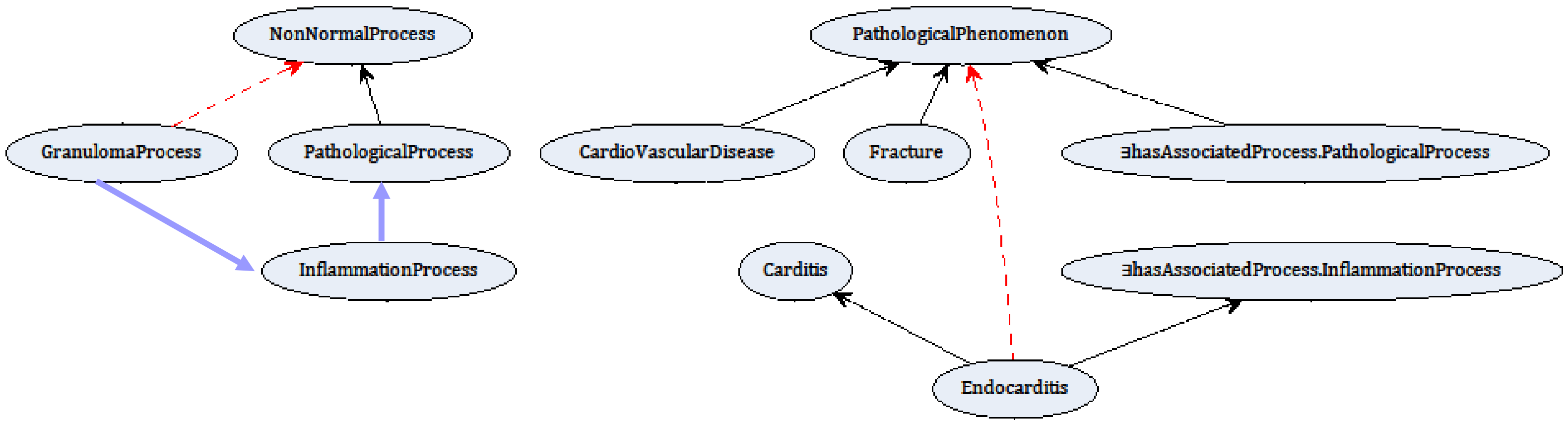
Combining with priority for semantic maximality

- A solution *S* to GTAP(**T**,**C**,Or,M) is maxmin optimal iff *S* is semantically maximal and there is no other semantically maximal solution that is a proper subset of *S*.



Combining with priority for subset minimality

- A solution *S* to GTAP(**T**,**C**,Or,M) is minmax optimal iff *S* is subset minimal and there is no other subset minimal solution that is more informative than *S*.



Combining with equal preferences

- A solution *S* to GTAP(**T**,**C**,Or,M) is skyline optimal iff there is no other solution that is a proper subset of *S* and that is equally informative than *S*.
  - All subset minimal, minmax optimal and maxmin optimal solutions are also skyline optimal solutions.
  - Semantically maximal solutions may or may not be skyline optimal.

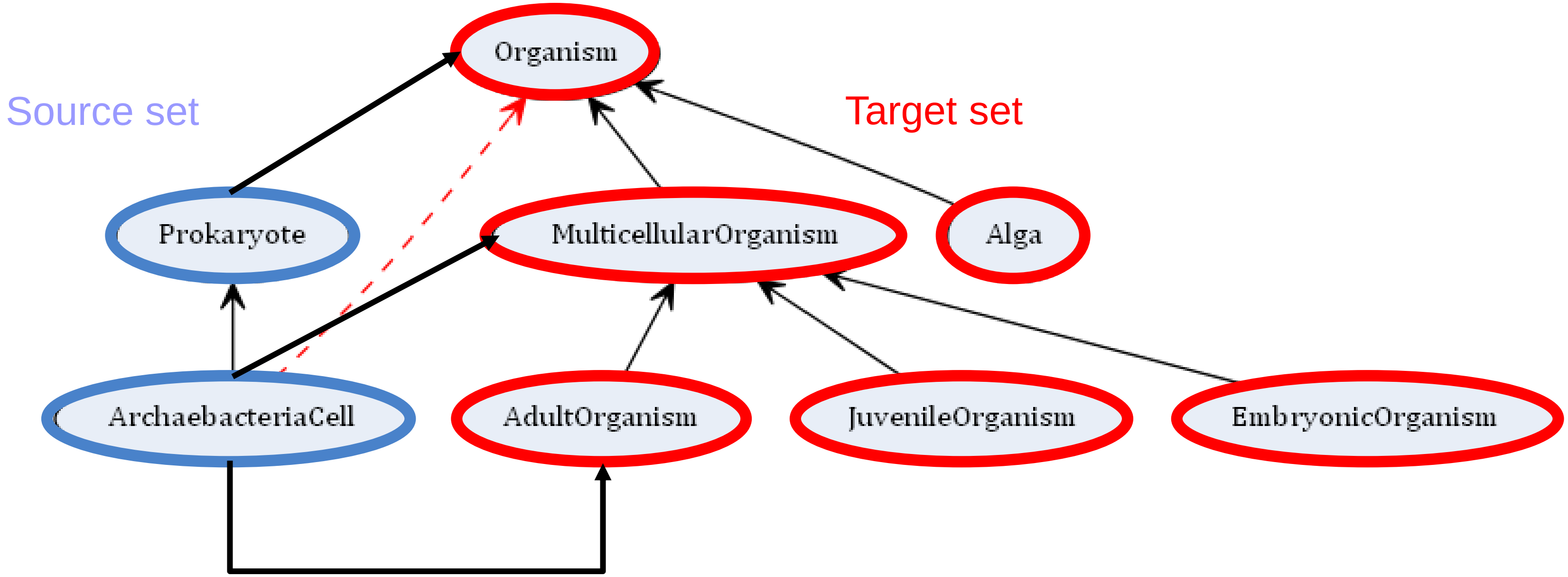
Preference criteria - conclusions

- In practice it is not clear how to generate maxmin or semantically maximal solutions (the preferred solutions)
- Skyline optimal solutions are the next best thing and are easy to generate

Approach

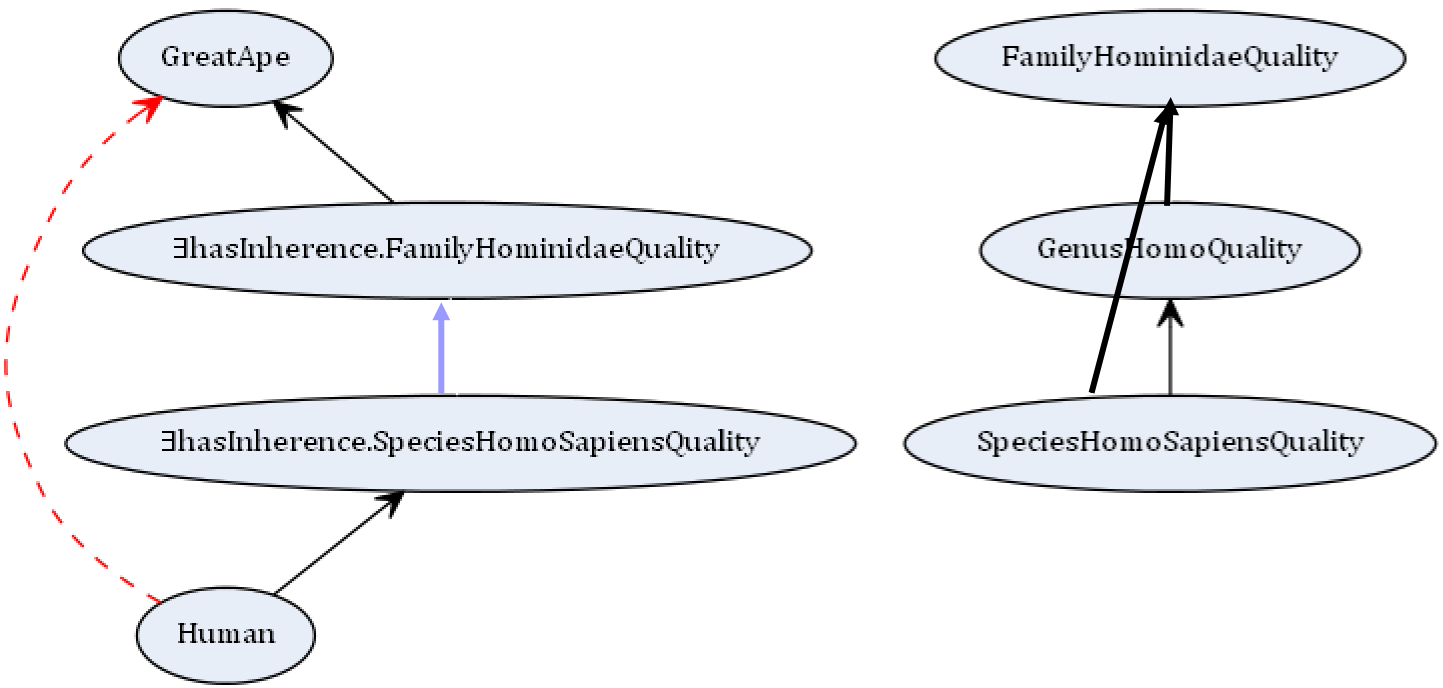
- Input
  - Normalized EL - TBox
  - Set of missing is-a relations (correct according to the domain)
- Output – a skyline-optimal solution to GTAP
- Iteration of three main steps:
  - Creating solutions for individual missing is-a relations
  - Combining individual solutions
  - Trying to improve the result by finding a solution which introduces additional new knowledge (more informative)

Intuition 1

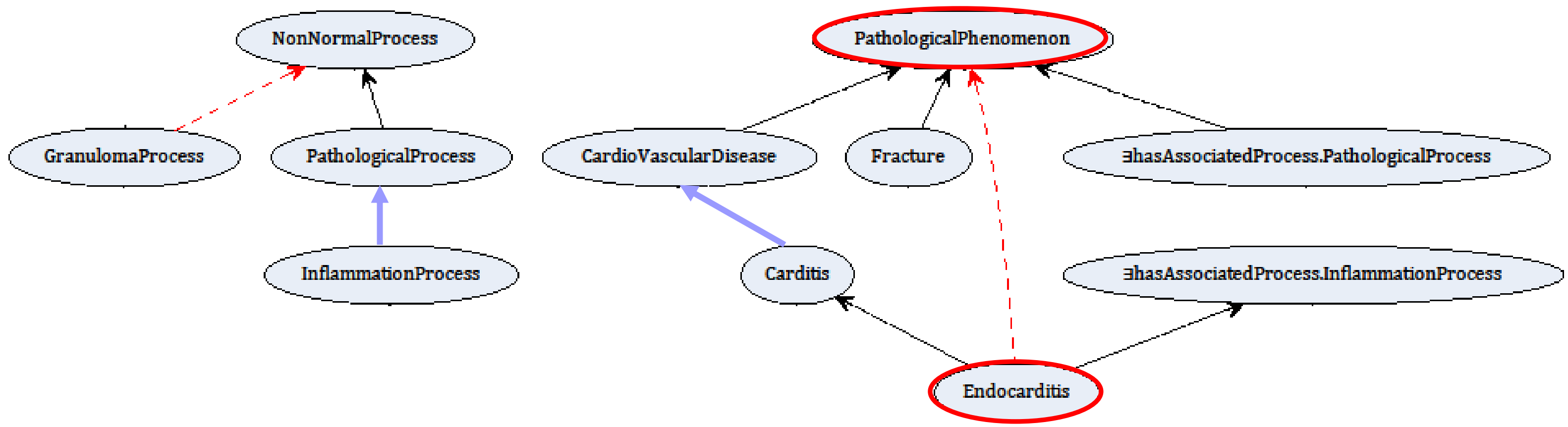


Source set
Target set
Organism
Prokaryote
MulticellularOrganism
Alga
ArchaebacteriaCell
AdultOrganism
JuvenileOrganism
EmbryonicOrganism

Intuitions 2/3



Example – repairing single is–a relation



~~Endocarditis $\dot{\sqsubseteq}$ PathologicalPhenomenon~~

~~Endocarditis $\dot{\sqsubseteq}$ Fracture~~ false

~~Endocarditis $\dot{\sqsubseteq}$ CardioVascularDisease~~

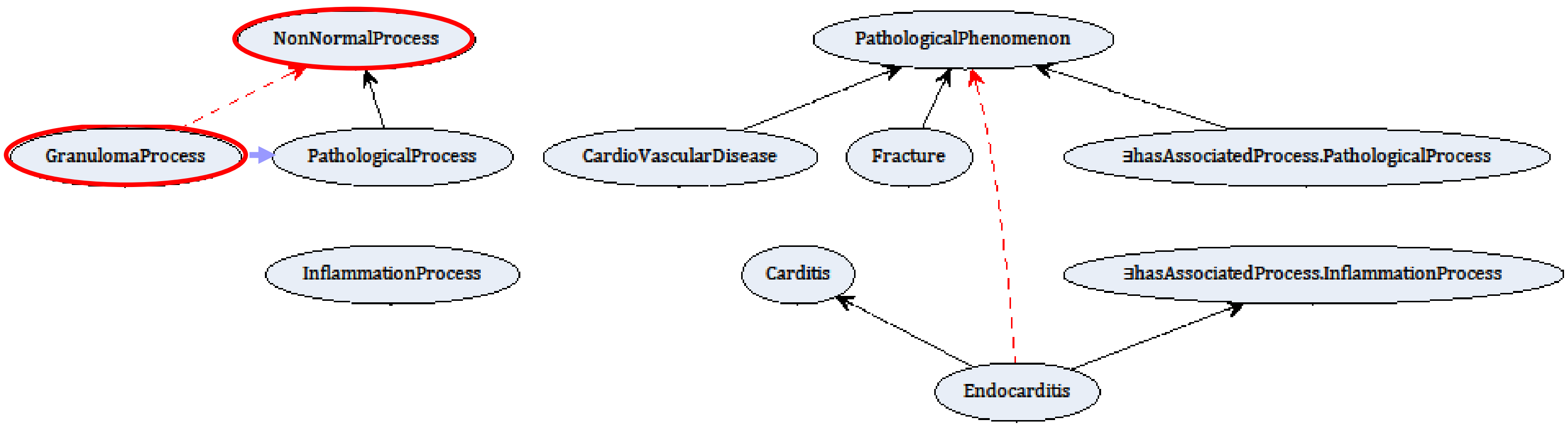
~~Carditis $\dot{\sqsubseteq}$ PathologicalPhenomenon~~

~~Carditis $\dot{\sqsubseteq}$ Fracture~~ false

Carditis $\dot{\sqsubseteq}$ CardioVascularDisease

InflammationProcess $\dot{\sqsubseteq}$ PathologicalProcess

Example – repairing single is–a relation



~~GranulomaProcess $\dot{\sqsubseteq}$ NonNormalProcess~~

GranulomaProcess $\dot{\sqsubseteq}$ PathologicalProcess

Algorithm - Repairing multiple is-a relations

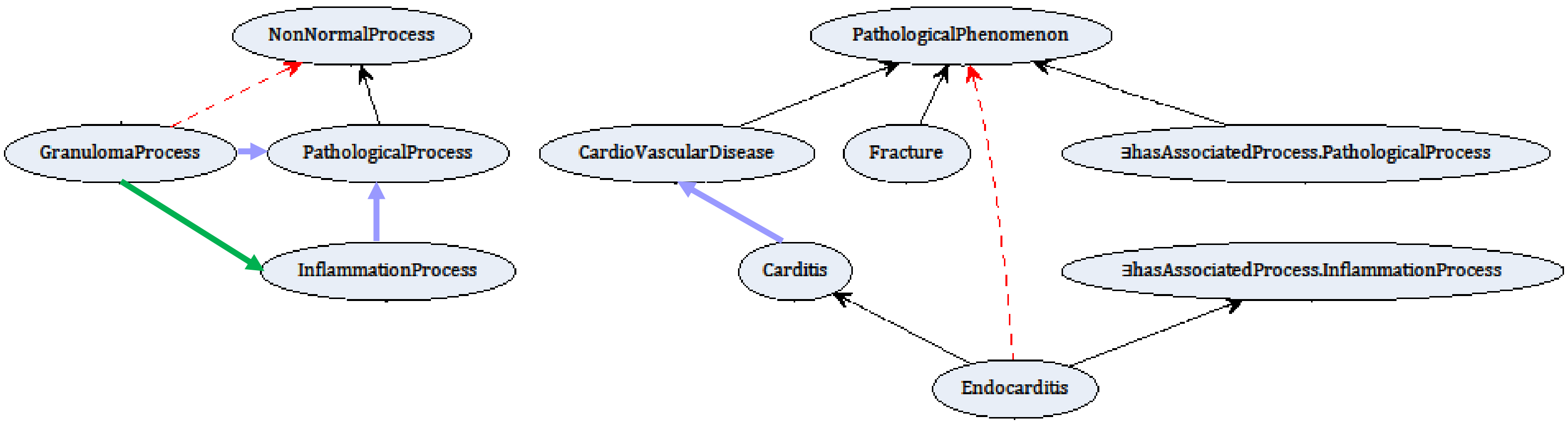
- Combine solutions for individual missing is-a relations
- Remove redundant relations while keeping the same level of informativness
- Resulting solution is a skyline optimal solution

$$\{\text{InflammationProcess} \dot{\sqsubseteq} \text{PathologicalProcess},\\ \text{Carditis} \dot{\sqsubseteq} \text{CardioVascularDisease},\\ \text{GranulomaProcess} \dot{\sqsubseteq} \text{PathologicalProcess}\}$$

Algorithm – improving solution

- Solution S from previous step may contain relations which are not derivable from the ontology.
- These can be seen as new missing is-a relations.
- We can solve a new GTAP problem: GTAP(**T** U *S*, **C**, Or, *S*)

Example – improving solutions



$$\text{GranulomaProcess} \mathrel{\dot{\sqsubseteq}} \text{InflammationProcess}$$

$$\{\text{InflammationProcess} \mathrel{\dot{\sqsubseteq}} \text{PathologicalProcess},\\ \text{Carditis} \mathrel{\dot{\sqsubseteq}} \text{CardioVascularDisease},\\ \text{GranulomaProcess} \mathrel{\dot{\sqsubseteq}} \text{InflammationProcess}\}$$

Algorithm properties

- Sound
- Skyline optimal solutions

Experiments

Two use-cases

- Case 1: given missing is-a relations
  AMA and a fragment of NCI-A ontology – OAEI 2013
  - AMA (2744 concepts) – 94 missing is-a relations
    → 3 iterations, 101 in repairing (47 additional new knowledge)
  - NCI-A (3304 concepts) – 58 missing is-a relations
    → 3 iterations, 54 in repairing (10 additional new knowledge)

- Case 2: no given missing is-a relations
  Modified BioTop ontology
  - Biotop (280 concepts, 42 object properties)
    randomly choose is-a relations and remove them: 47 ‘missing’
    → 4 iterations, 41 in repairing (40 additional new knowledge)

Further reading

Starting points for further studies

Further reading ontology debugging

Debugging and Completing Ontologies

- Lambrix P, Completing and Debugging Ontologies: state of the art and challenges, 2019. arXiv:1908.03171

Debugging Ontologies

- Schlobach S, Cornet R. Non-Standard Reasoning Services for the Debugging of Description Logic Terminologies. *18th International Joint Conference on Artificial Intelligence - IJCAI03*, 355-362, 2003.
- Schlobach S. Debugging and Semantic Clarification by Pinpointing. *2nd European Semantic Web Conference - ESWC05*, LNCS 3532, 226-240, 2005.

Further reading ontology debugging

Completing ontologies

- Fang Wei-Kleiner, Zlatan Dragisic, Patrick Lambrix. Abduction Framework for Repairing Incomplete EL Ontologies: Complexity Results and Algorithms. 28th AAAI Conference on Artificial Intelligence - AAAI 2014, 1120-1127, 2014.

- Lambrix P, Ivanova V, A unified approach for debugging is-a structure and mappings in networked taxonomies, *Journal of Biomedical Semantics* 4:10, 2013.

- Lambrix P, Liu Q, Debugging the missing is-a structure within taxonomies networked by partial reference alignments, *Data & Knowledge Engineering* 86:179-205, 2013.