Semantical Reflection for Computational Structures

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and collaborators

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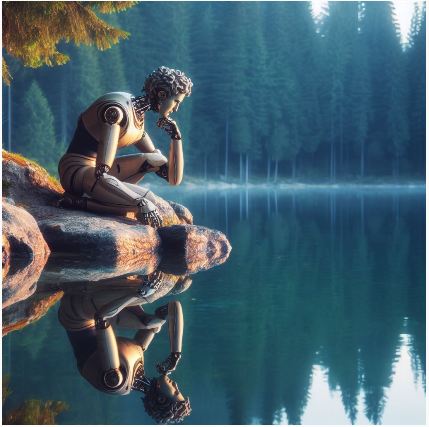
University of Oslo

Reflection

What is Reflection?

- Reasoning about oneself
- Reasoning about the relation to the environment
- Forming insights: expectations and memories
- Acting on reflective insights

Reflection



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How can we program reflective applications?

Appearance

Beyond OO Reflection

In programming, reflection refers to the ability to manipulate runtime structures, such as classes directly – We want more:

- Reasoning about runtime structures
- Relate runtime structures to application domain
- Formulate models and data based on this relation

- How to connect a program with its application domain?
- How to interpret a program through the lens of it domain?
- How to express and adhere to domain knowledge at runtime?

Semantically Lifted Programs

Knowledge Graphs

Triple-Based Knowledge Representation

Knowledge Graphs are a framework to represent (RDF), reason (OWL) over, and query (SPARQL) domain knowledge and data. Example: Asset model of a house.

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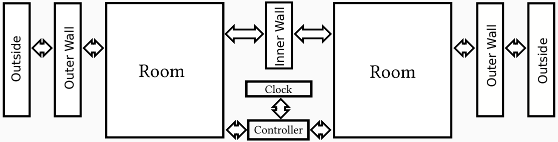

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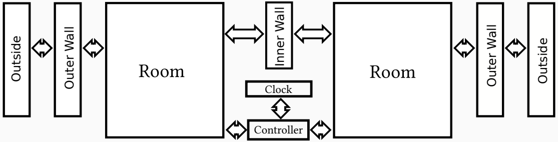


```
ast:heater1 a ast:Heater. ast:heater1 ast:in ast:room1.
ast:heater2 a ast:Heater. ast:heater2 ast:in ast:room2.
ast:heater1 ast:id 13. ast:heater2 ast:id 12.
ast:room1 ast:leftOf ast:room2.
```

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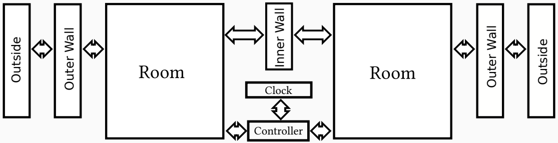


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ast:heater1 ast:id 13. ast:heater2 ast:id 12.
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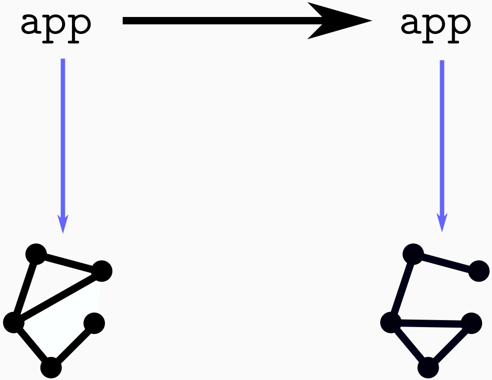
```

`htLeftOf` **subPropertyOf** `ast:in` **o** `ast:leftOf` **o** **inverse**(`ast:in`)

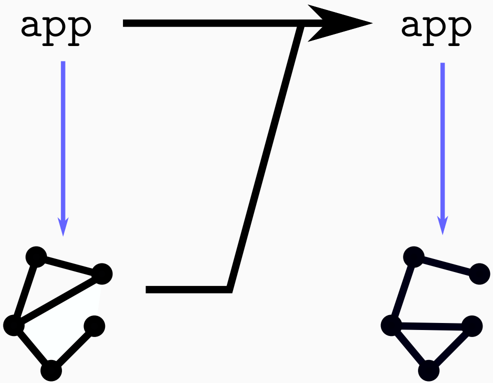
Semantically Lifted Programs

`app` ⟶ `app`

Semantically Lifted Programs



Semantically Lifted Programs



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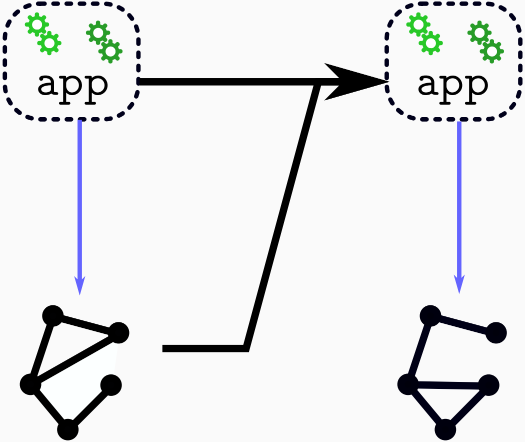

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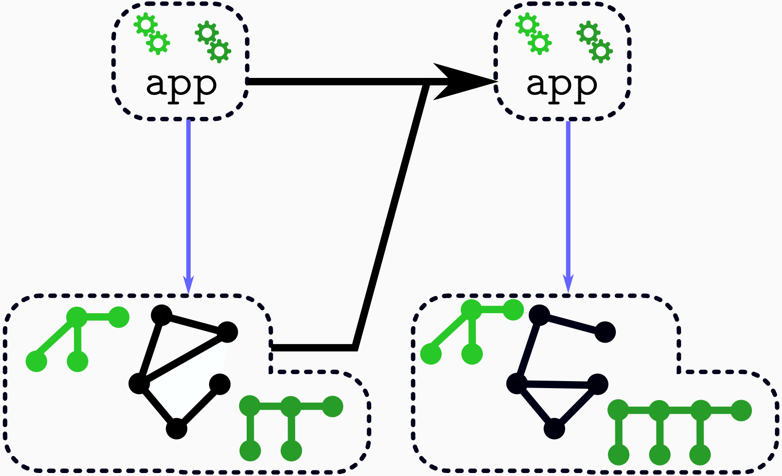

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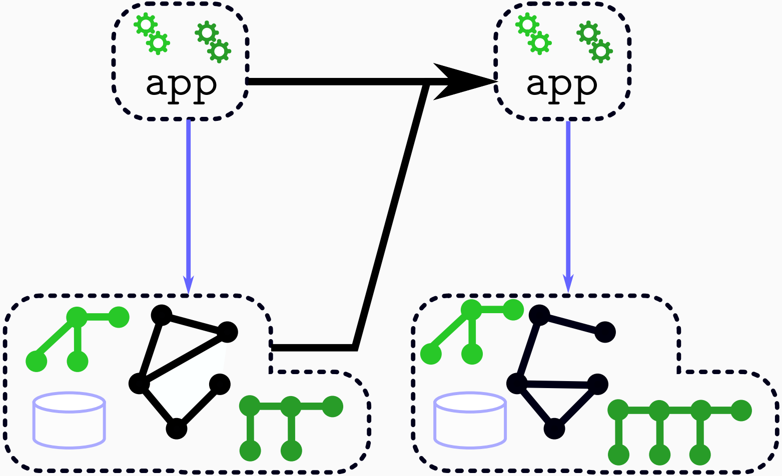

Direct Mapping of Program States

SMOL: Integration of Semantics and Semantic Technologies

Map each program state to a knowledge graph and allow program to operate on the KG. Implemented in SMOL (`smolang.org`).

```
class C (Int i) Unit inc(){ this.i = this.i + 1; } end
Main C c = new C(5);  Int i = c.inc(); end
```

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```

```
prog:C a prog:class. prog:C prog:hasField prog:i.
run:obj1 a prog:C.   run:obj1 prog:i 5.
run:proc1 a prog:process.
run:proc1 prog:runsOn run:obj1.
....
```

[K. et al., *Programming and Debugging with Semantically Lifted States*, ESWC'21]

Semantic Reflection: Reasoning about oneself

```
class Building(List<Room> rooms) ... end
class Inspector(List<Building> buildings)
 Unit inspectStreet(String street)
  List<Building> l := access("SELECT ?x WHERE {?x a Villa. ?x :in %street}");
  this.inspectAll(l);
 end
end
```

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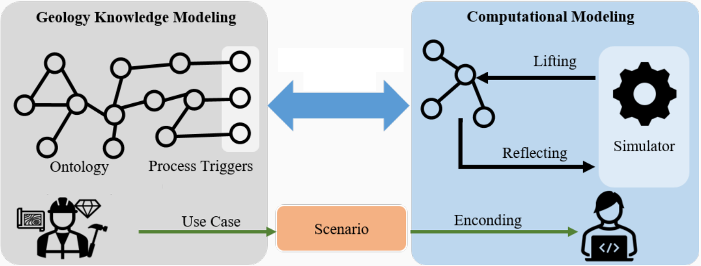
```

`Villa EquivalentTo: rooms o length some xsd:int [>= 3]`

Semantic Reflection: Reasoning about oneself – GeoSimulator

Case study of using SMOL for a geological simulator

- SMOL simulators describes the effects of the process
- SMOL state is interpreted through ontology
- Geological ontology describes under which conditions a geological process starts



[Qu, K., and Giese, *A Geological Case Study on Semantically Triggered Processes*, ESWC'23]

Semantic Reflection: Reasoning about oneself – GeoSimulator

Modeling of a geological shale structure in SMOL

```
class ShaleUnit extends GeoUnit
 (Double temperature,
  Boolean hasKerogenSource,
  Int maturedUnits)
  models
  "a GeoReservoirOntology_sedimentary_geological_object;
      location_of [a domain:amount_of_organic_matter];
      GeoCoreOntology_constituted_by [a domain:shale];
      has_quality [domain:datavalue %temperature; a domain:temperature
 ].";
end
```

Semantic Reflection: Reasoning about oneself – GeoSimulator

Resulting (part of the) knowledge graph

```
run:obj1 smol:models domain:obj1.
domain:obj1 a GeoReservoirOntology_sedimentary_geological_object;
   location_of [a domain:amount_of_organic_matter];
   GeoCoreOntology_constituted_by [a domain:shale];
   has_quality [domain:datavalue "10.0"^^xsd:Double; a domain:temperature].
```

Semantic Reflection: Reasoning about oneself – GeoSimulator

Simulation driver

```
List<ShaleUnit> fs =
member(domain:models some (obo:participates_in some domain:
 oil_window_maturation_trigger));
while fs != null do
  fs.content.mature(); fs = fs.next;
end
```

For Mandal-Ekofisk field, simulation gives similar results as original study (2*mya* steps)

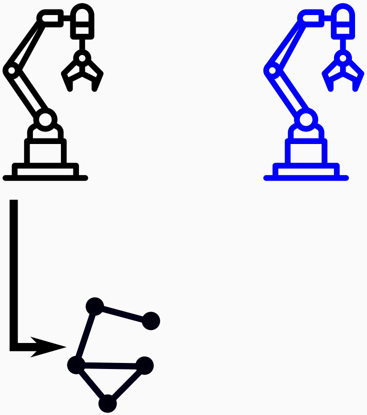
	SMOL	Cornford'94	Time Difference
Start M.	52*ma*	∼50*ma*	∼2*mya*
End M.	14*ma*	∼23*ma*	∼9*mya*
Crit. Moment	28*ma*	∼30*ma*	∼2*mya*

Semantic Reflection: Structurally Self-Adaptive Digital Twins

Semantic Reflection: Comparing with Expectations

Is our digital twin twinning the right thing?

- Export asset model of physical system as KG
- Export program state with simulators as KG
- Formulate constraints over combined KG



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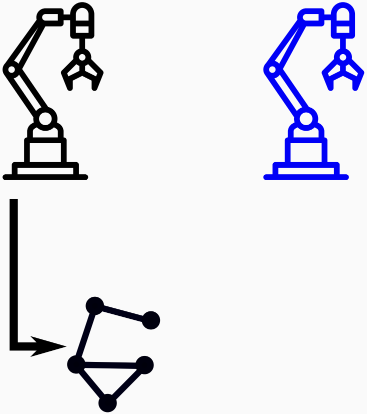

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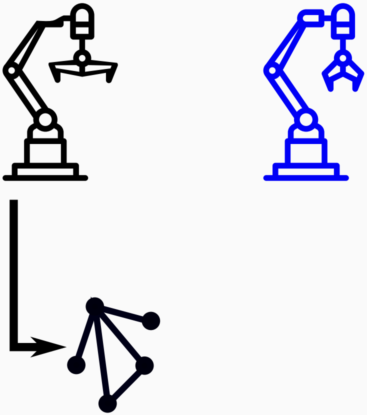

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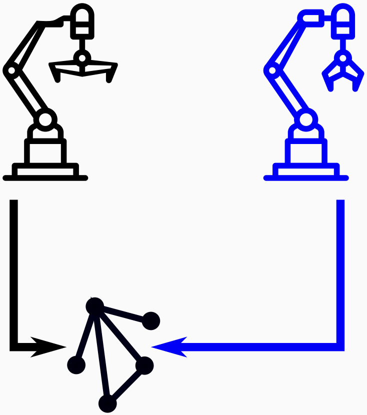

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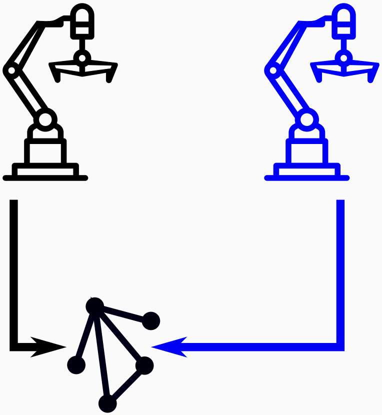

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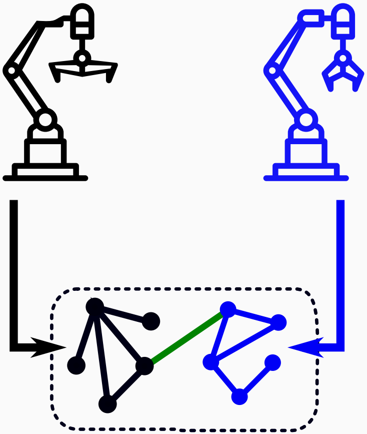

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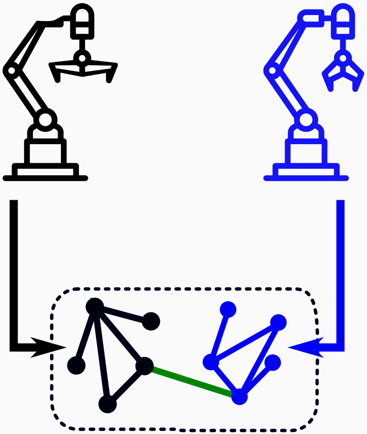

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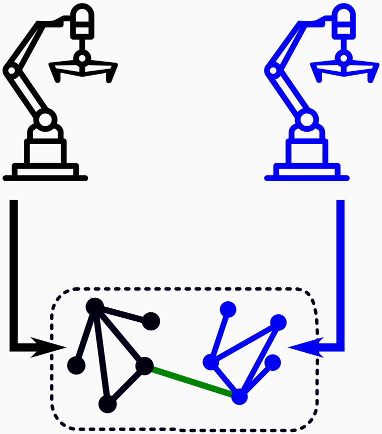

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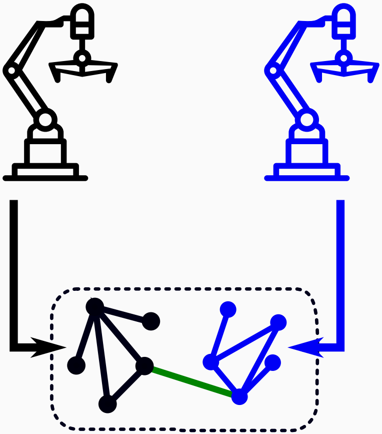
Possible Constraints

- Constraint on program
  "Is this a sensible simulation structure?"
- Constraints on twinning
  "Does the program have the same structure as the asset?"



Semantic Reflection: Structurally Self-Adaptive Digital Twins – SMOL/FMI

Functional Mock-Up Interface (FMI)

Standard for (co-)simulation units, called function mock-up units (FMUs). Can also serve as interface to sensors and actuators.

Semantic Reflection: Structurally Self-Adaptive Digital Twins – SMOL/FMI

Functional Mock-Up Interface (FMI)

Standard for (co-)simulation units, called function mock-up units (FMUs). Can also serve as interface to sensors and actuators.

```
//simplified shadow
class Monitor(FMO[out Double val] sys,
              FMO[out Double val] shadow)
  Unit run(Double threshold)
    while shadow != null do
      sys.doStep(1.0);  shadow.doStep(1.0);
      if(sys.val - shadow.val >= threshold) then ... end
    end ...
```

Knowledge Structures over Simulation Units, K. and Johnsen. [ANNSIM'22]

Semantic Reflection: Structurally Self-Adaptive Digital Twins

SPARQL

Define structural requirements as queries in SPARQL on *combined* knowledge graph, to use domain constraints on digital twins.

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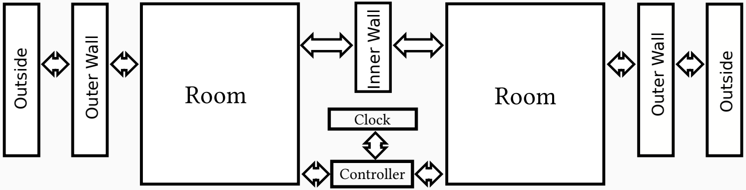

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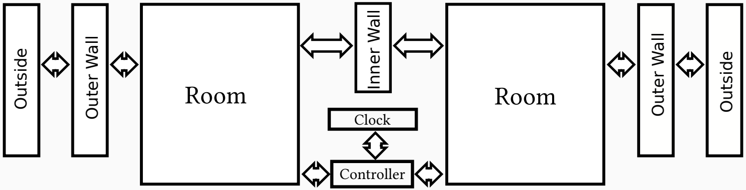


```
class Room(FMO f, Wall inner, Wall outer, Controller ctrl, Int id) end
class Controller(FMO f, Room left, Room right, Int id) end
class InnerWall(FMO f, Room left, Room right) end
```

Semantic Reflection: Structurally Self-Adaptive Digital Twins

SPARQL

Define structural requirements as queries in SPARQL on *combined* knowledge graph, to use domain constraints on digital twin.

Query to detect non-sensical setups:

```
SELECT ?room WHERE { ?ctrl a prog:Controller.
                     ?ctrl prog:left ?room.
                     ?ctrl prog:right ?room }
```

Semantic Reflection: Structurally Self-Adaptive Digital Twins

SPARQL

Define structural requirements as queries in SPARQL on *combined* knowledge graph, to use domain constraints on digital twin.

Query to check structural consistency for heaters:

```
SELECT * WHERE { ?o1 prog:id ?id1. ?h1 ast:id ?id1.
                 ?o2 prog:id ?id2. ?h2 ast:id ?id2.
                 ?h1 htLeftOf ?h2.
                 ?c a prog:Controller.
                 ?c prog:left ?o1. ?c prog:right ?o2.}
```

Semantic Reflection: Structurally Self-Adaptive Digital Twins

Semantic Reflection

One can use the knowledge graph *within* the program to detect structural drift: Formulate query to retrieve all mismatching parts

```
....
List<Repairs> repairs =
 construct("SELECT ?room ?wallLeft ?wallRight WHERE
   {?x ast:id ?room.
    ?x ast:right [ast:id ?wallRight].
    ?x ast:left [ast:id ?wallLeft].
    FILTER NOT EXISTS {?y a prog:Room; prog:id ?room.}}");
```

[K. et al., *Digital Twin Reconfiguration Using Asset Models*, ISoLA'22]

Semantic Reflection: Software Engineering Aspects

Software Engineering Semantic Reflection

Static Guarantees

How can we ensure that semantic reflection does not cause runtime errors?

```
class Building(List<Room> rooms) ... end
class Inspector(List<Building> buildings)
 Unit inspectStreet(String street)
  List<Building> l := access("SELECT ?x WHERE {?x a Villa}");
  this.inspectAll(l);
 end
end
```

Type checking reflection reduces to query containment, if the ontology $\mathcal{K}$ is known.

$$\texttt{Villa} \sqsubseteq_{\mathcal{K}} \texttt{Building}$$

[K. and Kostylev, *Type Checking Semantically Lifted Programs via Query Containment under Entailment Regimes*, DL'21]

Software Engineering Semantic Reflection

Connecting Class Models

How can we connect OWL and OO class models?

- Generate program classes from ontology
- Generate program classes for RDF structures
- Generate program classes for *queries*

Bridging the Gap

- Use retrieval queries as interface between class models
- Do not connect *concepts*, define *data retrieval*
- Annotate query to class, not execution point
- Implemented for Java, extended with Liskov Principle for subtyping

Example: Bike and Wheels

```
class Wheel (Int wheelId, Int year) end
class Bike (Int bId, Int year, Wheel front, Wheel back) end
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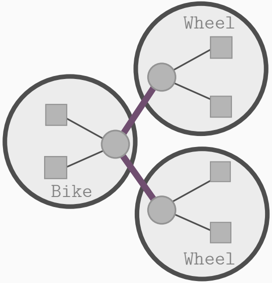
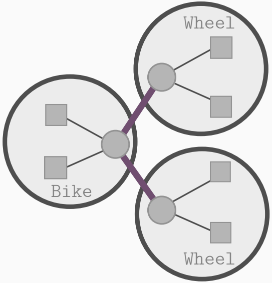



```
Q = SELECT * WHERE
  ?b :bId ?id;
     :prod ?year;
     :back ?back;
     :front ?front.
  ?back :wheelId ?wheelId1;
        :prod ?year1.
  ?front :wheelId ?wheelId2;
         :prod ?year2.
```

[K., Norstein and Giese, *Never mind the semantic gap*, ESWC'22]

Example: Bike and Wheels

```
List<Result> res = query(Q); Result r = res[0];
Wheel w1 = new Wheel(r.get("wheelId1"), r.get("year1"));
Wheel w2 = new Wheel(r.get("wheelId2"), r.get("year2"));
Bike b = new Bike(r.get("id"), r.get("year"), w1, w2);
print(b.front.id);
```

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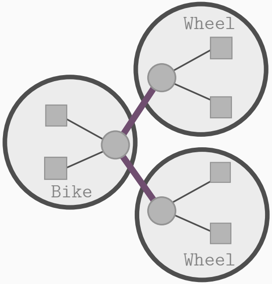
  ?back :wheelId ?wheelId1;
      :prod ?year1.
  ?front :wheelId ?wheelId2;
      :prod ?year2.
```

Example: Bike and Wheels

Challenges

- Data access is **not type safe**
- Query is **disconnected from class**
- Query is **non-modular**: class structure is ignored, no reuse

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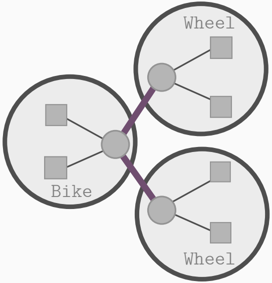
      :prod ?year1.
  ?front :wheelId ?wheelId2;
      :prod ?year2.
```

Links — Detailed Explanation

```
class Wheel anchor ?w (Int wheelId, Int year) end
  retrieve SELECT ?wheelId ?year { ?w :wheelId ?wheelId; :prod ?year. }

class Bike anchor ?b (Int bId;  Int year;
  link(?b :front ?front) Wheel front;
  link(?b :back ?back) Wheel back;
) end retrieve SELECT ?id ?year { ?b :bId ?bId; :prod ?year. }
```

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  ?b :bId ?bId;
     :prod ?year;
     :back ?back;
     :front ?front.
  ?back :wheelId ?wheelId1;
      :prod ?year1.
  ?front :wheelId ?wheelId2;
      :prod ?year2.
```

Evaluation

Slegge

- Slegge is a query corpus for exploration in energy industry.
- Remodeling of 8 queries in extended `SMOL` using 27 classes.
- Found one bug due to copy-paste

Software Engineering Semantic Reflection

Ontologies for Programs

Two tools developed for JVM: `jdi2owl` generates a knowledge graph of a JVM state through the debugging interface. `sjdb` enables debugging of Java applications.

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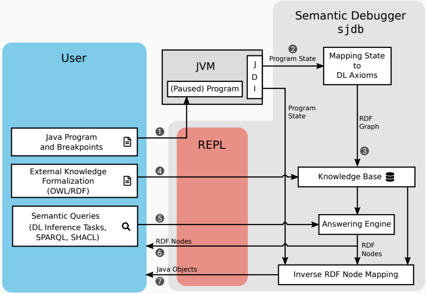

[Haubner, *Inspecting Java Program States with Semantic Web Technologies*, MSc'22]

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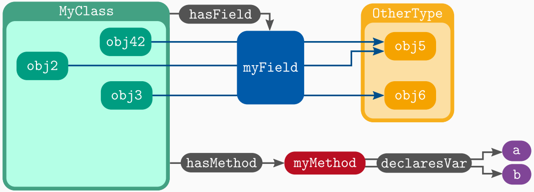

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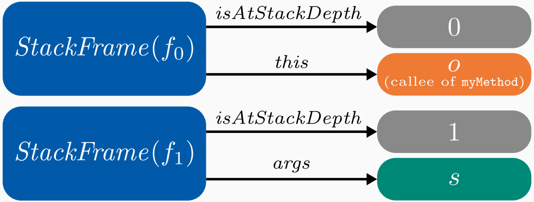

Semantically Lifted Systems

Lifting Software Architectures

Beyond Programs

- Lifting larger programs does not scale up
- Instead: Software architecture to lift only components

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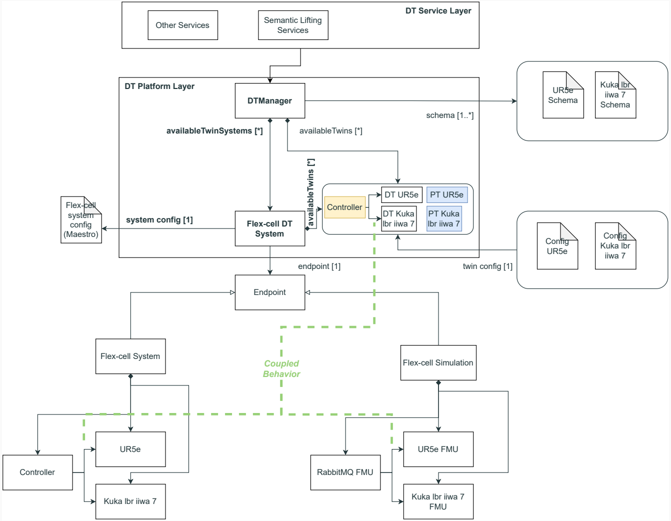
[Gil, K., Talasila, Larsen, *An Architecture for Coupled Digital Twins with Semantic Lifting*, u.S.]

Lifting Software Architectures

Beyond Programs

- Lifting larger programs does not scale up
- Instead: Software architecture to lift only components



Semantic Experiment Management

Reasoning for Reuse

- Lifting larger programs does not scale up
- We may not be interested in the program, but computation results
- Lifting is used to detect whether reuse of computations is possible

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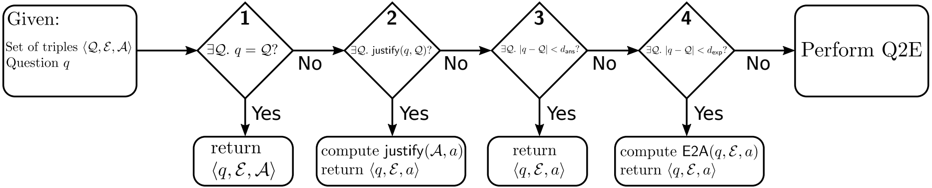
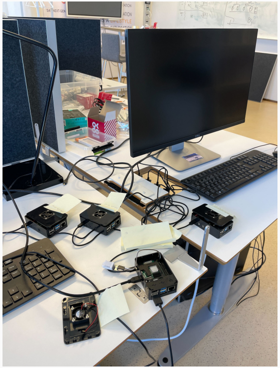
Combining Case-Based Reasoning and Deduction

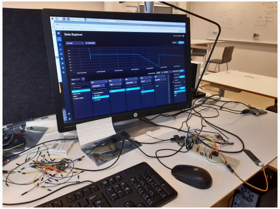


[Cederbladh et al., *Symbolic Reasoning for Early Decision-Making in Model-Based Systems Engineering*, MBSE@Models'23]

Conclusion

Digital Twin Lab





Digital Twin Lab

- Working with realistic software stack
- Evaluation of proposed architectures

Verification of Domain Contracts

Towards Axiomatic Domain Semantics

So far, we have discussed how to program and use knowledge graphs.

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$$\{\mathit{pre}\}\mathtt{s}\{\mathit{post}\}$$

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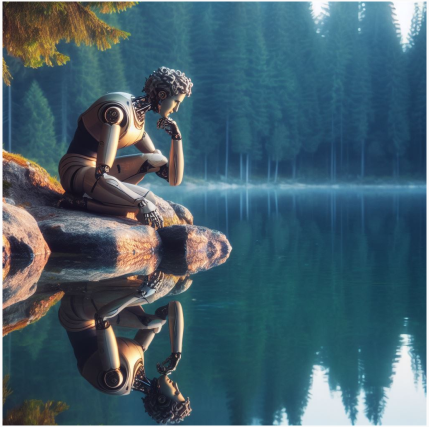
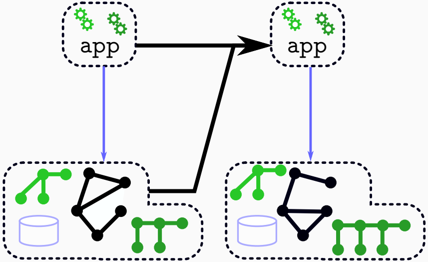
Outlook

- Ontology alignment for process and asset ontologies
- Optimization and correctness
- Long-term: Software Engineering for Symbolic AI and Reflection

Conclusion





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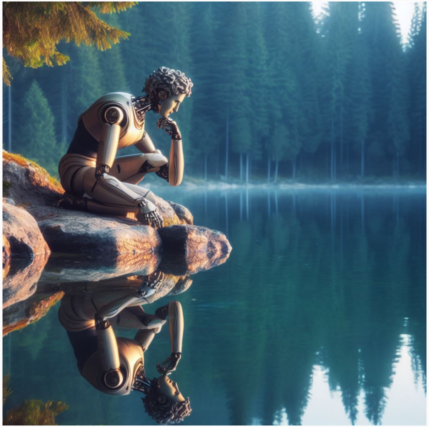

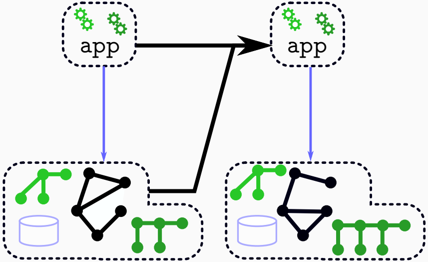

Thank you for your attention