Semantically Lifted Programming

Eduard Kamburjan

University of Oslo
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Knowledge Representation with Ontologies

Ontologies are logically formalized domain knowledge

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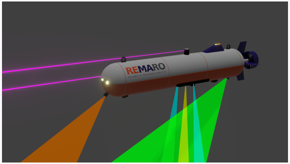

REMARO
RELIABLE AI FOR MARINE ROBOTICS

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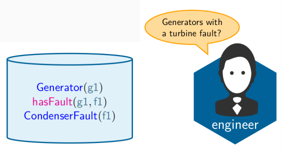

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GENEONTOLOGY
Unifying Biology

SNOMED CT
The global
language of
healthcare

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READI

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READI

Surrounding theories and tools are Semantic Technologies

… and Programs

How to use ontologies in programming?

- Make domain knowledge available to the programmer
- Reduce redundancy between program and other artifacts
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- Using multiple Semantic Web technologies can be tricky
- Programmer must be aware of logical and formal pitfalls
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This Talk

- First results, challenges, on-going research
- Use ontologies in programming to enable Digital Twins.

Semantic Technologies

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Knowledge Graphs are a framework to (a) represent, (b) reason over, and (c) query domain knowledge and data.

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```
Peter a Person. Paul a Person. Maria a Person.
Peter hasChild Paul. Paul hasChild Maria.
```

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`hasChild` **some** (`hasChild` **some** `Person`)

subClassOf `GrandParent`

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subClassOf `GrandParent`

SPARQL: `SELECT ?x WHERE { ?x a GrandParent }`

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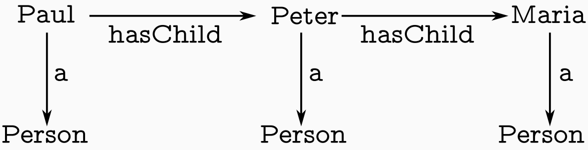

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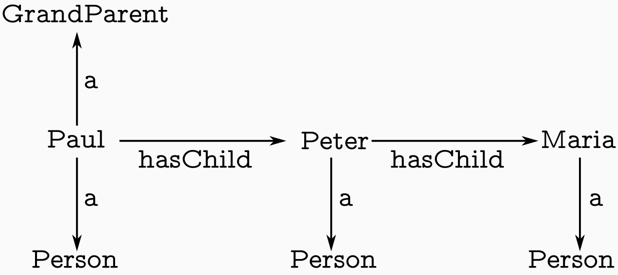

Semantically Lifted Programs and Digital Twins

Semantically Lifted States

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$$\text{conf} \xrightarrow{\texttt{x} := 0} \text{conf'}$$

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

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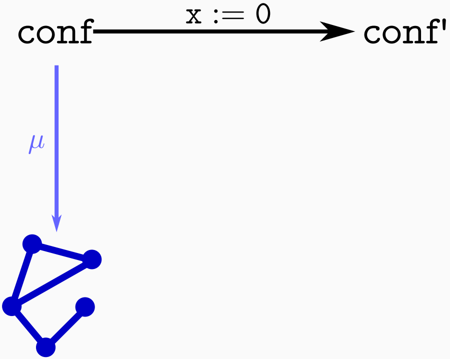

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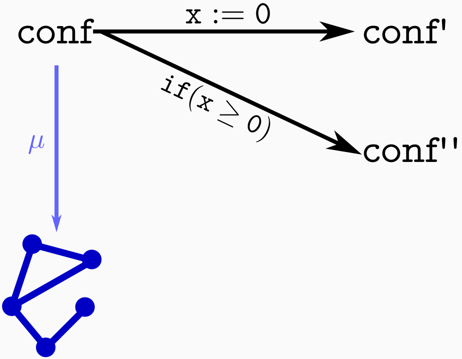

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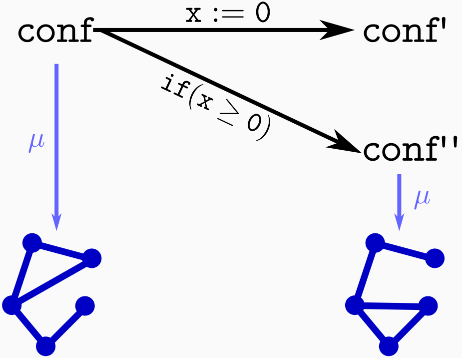

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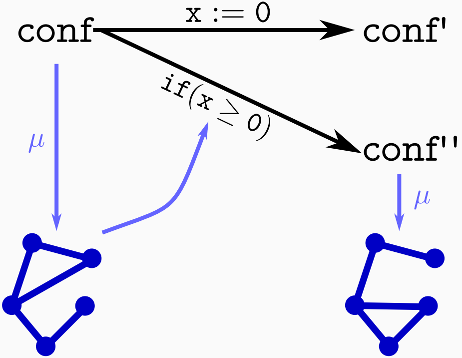

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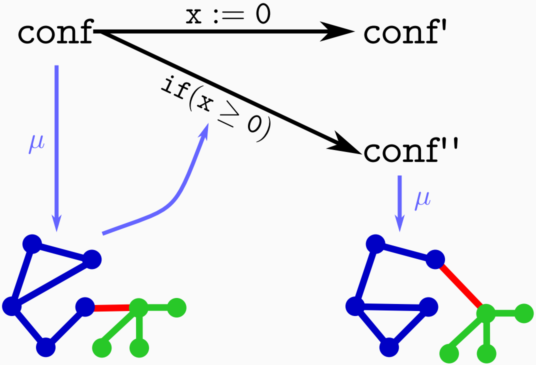

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Example

```
class C (Int i) Unit inc() this.i = this.i + 1; end 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.
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```

A representation of (a) the full AST and (b) the full runtime state.

SMOL

Given the lifted state, we can use it for multiple operations.

- **Access it** to retrieve objects without traversing pointers.
- **Enrich it** with an ontology, perform logical reasoning and retrieve objects using a query *using the vocabulary of the domain*.
- **Combine it** with another knowledge graph and access external data based on information from the current program state.

Semantic Programming

```
class Platform(List<Server> serverList) ... end
class Server(List<Task> taskList) ... end
class Scheduler(List<Platform> platformList)
 Unit reschedule()
  List<Platform> l
    := access("SELECT ?x WHERE {?x a :Overloaded}");
  this.adaptPlatforms(l);
 end
end
```

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```
:Overloaded
 owl:equivalentClass [
   owl:onProperty (:tasks, :length);
   owl:minValue 3;
 ].
```

Digital Twin

A digital twin system connects a physical asset with its own (simulation) models using data streams and commands.

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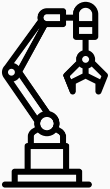

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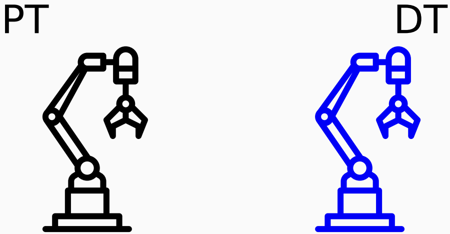

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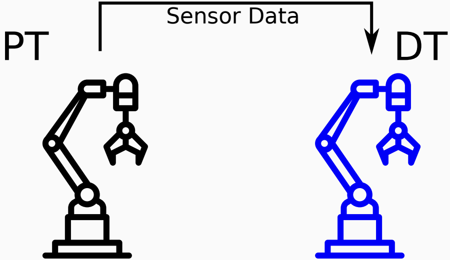

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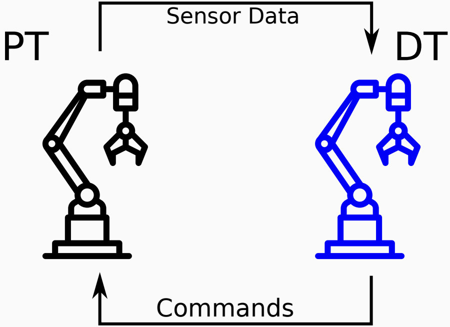

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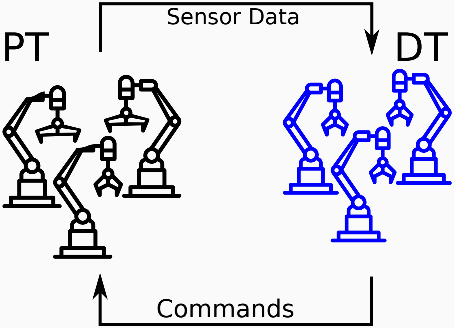

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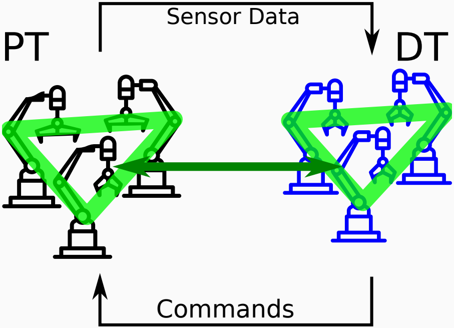

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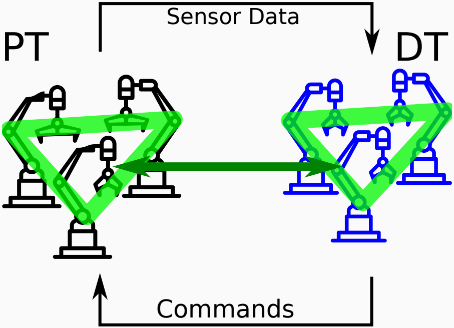

- Common data representation
- Data view on both twins: Twinning as a data property

Knowledge Graphs and Asset Models

Asset Model

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Our Asset Model

A knowledge graph describing the structure of the physical twin.

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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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```

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

Checking the Twinning Property

Combining the Knowledge

- Export asset model of physical system as knowledge graph
- Export program state with simulators as knowledge graph
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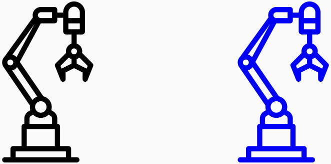

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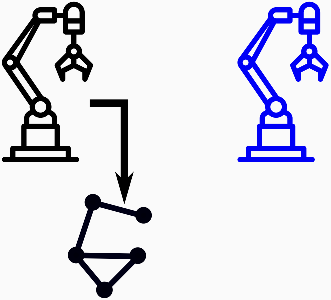

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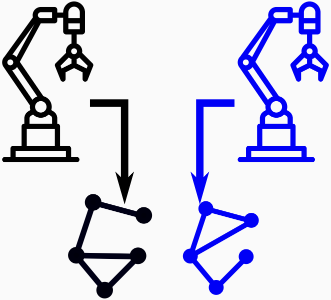

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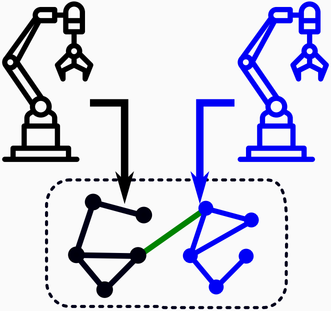

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Possible Constraints

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

SMOL and 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.

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```
//simplified shadow
class Monitor(Cont[out Double val] sys,
              Cont[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 ...
```

Constraints on Digital Twins

SMOL and FMI

SMOL with FMOs

FMOs are objects, so they are part of the knowledge graph.

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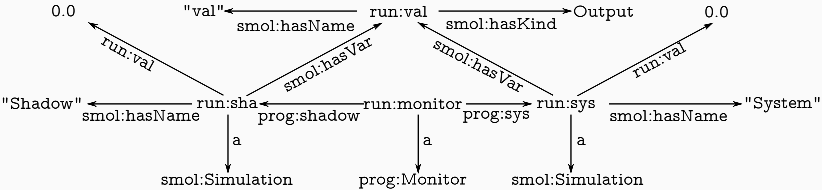

Knowledge Structures over Simulation Units, Kamburjan and Johnsen. [ANNSIM'22]

Semantically Lifting the Digital Twin

SPARQL

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

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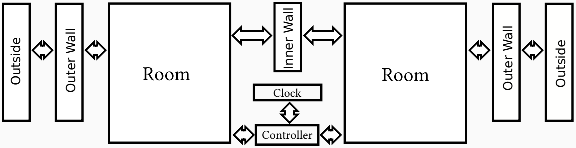

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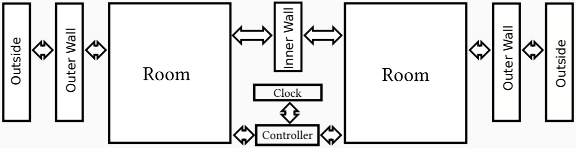

```
class Room(Cont[...] f,
           Wall inner, Wall outer, Controller ctrl,
           Int id) end
class Controller(Cont[...] f,
                 Room left, Room right, Int id) end
class InnerWall(Cont[...] f, Room left, Room right) end
```

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Query to detect non-sensical setups:

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

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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.}
```

On-Going Work: Repairing your Twin

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.}}");
```

Repair function must restore structure.

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

Program Analysis and Optimization

Challenges

Optimization and Static Analysis of SMOL

- Every program optimization is unsound for SMOL, because the whole AST can be accessed through semantic reflection.
- Similarly, Garbage Collection is not possible, because every objects can be accessed even if no pointers to it exist.
- Static Analysis requires to analyze possible results of queries

Tools from Description Logic

First results that two notions from Description Logics can help with garbage collection and typing: *ontology modules* and *query subsumption*.

Ontology Modules

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Ontology Module

Given a KB $\mathcal{K}$ and a signature Σ, the module $\mathcal{M}_{\mathcal{K}}^{\Sigma}$ of $\mathcal{K}$ w.r.t. Σ is a sub-KB that gives the same answers w.r.t. Σ.

- $\mathcal{M}_{\mathcal{K}}^{\Sigma} \subseteq \mathcal{K}$
- $\forall q.\ (\mathbf{sig}(q) \subseteq \Sigma) \rightarrow \mathsf{ans}(\mathcal{K}, q) = \mathsf{ans}(\mathcal{M}_{\mathcal{K}}^{\Sigma}, q)$

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- Modules may expand signature $\mathbf{sig}(\mathcal{M}^{\Sigma}_{\mathcal{K}}) \supseteq \Sigma$
- Multiple notions of modules available
- Beware: ontology modules are *extracted*

Ontology Modules: Example

$$\mathcal{K} = \{\alpha_1 = \texttt{Busy} \sqsubseteq \texttt{Platform} \sqcap \texttt{NonEmpty},$$
$$\alpha_2 = \texttt{NonEmpty} \sqsubseteq \exists \texttt{servers.List}, \alpha_3 = \texttt{Task} \sqsubseteq \texttt{Object},$$
$$\texttt{Platform}(\mathsf{a}), \texttt{List}(\mathsf{b}), \texttt{Task}(\mathsf{c}), \texttt{servers}(\mathsf{a}, \mathsf{b})\}$$

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Optimizing Semantically Lifted Programs through Ontology Modularity, Kamburjan and Chen [NWPT'21]

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$$\begin{aligned}\mathcal{M}_{\mathcal{K}}^{\Sigma} = \{&\alpha_1 = \texttt{Busy} \sqsubseteq \texttt{Platform} \sqcap \texttt{NonEmpty},\\ &\alpha_2 = \texttt{NonEmpty} \sqsubseteq \exists\texttt{servers.List},\\ &\texttt{Platform}(\mathsf{a}), \texttt{List}(\mathsf{b}), \texttt{servers}(\mathsf{a}, \mathsf{b})\}\end{aligned}$$

Optimizing Semantically Lifted Programs through Ontology Modularity, Kamburjan and Chen [NWPT'21]

Ontology Modules: Example

$$\begin{aligned}\mathcal{K} = \{&\alpha_1 = \texttt{Busy} \sqsubseteq \texttt{Platform} \sqcap \texttt{NonEmpty},\\ &\alpha_2 = \texttt{NonEmpty} \sqsubseteq \exists \texttt{servers}.\texttt{List}, \alpha_3 = \texttt{Task} \sqsubseteq \texttt{Object},\\ &\texttt{Platform}(\mathsf{a}), \texttt{List}(\mathsf{b}), \texttt{Task}(\mathsf{c}), \texttt{servers}(\mathsf{a}, \mathsf{b})\}\\ \Sigma = \{&\texttt{Busy}\}\\ \mathcal{M}^{\Sigma}_{\mathcal{K}} = \{&\alpha_1 = \texttt{Busy} \sqsubseteq \texttt{Platform} \sqcap \texttt{NonEmpty},\\ &\alpha_2 = \texttt{NonEmpty} \sqsubseteq \exists \texttt{servers}.\texttt{List},\\ &\texttt{Platform}(\mathsf{a}), \texttt{List}(\mathsf{b}), \texttt{servers}(\mathsf{a}, \mathsf{b})\}\end{aligned}$$

Application

- Use $\mathcal{M}^{\textbf{sig}(\texttt{Q})}_{\mathcal{K}}$ to approximate dependencies of `access(Q)`.
- E.g., garbage collection: remove object if it is in no module.

Optimizing Semantically Lifted Programs through Ontology Modularity, Kamburjan and Chen [NWPT'21]

Type System

Challenge

Does **List**`<C> l := access(...);` indeed return a list of `C` objects?

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$$\textbf{(acc-type)}\ \frac{\Gamma \vdash \texttt{l} : \textbf{List}\texttt{<C>} \qquad \texttt{SELECT ?x } \{\texttt{P}\} \ \subseteq^{\mathcal{K}}_{\text{er}} \ \texttt{SELECT ?x } \{\texttt{?x a prog:C}\}}{\Gamma \vdash^{\mathcal{K}}_{\text{er}} \texttt{l:=access("SELECT ?x } \{\texttt{P}\}\texttt{")}}$$

Where $\mathcal{K}$ does *not* contain the lifted state, but only the ontology.

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

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Semantically Lifted Programs and Semantic Reflection

- Combining knowledge representation and programming
- Fully formal setting for digital twins
- Future work: static analysis, concurrency

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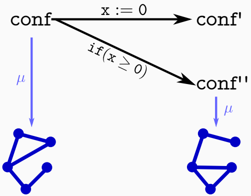

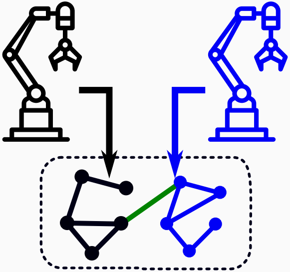

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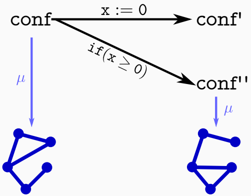

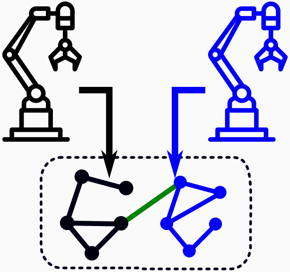

Thank you for your attention