Unified LTL Verification and Embedded Execution of UML Models

Scientific Seminar, MOCS Team

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Context

Observations

- Increasing complexity of embedded systems
- Emergence of new needs and applications
- Connection of these systems to networks (IoT)

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- Emergence of new needs and applications
- Connection of these systems to networks (IoT)

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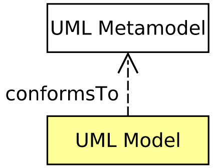
- More prone to uncertain behaviors, security flaws, and design mistakes
- More safety and security requirements

Consequence on software development

- Increasing need of verification and validation

Classical UML-based Approaches



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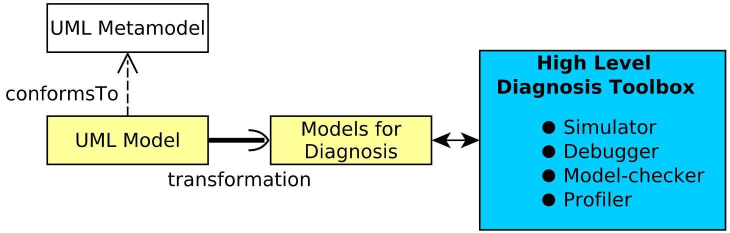

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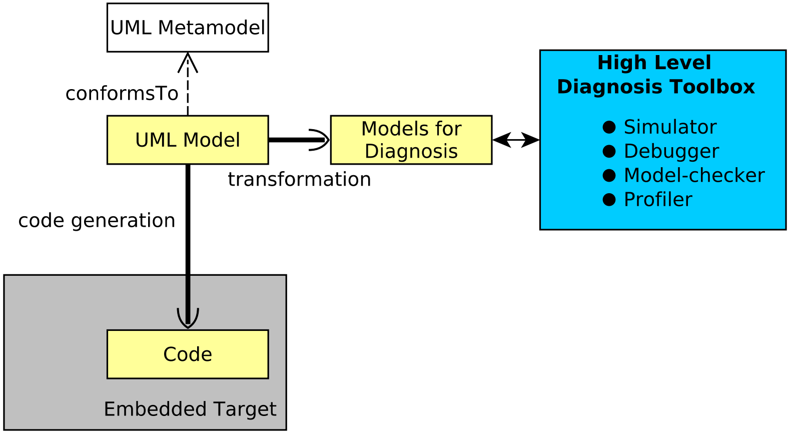

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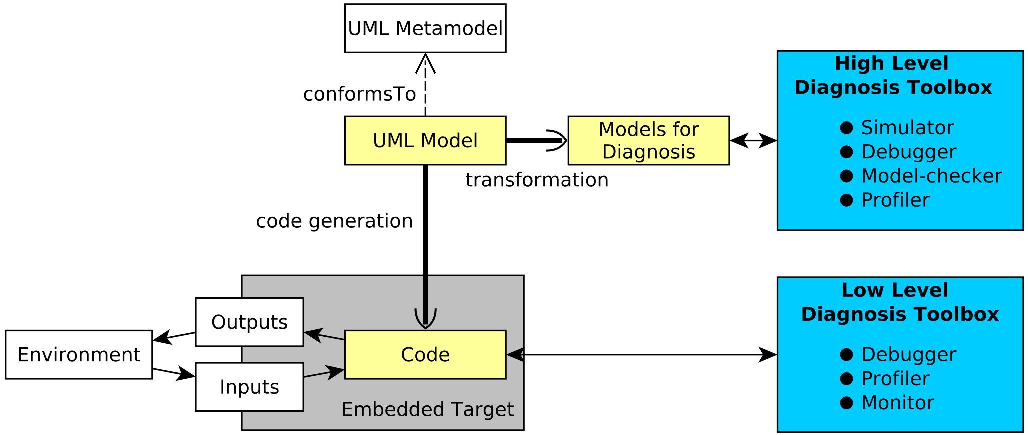
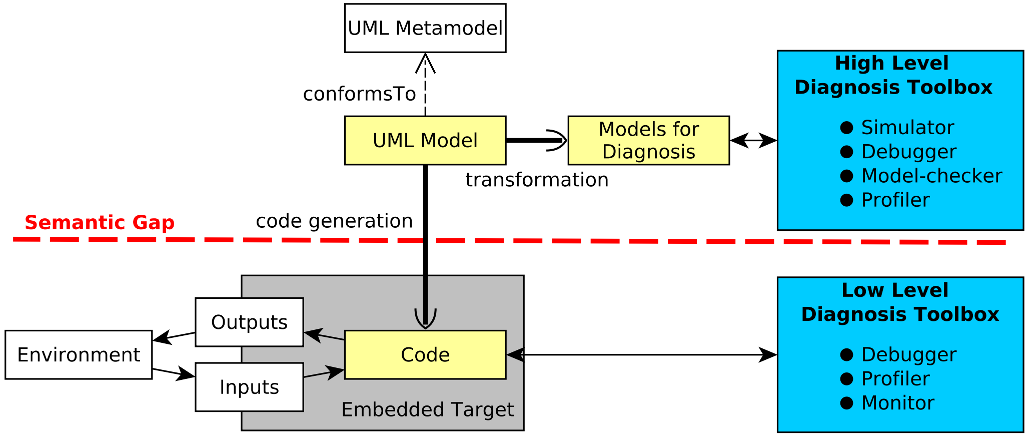
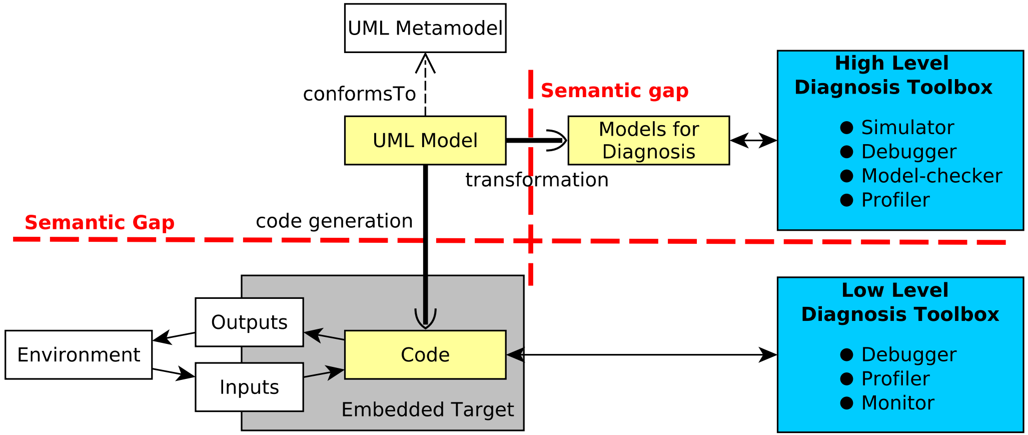


Some Problems



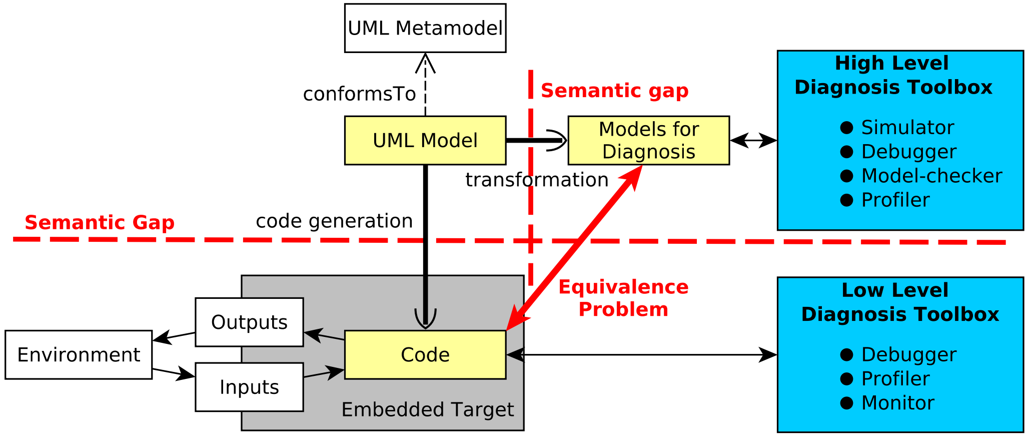
First issue: Semantic gap between design model and executable code.

Some Problems



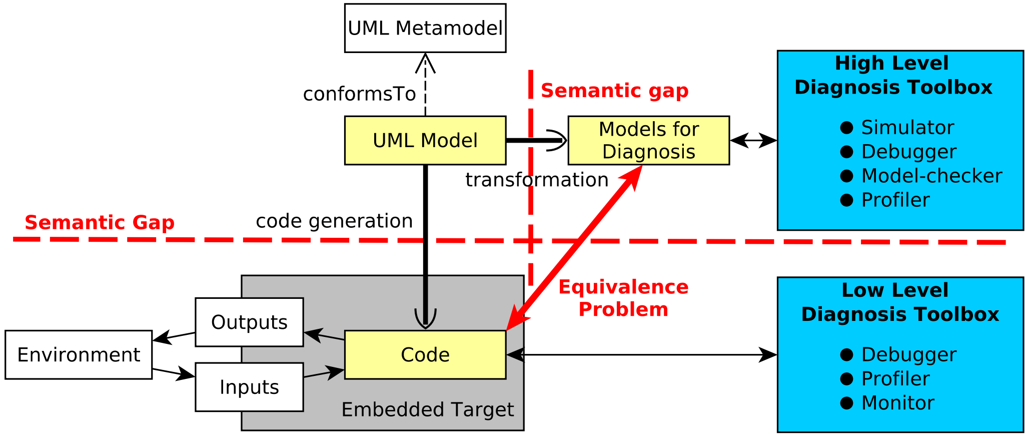
Second issue: Semantic gap between design model and diagnosis model.

Some Problems



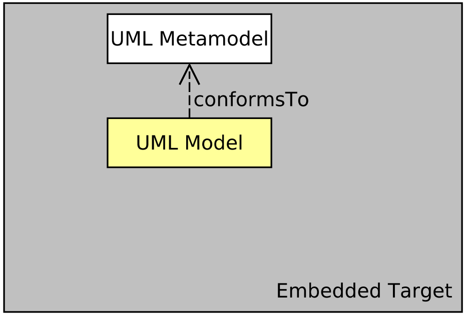
Third issue: An equivalence relation between verified formal models and deployed code should be built, proven, and maintained.

Some Problems



Main cause of these problems: Multiple definitions of the modeling language semantics.

Our Approach: A Unified Modeling Language Semantics



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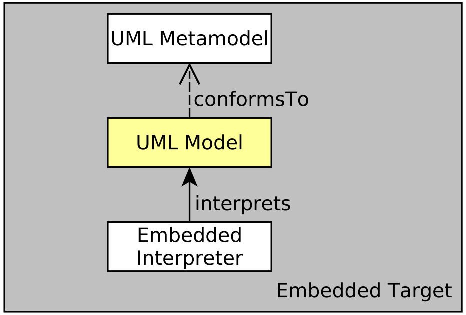

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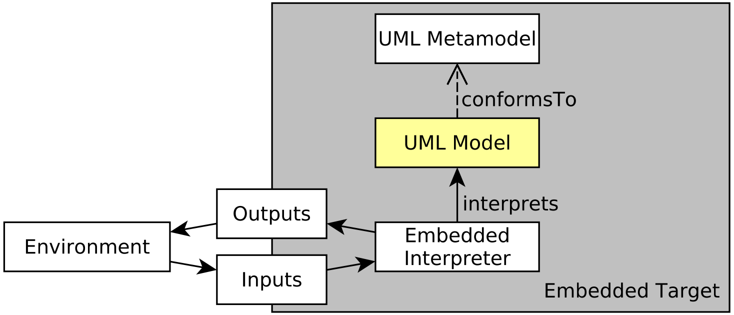

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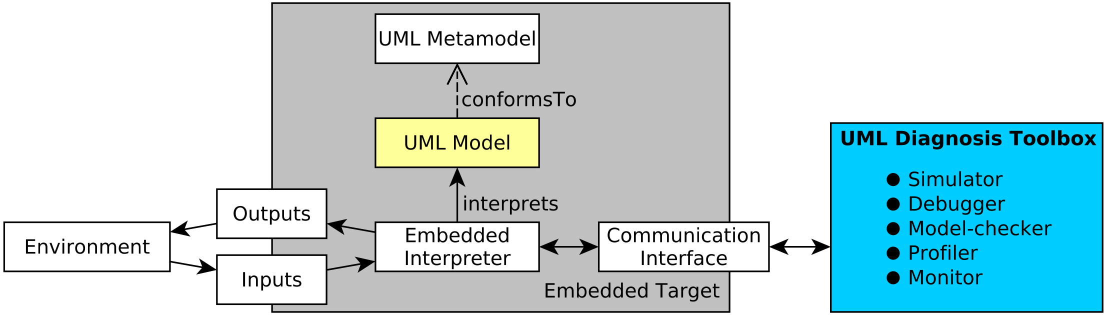

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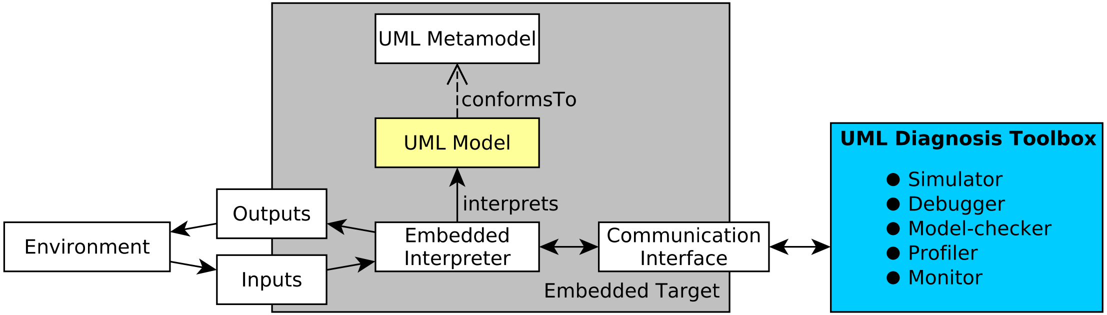
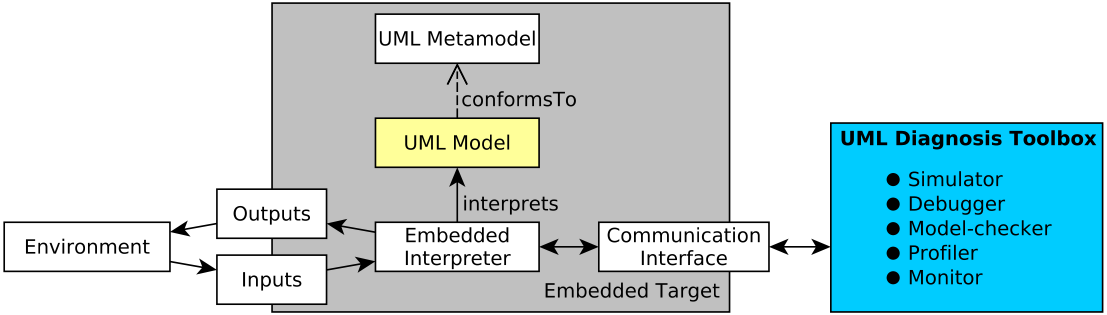


Other tools are able to execute and analyze models:
GEMOC Studio [Bousse et al., 2016], Moliz [Mayerhofer et al., 2012], Moka [Revol et al. 2018], GUML [Charfi et al, 2012], Unicomp [Ciccozzi, 2018], Mbeddr [Voelter et al., 2012], etc.

Our Approach: A Unified Modeling Language Semantics



A single implementation of the language semantics
for all activities: simulation, execution, and diagnosis.

Results

Simulation

- Trace-based simulation

Execution

- On bare-metal (without operating system) embedded targets
- On desktop computers

Diagnosis

- State-space exploration
- Deadlock detection
- Model-checking of Linear Temporal Logic (LTL) properties

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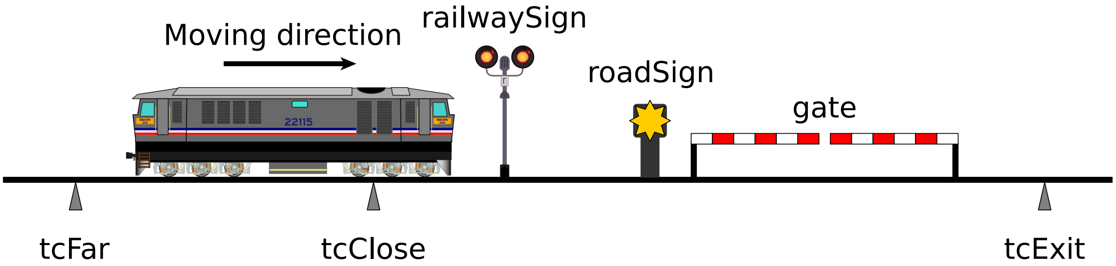
Level Crossing Overview



Goal

Ensure safety during the passage of the train

Level Crossing Model Requirements

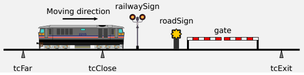
Deadlock detection

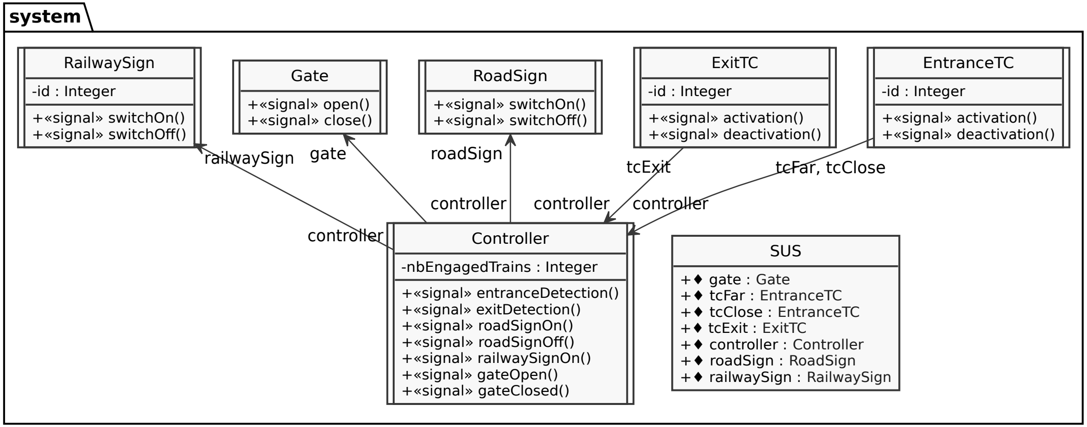
- Ensuring that the model is deadlock free.

System requirements

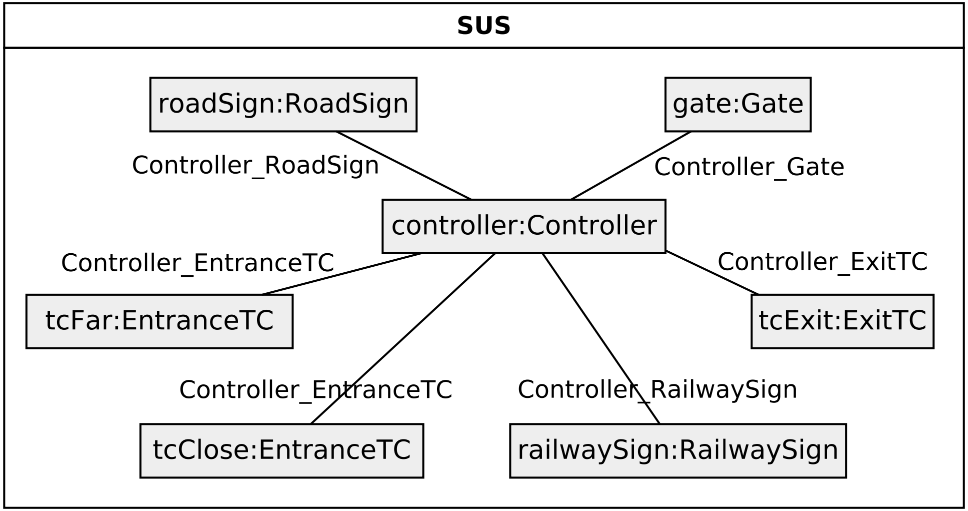
1. The Gate is closed when the Train is on the level crossing.
2. The light of the RoadSign is active when the Train is on the level crossing.
3. The Gate finally opens after being closed.
4. The light of the RoadSign is finally turn off after being activated.

Level Crossing Model (Class Diagram)

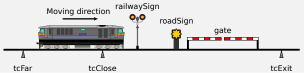


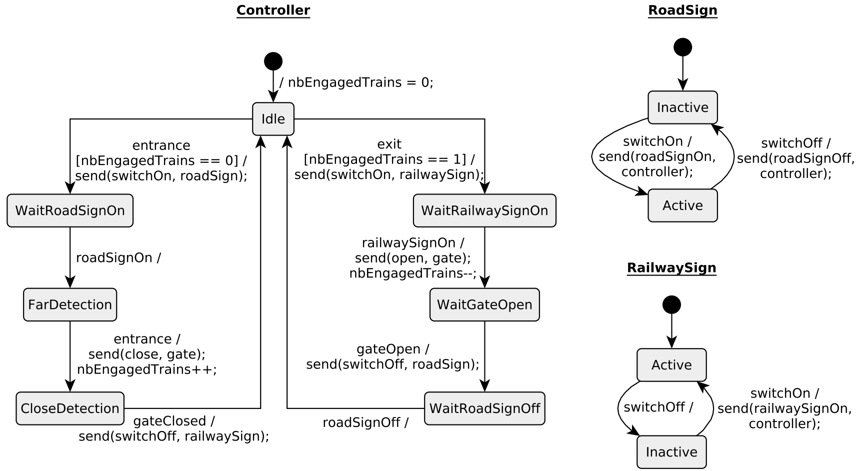


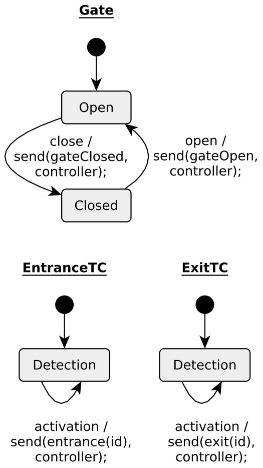
Level Crossing Model (Composite Structure Diagram)



Level Crossing Model (State Machines)




Controller
/ nbEngagedTrains = 0;
Idle
entrance [nbEngagedTrains == 0] / send(switchOn, roadSign);
exit [nbEngagedTrains == 1] / send(switchOn, railwaySign);
WaitRoadSignOn
WaitRailwaySignOn
roadSignOn /
railwaySignOn / send(open, gate); nbEngagedTrains--;
FarDetection
WaitGateOpen
entrance / send(close, gate); nbEngagedTrains++;
gateOpen / send(switchOff, roadSign);
CloseDetection
WaitRoadSignOff
gateClosed / send(switchOff, railwaySign);
roadSignOff /
RoadSign
Inactive
switchOn / send(roadSignOn, controller);
switchOff / send(roadSignOff, controller);
Active
RailwaySign
Active
switchOff /
switchOn / send(railwaySignOn, controller);
Inactive


Gate
Open
close / send(gateClosed, controller);
open / send(gateOpen, controller);
Closed
EntranceTC
Detection
activation / send(entrance(id), controller);
ExitTC
Detection
activation / send(exit(id), controller);

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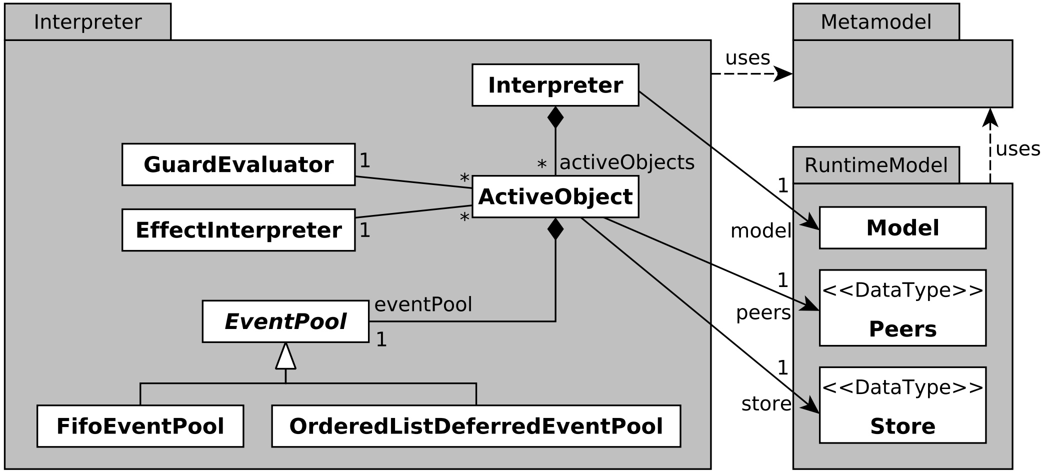
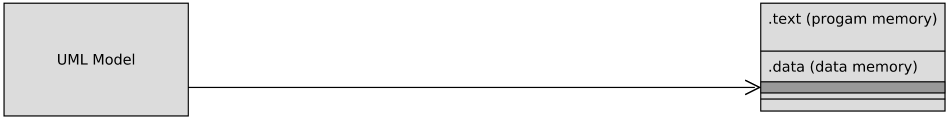
UML Interpreter Design



Loading the Runtime Model at Compile-Time

Principle



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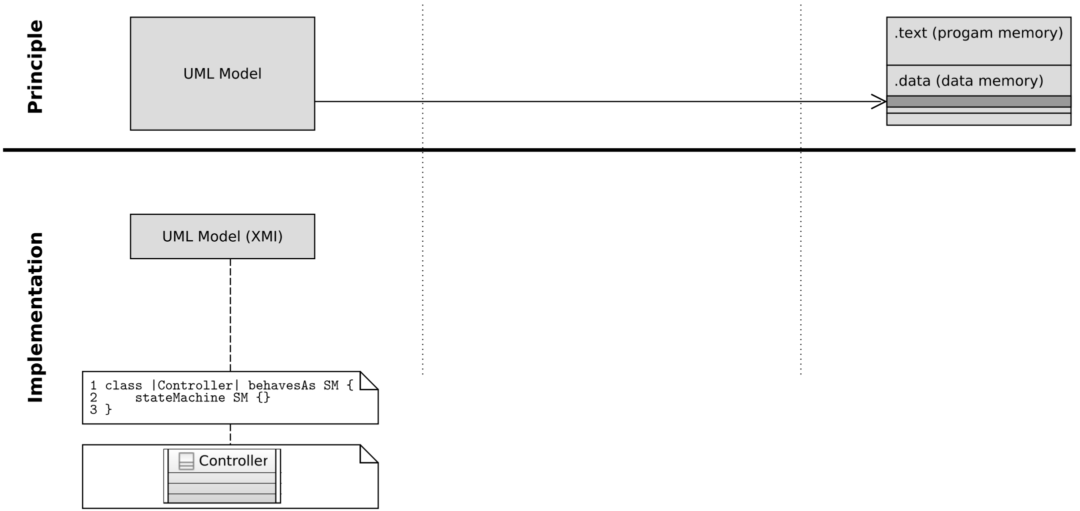
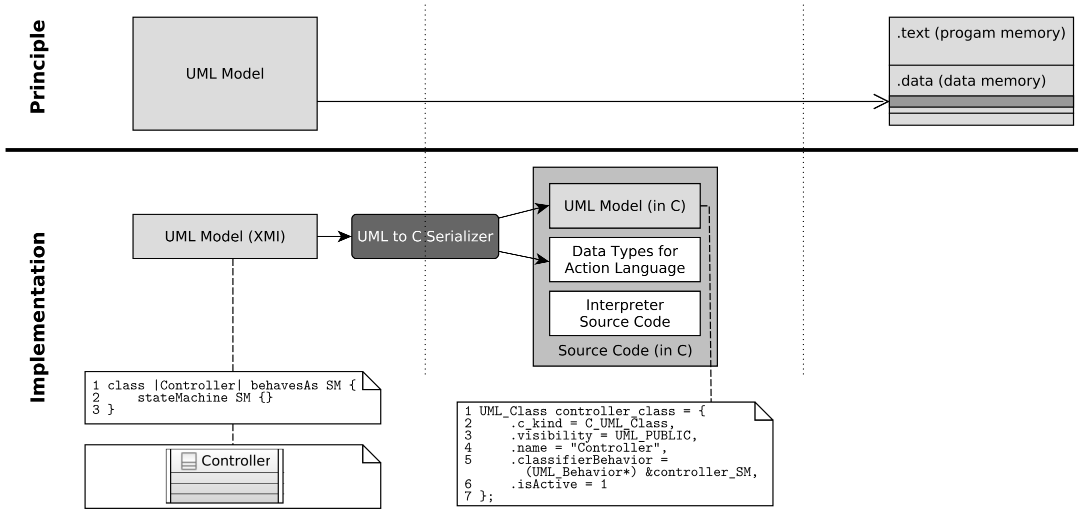


```
class |Controller| behavesAs SM {
    stateMachine SM {}
}
```

Loading the Runtime Model at Compile-Time



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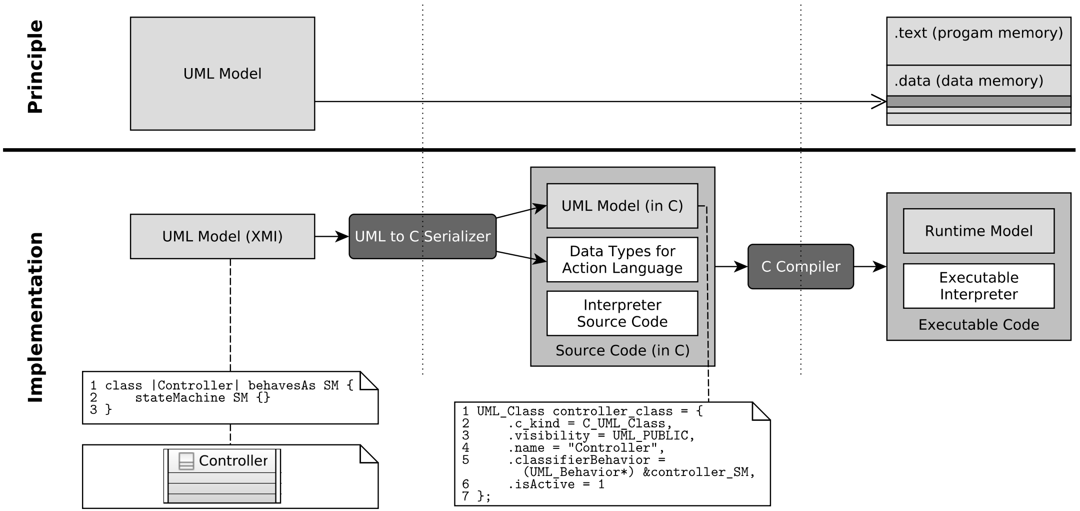
class |Controller| behavesAs SM {
    stateMachine SM {}
}
```

```
UML_Class controller_class = {
    .c_kind = C_UML_Class,
    .visibility = UML_PUBLIC,
    .name = "Controller",
    .classifierBehavior =
      (UML_Behavior*) &controller_SM,
    .isActive = 1
};
```

Loading the Runtime Model at Compile-Time



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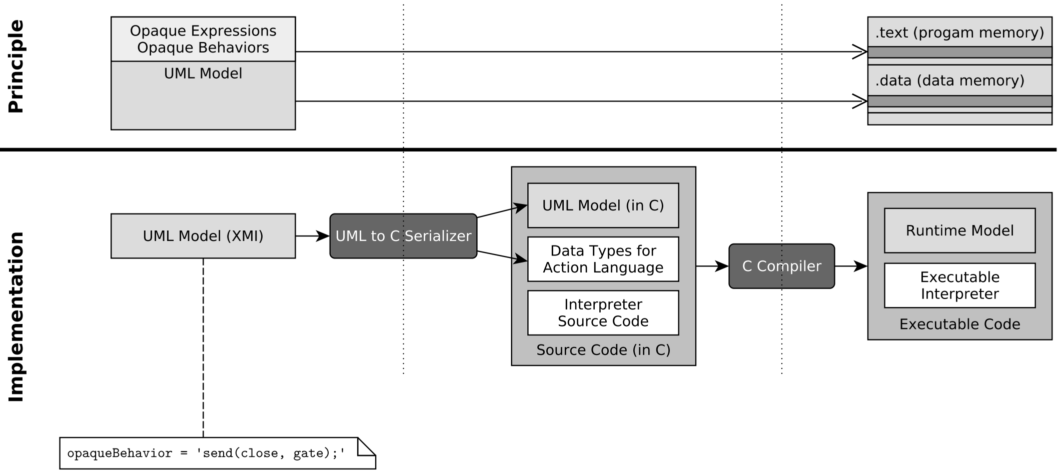

```
opaqueBehavior = 'send(close, gate);'
```

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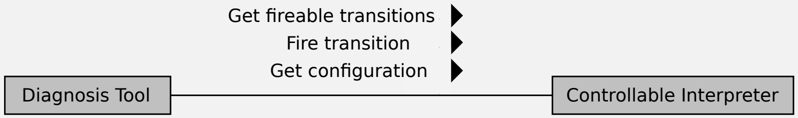
UML Model Diagnosis: Goals and Requirements

Our goals

- Simulate the model

Requirements to achieve these goals



UML Model Diagnosis: Goals and Requirements

Our goals

- Simulate the model (with rollback for back-in-time simulation)
- Explore the model state-space
- Detect deadlocks

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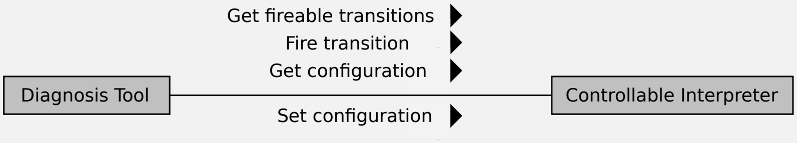
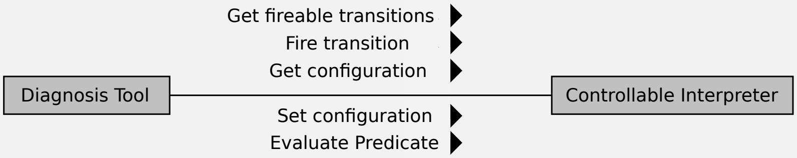


UML Model Diagnosis: Goals and Requirements

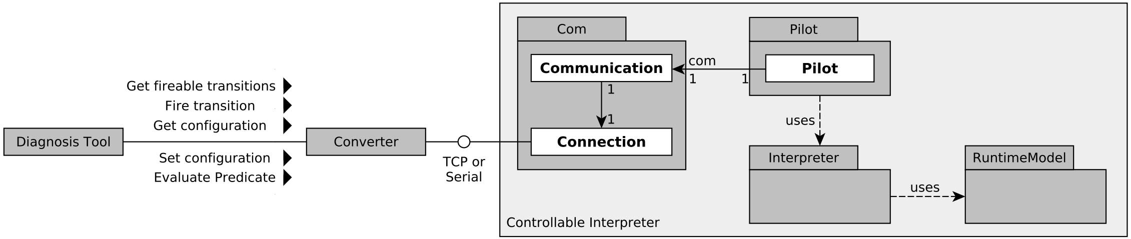
Our goals

- Simulate the model (with rollback for back-in-time simulation)
- Explore the model state-space
- Detect deadlocks
- Verify formal properties via model-checking

Requirements to achieve these goals



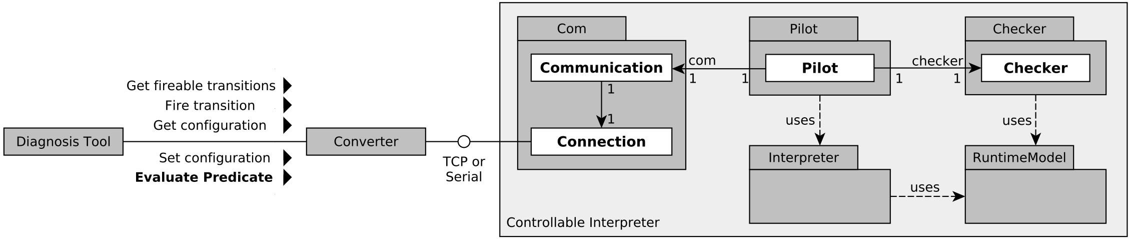
Diagnosis Design



Design of an application layer protocol over:

- TCP connection
- Serial connection (e.g., UART, USB)

Diagnosis Design



A formal property consists of:

- Atomic propositions (i.e., predicates related to model concepts)
  - $\rightarrow$ Compiled into executable code by the converter
  - $\rightarrow$ Evaluated by the controllable interpreter
- Logical operators used to link atomic propositions together
  - $\rightarrow$ Evaluated by the diagnosis tool (model-checker)

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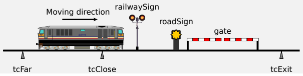
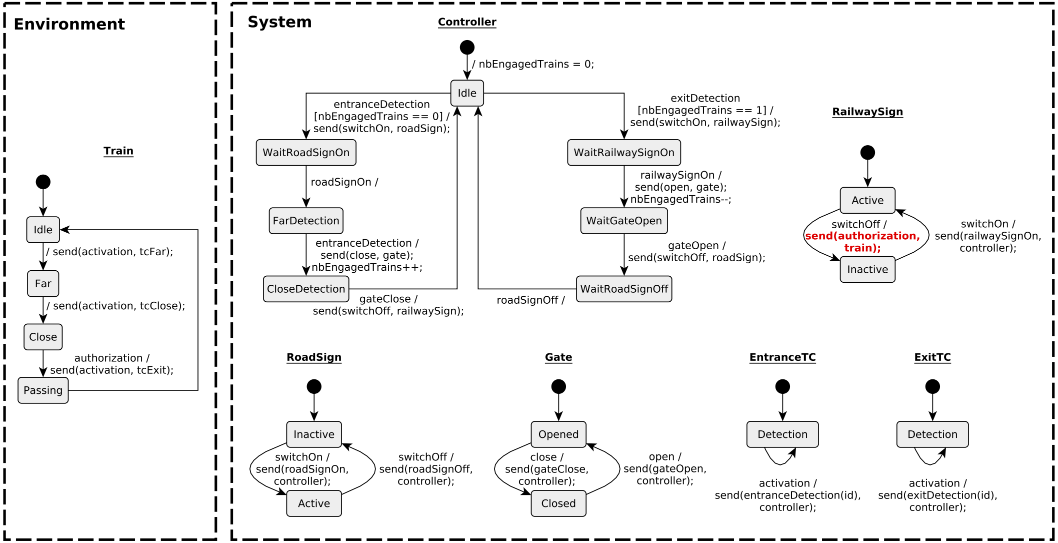
Level Crossing Model Under Verification





Model-Checking of the Level Crossing Model

Expression of Properties into LTL

1. `[] !(trainIsPassing && gateIsOpen)`
2. `[] !(trainIsPassing && roadSignIsOff)`
3. `[] (gateIsClosed -> <> gateIsOpen)`
4. `[] (roadSignIsOn -> <> roadSignIsOff)`

Model-Checking of the Level Crossing Model

Expression of Properties into LTL

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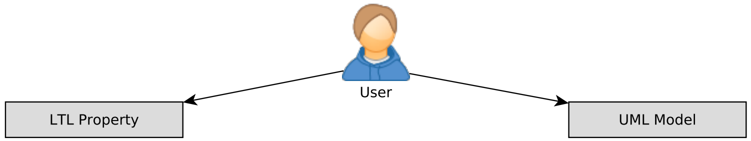
4. `[] (roadSignIsOn -> <> roadSignIsOff)`

Expression of Atomic Propositions

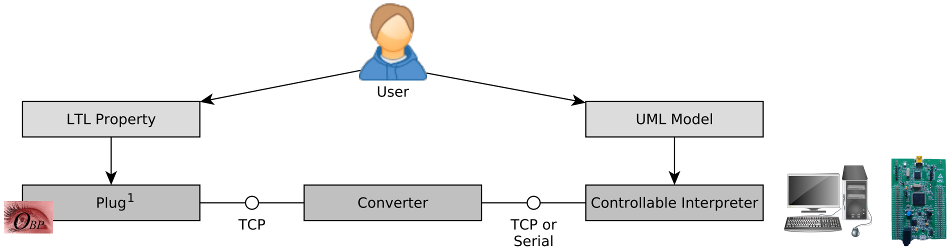
- `trainIsPassing = |train.state == PASSING|`
- `gateIsClosed = |gate.state == CLOSED|`
- `gateIsOpen = |gate.state == OPEN|`
- `roadSignIsOn = |roadSign.state == ACTIVE|`
- `roadSignIsOff = |roadSign.state == INACTIVE|`

Experiments



[1]https://plug-obp.github.io/

Experiments



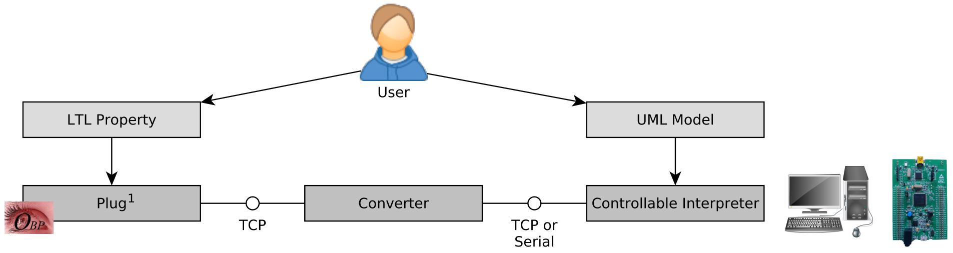
Experiments

Diagnosis of the level-crossing model on:

- Desktop computer
- STM32 discovery

[1]https://plug-obp.github.io/

Experiments



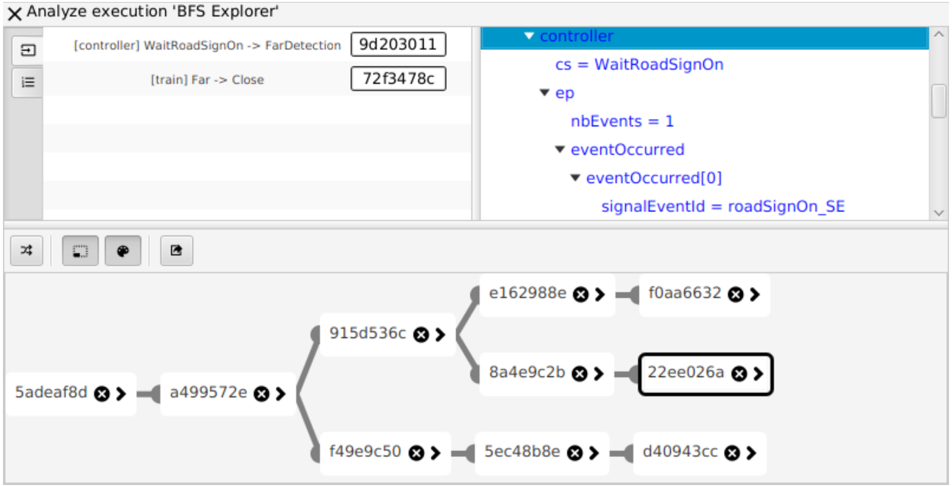
Experiments

Using the two implementations of the event pool

- the FIFO implementation that drops ignored events
- the ordered list implementation that defers ignored events

[1] `https://plug-obp.github.io/`

Results - Simulation



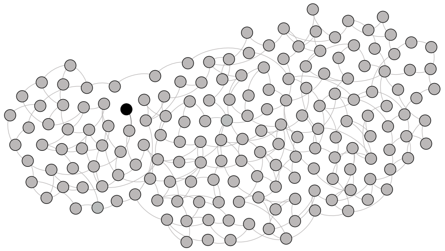
Analyze execution 'BFS Explorer'

[controller] WaitRoadSignOn -> FarDetection	9d203011
[train] Far -> Close	72f3478c

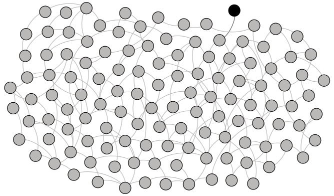
```
▼ controller
    cs = WaitRoadSignOn
  ▼ ep
      nbEvents = 1
    ▼ eventOccurred
      ▼ eventOccurred[0]
          signalEventId = roadSignOn_SE
```

Results - State-space Exploration

	FIFO (drops)	OrderedList (defers)
Nb configurations	173	122
Nb transitions	276	209



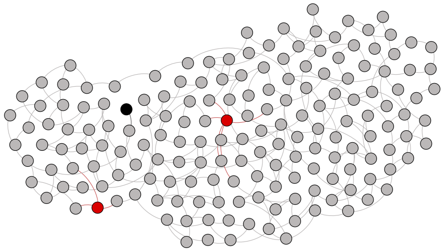
State-space graph with FIFO

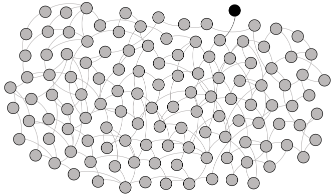


State-space graph with OrderedList

Results - Deadlock Detection

	FIFO (drops)	OrderedList (defers)
Nb configurations	173	122
Nb transitions	276	209
Nb deadlocks	2	0


State-space graph with FIFO


State-space graph with OrderedList

Results - LTL Model-checking

	FIFO (drops)	OrderedList (defers)
`[] !(trainIsPassing && gateIsOpen)`	✓	✓
`[] !(trainIsPassing && roadSignIsOff)`	✓	✓
`[] (gateIsClosed -> <> gateIsOpen)`	✗	✓
`[] (roadSignIsOn -> <> roadSignIsOff)`	✓	✓

✓: Property verified ✗: Property violated

Execution performance

Verification of the 4 properties on a desktop computer[1] in 1.71 seconds

[1] Intel® Core™ i7-8550U CPU at 1.80GHz with 4 cores, 16GB DDR4 2400MHz RAM, running a Linux OS

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Conclusion

Our contribution

- Use the same operational semantics implementation for execution and LTL verification
- What is checked during model diagnosis is what is executed at runtime

[1]Preliminary study: `https://plug-obp.github.io/experiments/`

Conclusion

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Limitations

- No support for UML activities
- No evaluation of the resource overhead of the interpreter

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Conclusion

Our contribution

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- What is checked during model diagnosis is what is executed at runtime

Limitations

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- No evaluation of the resource overhead of the interpreter

Perspectives

- Support multiple action languages (e.g., UML activities / Alf)
- Integrate the tool with UML modelers (e.g., Papyrus) [1]
- Apply this approach to other domain-specific languages (e.g., Capella in Eclipse PolarSys)

[1] Preliminary study: `https://plug-obp.github.io/experiments/`

Thank you for your attention

Bibliography I

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Interpreter Execution

- At startup: initialization of all active objects
- At each interpretation step:
  - Compute the set of fireable transitions by
    - Evaluating transitions guards
    - Checking if transitions triggers are satisfied
  - Fire the first fireable transition of each active object by:
    - Executing transitions effects
    - Updating current states of active objects

Verification of Formal Properties

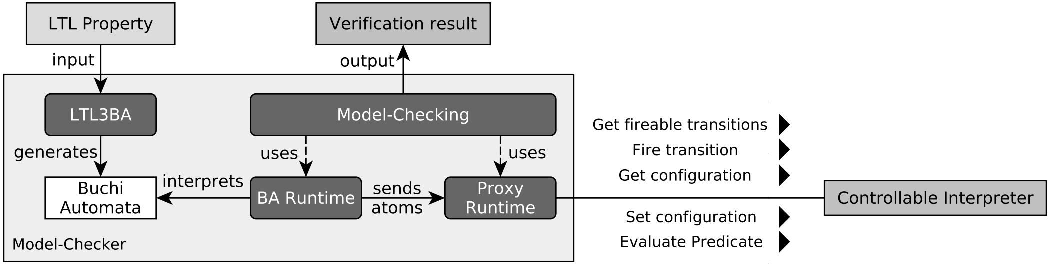
A formal property consists of:

- Atomic propositions (i.e., predicates related to model concepts)
  $\Rightarrow$ Evaluated by the interpreter
- Logical operators link atomic propositions together
  $\Rightarrow$ Evaluated by the model-checker

Process to Evaluate an Atomic Proposition

- Express atomic proposition using the action language of the interpreter
- Generate the corresponding C function (on Converter)
- Compile the C function into a dynamic library (on Converter)
- Load dynamically the library into the interpreter
- Request evaluation of the atomic proposition by the **Checker**

Application to Model-Checking



Connection to Plug (`https://plug-obp.github.io/`), an extension of the OBP model-checker:

- ProxyRuntime implements a TCP client and the application layer protocol
- Nested DFS algorithm [7]
- Verification of LTL properties