Automated Goal Operationalisation based on Interpolation and SAT Solving

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{rdegiovanni, naguirre}@dc.exa.unrc.edu.ar
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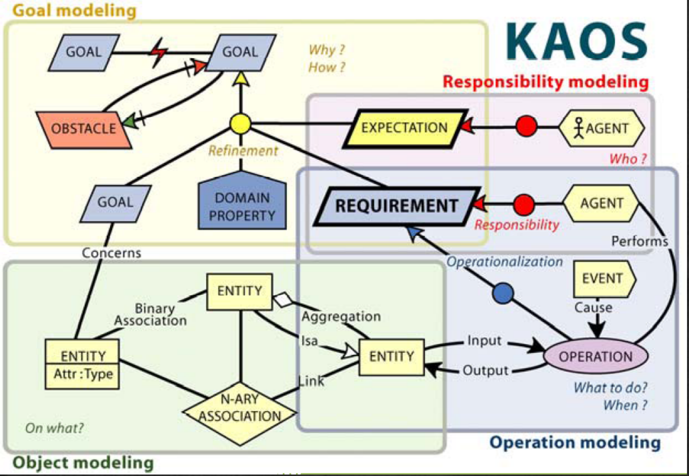
Goal Oriented Requirements Engineering

- Goals are objectives the system under consideration must achieve.
- GORE refers to the use of goals for requirements elicitation, elaboration, organization, specification, analysis, documentation and evolution.
- KAOS Knowledge Acquisition in autOmated Specifications:
  - a conceptual model for acquiring and structuring requirements models;
  - a set of strategies for elaborating requirements using this framework;
  - an automated assistant to provide guidance in the acquisition process.

KAOS specifications



Goal Model

Objectives the system should meet are defined in this model and interrelated through AND/OR refinement links.

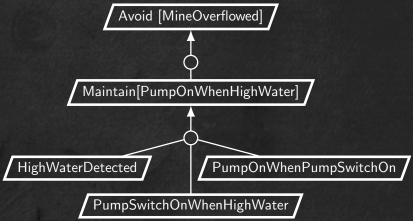


Figura: Goal Model.

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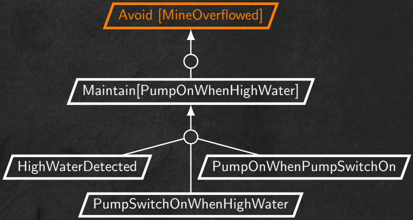

Figura: Goal Model.

- High level goals

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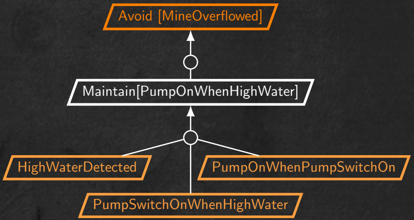

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- High level goals
- Low level goals

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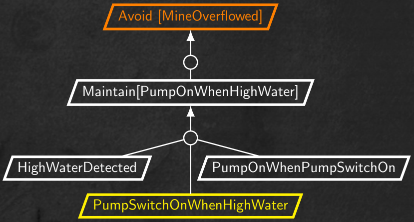

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- High level goals
- Low level goals
- Requirements

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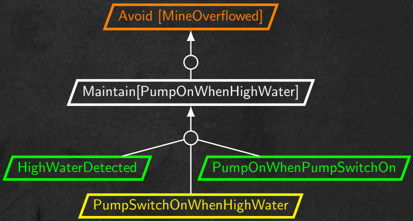

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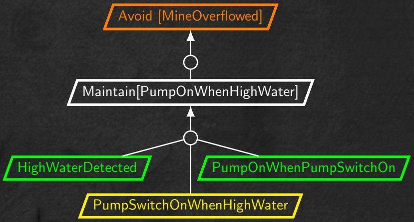


Figura: Goal Model.

- High level goals
- Low level goals
- Requirements
- Expectations
- Goal patterns:
  - Avoid: $C \Rightarrow \neg T$
  - Maintain: $C \Rightarrow T$

Object Model

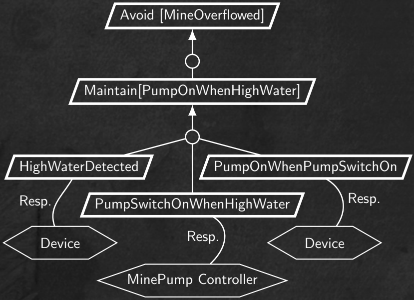
This model defines the domain entities, relationships and attributes that are relevant to goal formulations.

Figura: Object Model.

- Objects can be specified formally by means of domain invariants.

Responsibility Model

The agents in the system are described together with their interfaces and responsibilities with respect to the goals.



- Responsibility assignments provide a criterion for stopping the goal refinement process.
- A goal assigned as the responsibility of a single agent must not be refined further.

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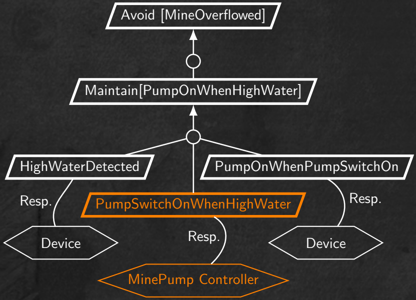

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Operation Model

This model defines the services to be provided by software agents.

```
Operation switchPumpOn
   DomPre   !PumpOn
   DomPost  PumpOn
   ReqPre   True
   ReqTrig  False
```

- input-output relations over components of the object model.
- operation applications define state transitions.

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- input-output relations over components of the object model.
- operation applications define state transitions.
- domain conditions capture the elementary state transitions in the domain.
- required conditions capture additional strengthenings to meet the goals.
  - ReqPre: enabling condition.
  - ReqTrig: triggering condition.

Goal Operationalisation

Operation *switchPumpOn*
  DomPre `!PumpOn`
  DomPost `PumpOn`
  ReqPre `True`
  ReqTrig `False`

Operationalization refers to the process of prescribing additional pre-, trigger-, and postconditions on operations in order to achieve goal specifications.

Safety Goal [PumpOnWhenHighWaterAndNoMethane]

$$\Box(\mathtt{HighWater} \wedge \neg\mathtt{Methane} \rightarrow \bigcirc\mathtt{PumpOn})$$

Goal Operationalisation

Operation *switchPumpOn*
DomPre !PumpOn
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A goal is correctly operationalised by a set of operations, if satisfying all required conditions in the set guarantees the satisfaction of the goal.

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DomPre !PumpOn
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HighWater & !Methane

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Safety Goal [PumpOnWhenHighWaterAndNoMethane]

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Interpolation

Given two sets A and B of formulas such that $A \cup B$ is unsatisfiable, an interpolant for A and B is a formula I such that:

- I is `true` in all models of A,
- I is `false` in all models of B, and
- I is in $\mathcal{L}(A) \cap \mathcal{L}(B)$, i.e., the common language of A and B.

Simple Example

$A \equiv p \wedge q \qquad B \equiv \neg q \wedge r \qquad I \equiv q$

Interpolation to Refine Requirements

Suppose we obtain a counterexample trace T, violating a particular goal G.

- If we build a formula F_T capturing trace T, and a formula F_G capturing the fact that G holds at the last state
    - clearly $F_T \wedge F_G$ is unsatisfiable.
- We can produce an interpolant I from these formulas, that provides a condition whose validity leads to the goal violation.

Interpolation to Refine Requirements

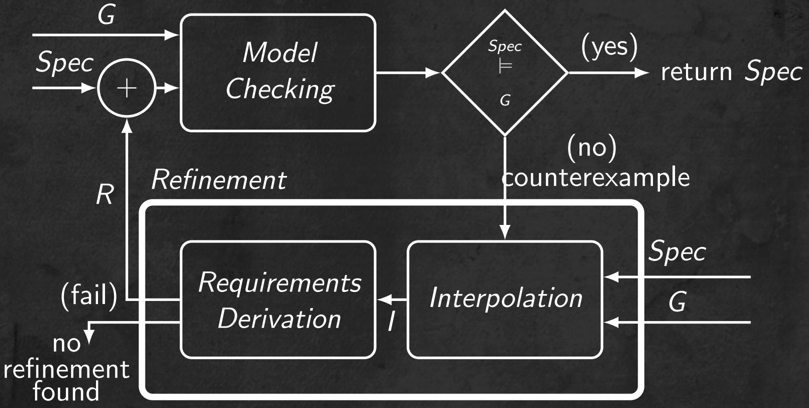
- I is a property of the trace T, which implies the negation of the goal G.
- The interpolant allows us to obtain a weaker "counterexample" than T, a condition reachable from the initial state which leads to the violation of a goal.
  - solely by removing I, we do not guarantee the satisfaction of G,
  - but not removing it guarantees its violation.
- Notice that interpolation is, in some sense, a form of generalisation.

Brief Overview

We present an approach for goal operationalisation, that automatically computes required pre/triggering conditions for operations, in order to fulfil a set of goals.

- Iterative,
- base on Interpolation and SAT solving,
- safety and the time progress goals,
- a wide range of liveness goals, namely, reactivity properties.

The Approach



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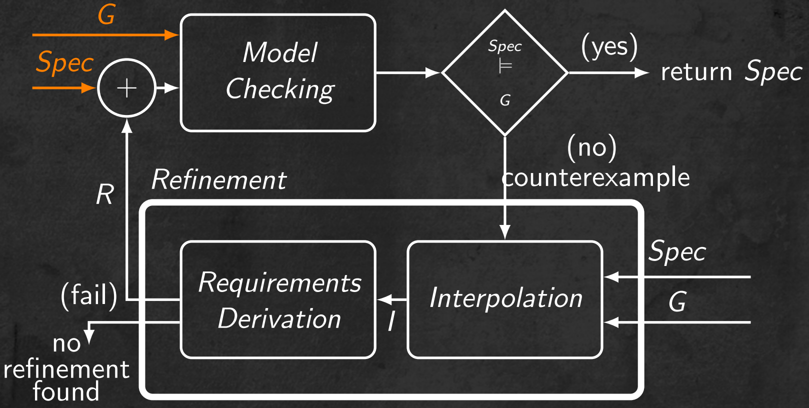

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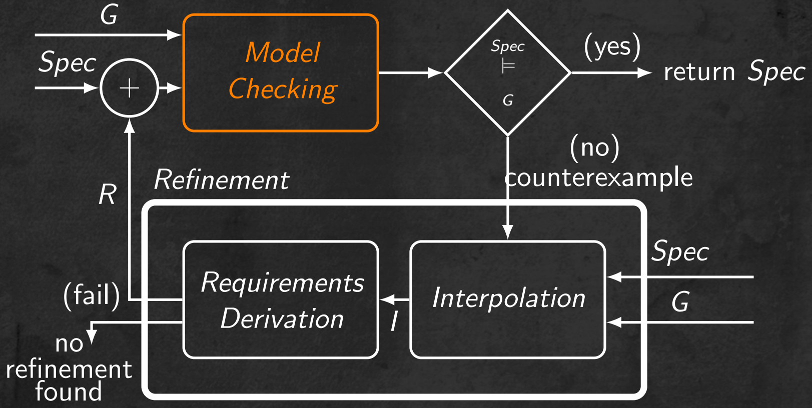

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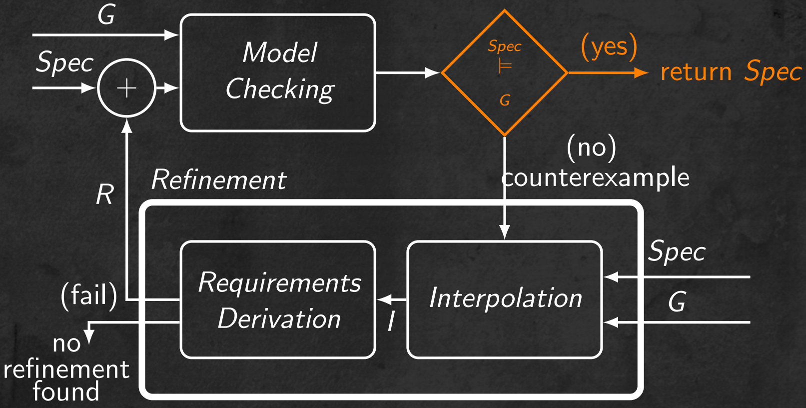

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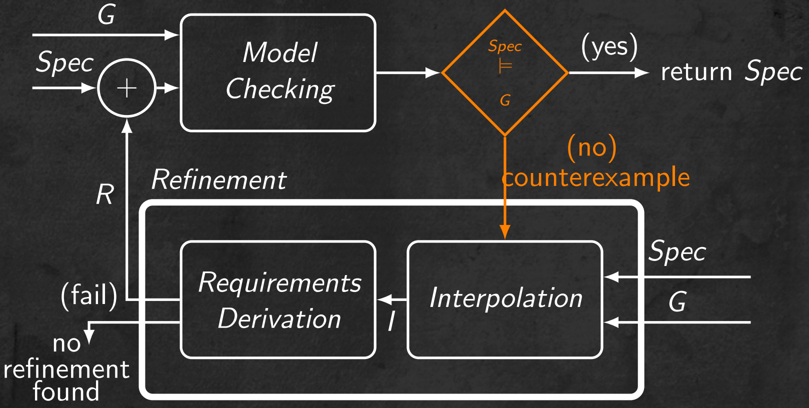

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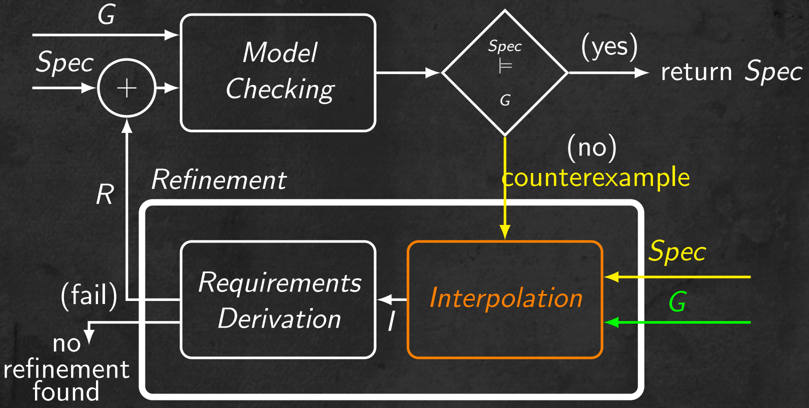

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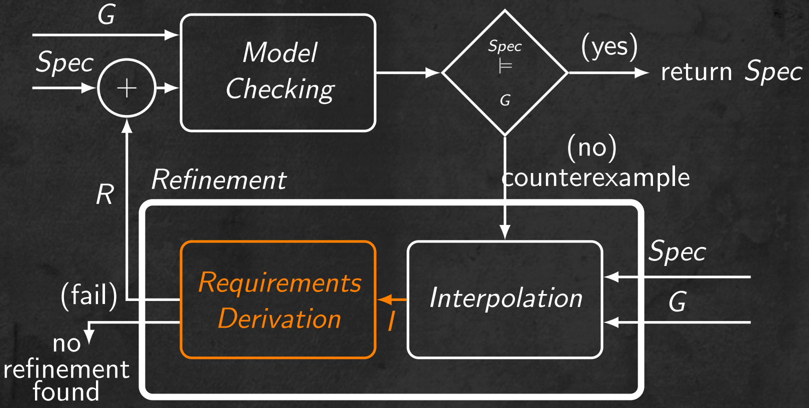

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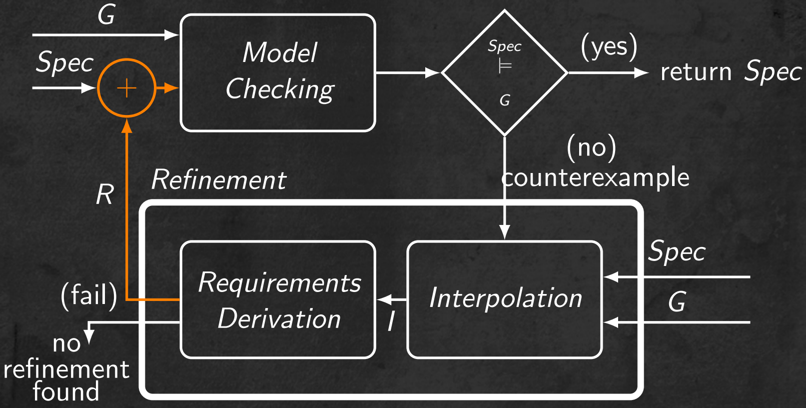

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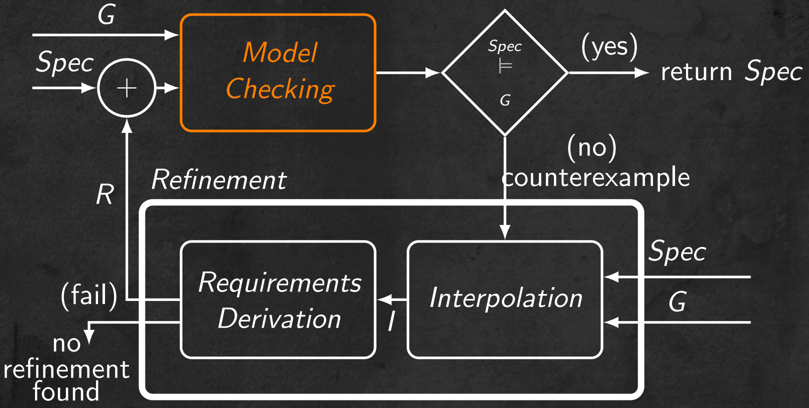

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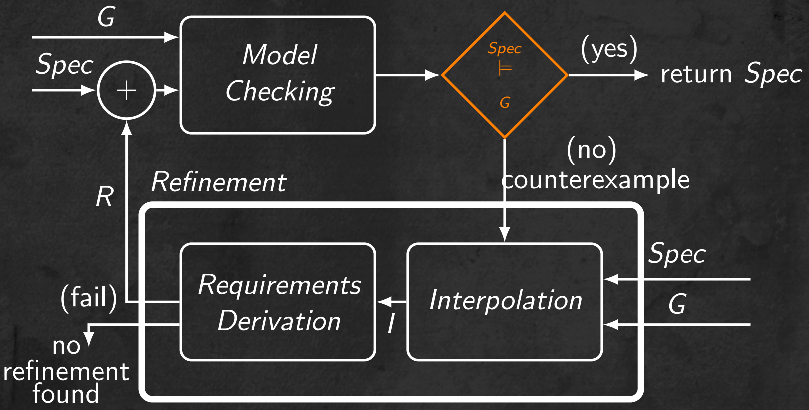

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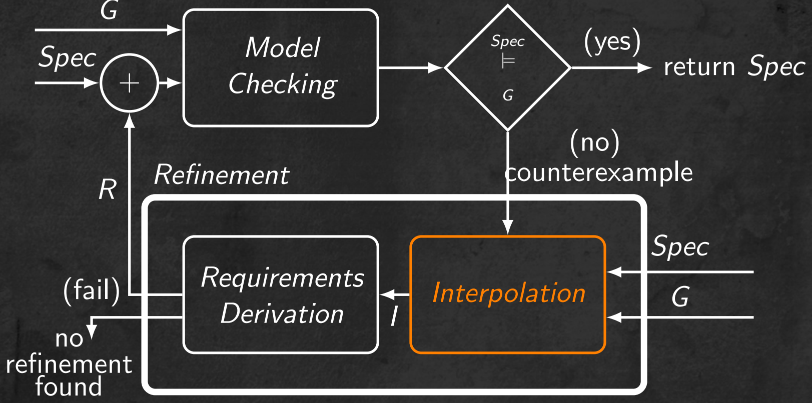

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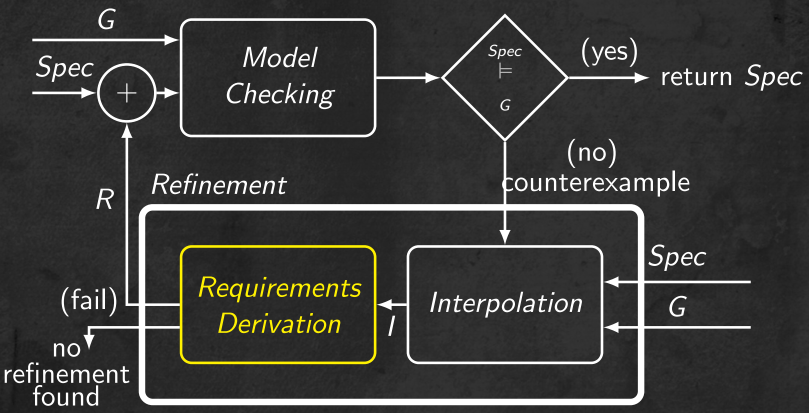
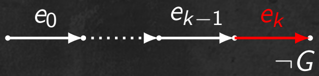


Requirements Derivation Phase

$$\bullet \xrightarrow{e_0} \bullet \cdots\cdots \blacktriangleright \bullet \xrightarrow{e_{k-1}} \bullet \xrightarrow{e_k} \underset{\neg G}{\bullet}$$

A counterexample may be removed either by:

Requirements Derivation Phase



A counterexample may be removed either by:

- prohibiting the occurrence of an operation from certain states
  - i.e., strengthening the operation's required precondition,

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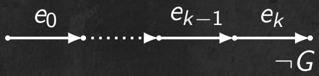

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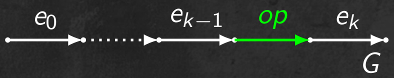

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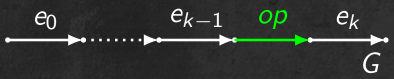

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- prohibiting the occurrence of an operation from certain states
  - i.e., strengthening the operation's required precondition,
- or forcing an operation to occur in certain states
  - i.e., weakening its required triggering condition.

The approach is concerned with automatically detecting which of the above cases is necessary.

- *weakest preconditions play an important role.*

Strengthening Required Preconditions

PumpOffWhenLowWater =
$\Box(\texttt{LowWater} \rightarrow \bigcirc\neg\texttt{PumpOn})$

Counterexample:

tick	LowWater
switchPumpOn	LowWater & PumpOn
tick	LowWater & PumpOn

$I = \texttt{LowWater} \wedge \texttt{PumpOn}$

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$$I' = WP(I, \texttt{switchPumpOn}) = \texttt{LowWater}$$

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$I = \texttt{LowWater} \wedge \texttt{PumpOn}$

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- we compute the weakest precondition of the interpolant with respect to the last operation.
- the operation switchPumpOn is able to control the value of the interpolant.

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- we compute the weakest precondition of the interpolant with respect to the last operation.
- the operation switchPumpOn is able to control the value of the interpolant.
- then by forbidding switchPumpOn to occur when LowWater, we get rid of this counterexample, and contribute to stop violating G.

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  - check it is not obliged to be executed when `LowWater`.

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$ReqPre(\texttt{switchPumpOn}) = \neg\texttt{LowWater}$

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Weakening Required Triggering Conditions

PumpOnWhenHighWaterAndNoMethane =

$\square(\mathtt{HighWater} \land \neg\mathtt{Methane} \rightarrow \bigcirc\mathtt{PumpOn})$

```
Counterexample:
tick    aboveLow    tick
aboveHigh  HighWater
tick       HighWater
tick       HighWater
```

$I = \mathtt{HighWater} \land \neg\mathtt{Methane} \land \neg\mathtt{PumpOn}$

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aboveHigh	HighWater	
tick	HighWater	
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- The operation to be triggered, say a_t, must meet two conditions:

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$$I \Rightarrow DomPre(a_t) \wedge ReqPre(a_t)$$

Weakening Required Triggering Conditions

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$$I \wedge \bigcirc DomPost(a_t) \Rightarrow \bigcirc\neg I$$

Weakening Required Triggering Conditions

PumpOnWhenHighWaterAndNoMethane =

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Counterexample:

```
tick      aboveLow   tick
aboveHigh HighWater
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$I = \texttt{HighWater} \wedge \neg\texttt{Methane} \wedge \neg\texttt{PumpOn}$

$ReqTrig(\texttt{switchPumpOn}) =$
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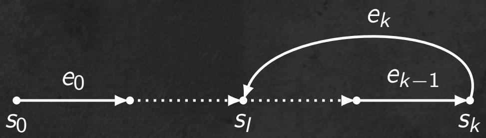
Reactivity Liveness Properties

- Manna and Pnueli's characterisation: `([]<>As -> []<>G)`.
- A violation of a property of this kind consists of a prefix (finite part) leading to a loop in which the *As* is satisfied, but not `G`.
- To compute an interpolant for this counterexample, we encode the reactivity goal: $P = (\bigvee_{i=l}^{k} As^i) \Rightarrow (\bigvee_{j=l}^{k} G^j)$



Reactivity Liveness Properties

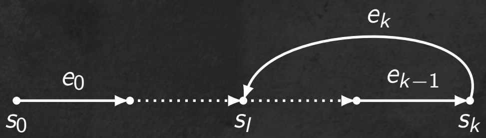
- The interpolant is a weaker representation of the loop part that explains what is wrong in the loop.
- We search for an operation a_t:
    - can be executed at some point in the loop,
    - a_t's execution reaches a states that does not satisfy the interpolant (i.e., "breaks" the loop).

Reactivity Liveness Properties

- If we find a_t, then we refine:

$$ReqTrig(a_t) = ReqTrig^{pre}(a_t) \vee (ReqPre(a_t) \wedge \neg G)$$

- Notice that we do not refine a new triggering condition based on the interpolant.
  - we may produce triggering conditions *weaker* than needed.



Conclusions and Future Works

- We presented an approach for goal operationalisation, that automatically computes required pre-/triggering conditions for operations, in order to fulfil a set of goals.
- The approach is correct, but it is not complete.
- It applies to safety goals and particular kinds of liveness goals, namely reactivity properties.
- We have developed some case studies, and compared with previous approaches.