Softwaretechnik / Software-Engineering

Lecture 17: Software Engineering Research

2015-07-16

Prof. Dr. Andreas Podelski, **Dr. Bernd Westphal**

Albert-Ludwigs-Universität Freiburg, Germany

Schedule of the Block “Invited Talks”

- **12:15 - 12:17:39** — Introduction
- **12:17:53 - 12:55**
  - “The Wireless Fire Alarm System:
    Ensuring Conformance to Industrial Standards through Formal Verification”

    Sergio Feo Arenis
- **12:55 - 13:05** — Break
- **13:05 - 13:30**
  - “Towards Successful Subcontracting for Software in Small to Medium-Sized Enterprises”

    Daniel Dietsch
- **13:30 - 13:55**
  - “Traces, Interpolants, and Automata:
    a New Approach to Automatic Software Verification.”

    Dr. Jochen Hoenicke

Introduction	L 1:	20.4., Mo
	T 1:	23.4., Do
Development Process, Metrics	L 2:	27.4., Mo
	L 3:	30.4., Do
	L 4:	4.5., Mo
	T 2:	7.5., Do
	L 5:	11.5., Mo
Requirements Engineering	-	14.5., Do
	L 6:	18.5., Mo
	L 7:	21.5., Do
	-	25.5., Mo
	-	28.5., Do
	T 3:	1.6., Mo
	-	4.6., Do
	L 8:	8.6., Mo
	L 9:	11.6., Do
	L 10:	15.6., Mo
	T 4:	18.6., Do
Architecture & Design, Software Modelling	L 11:	22.6., Mo
	L 12:	25.6., Do
	L 13:	29.6., Mo
	L 14:	2.7., Do
	T 5:	6.7., Mo
Quality Assurance	L 15:	9.7., Do
	L 16:	13.7., Mo
Invited Talks	L 17:	16.7., Do
	T 6:	20.7., Mo
Wrap-Up	L 18:	23.7., Do

The Wireless Fire Alarm System: Ensuring Conformance to Industrial Standards through Formal Verification

Sergio Feo-Arenis Bernd Westphal Daniel Dietsch
Marco Muñiz Siyar Andisha

Software Engineering
Albert-Ludwigs-University Freiburg

July 16th – 2015

Context

- Develop a wireless fire alarm system (safety critical).
- Requires certification to international standards.
- Small company with little to no experience with formal methods, but an acute need for product safety and quality.
- Project duration: ca. 2 years.

Goals

- Can formal methods handle development projects in the context af a small company (SME)? at which cost?
- How to tackle requirements from industrial standards using formal methods?
- What research ideas emerged from the project?

Scenario

Develop a Standard-compliant Fire Alarm System

- Use a wireless protocol that supports range extenders (repeaters).
- Maximize energy efficiency.
- Ensure compliance with the norm DIN EN-54 (Part 25).

Scenario

EN-54 Requirements

- Detect and display communication failures in at most 300+100 seconds.
- Display alarms timely:
    - In at most 10 seconds for single alarms.
    - The first in 10 seconds and the last in 100 seconds for 10 simultaneous.
- Fulfill even when there are other users of the frequency.

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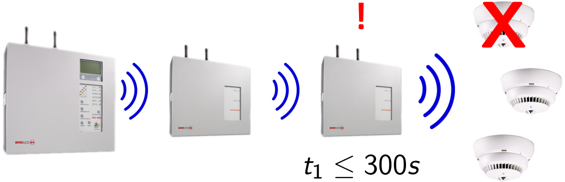

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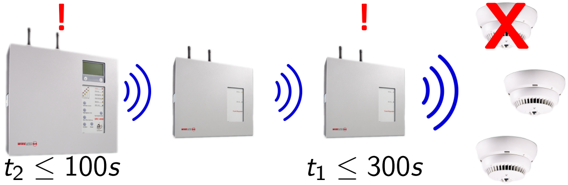

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Challenges

Testing a design is difficult:

- There is a very large number of possible system configurations.
- Requires a prototype implementation.
- Controlling timing and radio communication environments requires costly procedures.
- The requirements assume an inherent nondeterminism.

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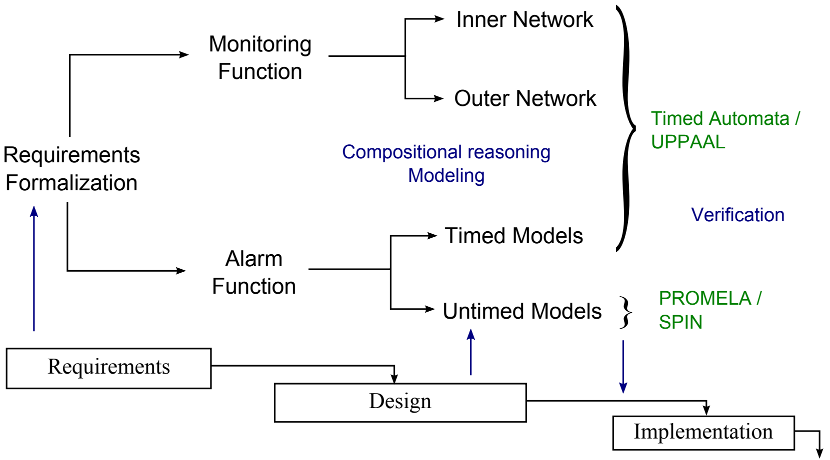
Thus:
Verification could help.

General Risks

- Development in a small company.
  - Development team of 3 people: 1 computer scientist, 1 programmer, 1 electrical engineer.
- Underspecified standard requirements.
- High cost of certification.
  - A failed certification attempt threatens the very existence of the company.
  - Market introduction deadlines have high priority.
- Lack of structure in the software development process.
  - Weak documentation practices.
  - No familiarity with model-based development.

Overview

We accompanied the conventional development process as consultants.



What to Verify: Requirements Formalization

EN-54 provides:

- High-level real-time requirements (hard to formalize).
- Test Procedures.

Effort required: Months. It was necessary to negotiate ambiguities with the certification authority.

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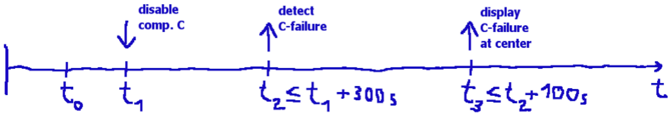
Chose duration calculus (DC) as formalism to generalize and capture the standard requirements based on test procedures.

- The formalism was not familiar to developers or the certificate authority.
- Required developing a graphical means of communication between the stakeholders. [Visual Narratives]

What to Verify: Requirements Formalization

$$\exists\, t_0, t_1, t_2, t_3 \bullet t_0 \leq t_1 \leq t_2 \leq t_3$$
$$\wedge\, FS(t_0) \wedge Disab_S(t_1) \wedge Det_S(t_2) \wedge Disp_S(t_3)$$
$$\wedge\, t_2 \leq t_1 + 300 \wedge t_3 \leq t_2 + 100$$
$$\wedge\, \forall\, t \bullet t \geq t_0 \wedge t \neq t_1 \wedge t \neq t_2 \wedge t \neq t_3 \implies \emptyset(t)$$

$$\downarrow$$



What to Verify: Requirements Formalization

Result of the DC formalization:

- Captured test procedures.
- Captured environment assumptions during tests (frequency jamming, simplifying assumptions).
- Generalized to cover all components in arbitrary system topologies.

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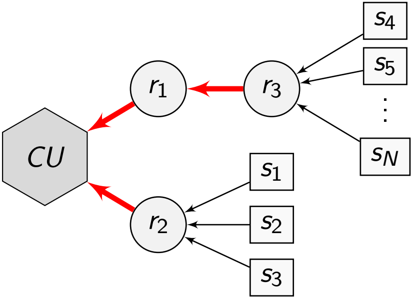
In total:

- 6 (quantified) observables
- 7 (quantified) testable DC formulae

Modeling: Monitoring Function

Topologies can be decomposed:



Modeling: Monitoring Function

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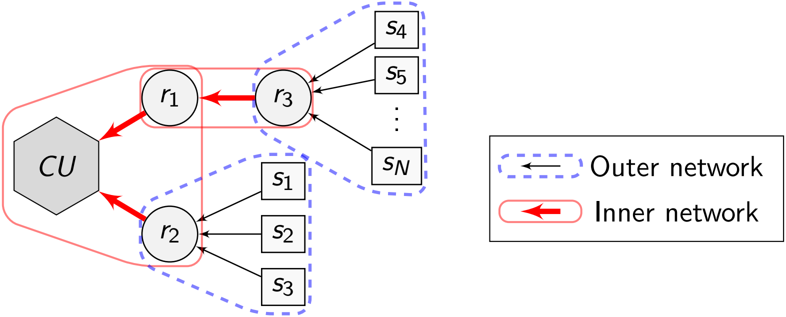

We modeled each "network" separately using networks of timed automata (UPPAAL).

Modeling: Monitoring Function

Decomposition gives way to additional proof obligations:

- No interference between networks (by design).
- No collisions (TDMA). [Guard time analysis]
- Topology subsumption: Verifying a maximal subnetwork is enough.

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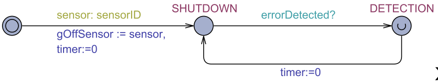
- Topology subsumption: Verifying a maximal subnetwork is enough.

To make models tractable, we require optimization:

- Each component has an individual clock. [Quasi-equal clock reduction]
- Support plug-in models: Separate environment and design.

Modeling: Sensor Failures

Modeled as timed automata networks with UPPAAL:



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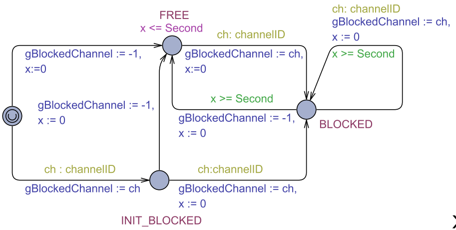

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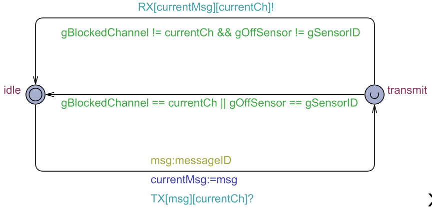

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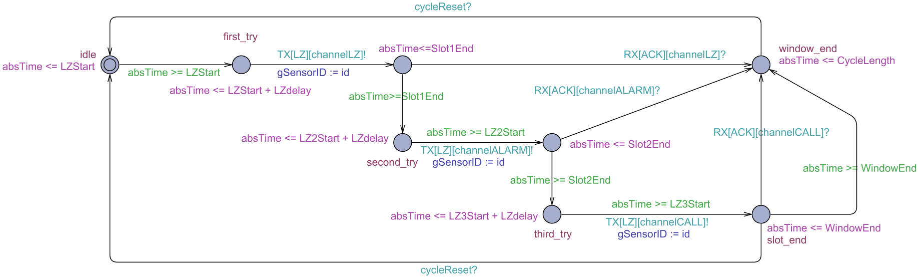

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Verification: Monitoring Function

Other model components:

- Auxiliary automata: Master, Central clock, Monitor
- Inner network: 10 Repeaters

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Found 2 flaws:

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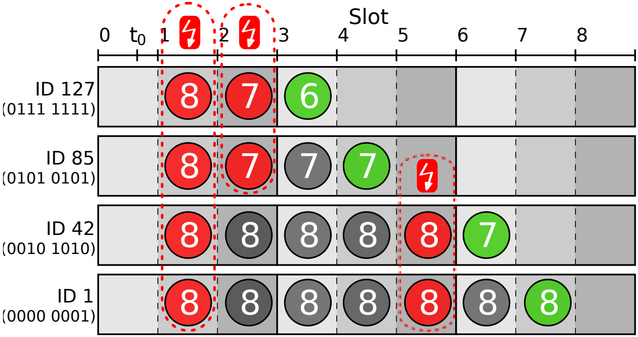
A revised design was successfully verified:

	Sensors as slaves			Repeaters as slaves		
Query	**seconds**	**MB**	**States**	**seconds**	**MB**	**States**
Detection	36,070.78	3,419.00	190M	231.84	230.59	6M
No Spurious	97.44	44.29	0.6M	3.94	10.14	0.15M
No LZ-Collision	12,895.17	2,343.00	68M	368.58	250.91	9.6M
Detection Possible	10,205.13	557.00	26M	38.21	55.67	1.2M

Verification is scalable for real world problems (!). But additional effort is required.

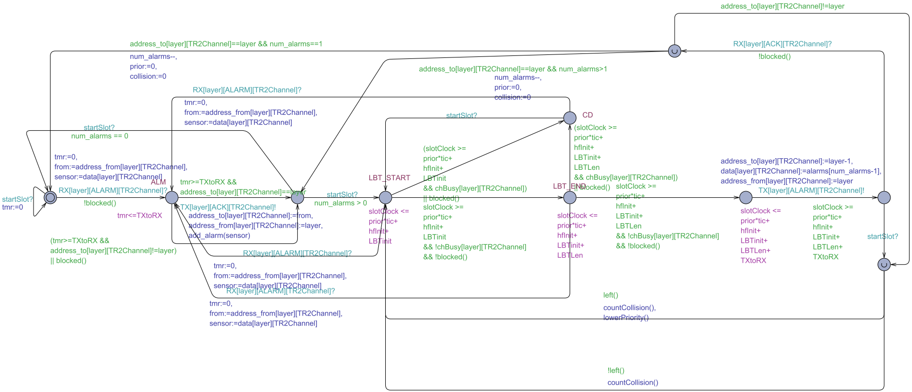
Modeling: Alarm Function

Alarms are transmitted (semi-)asynchronously using CSMA-CD / Collision resolution using tree splitting.



Each component ID induces a unique timing pattern for retrying transmissions.

Modeling: Alarm Function



Verification: Alarm Function

For single, explicit topologies: Timed automata / UPPAAL.

Full collision					
Query	**ids**	**seconds**	**MB**	**States**
OneAlarm	-	3.6 ± 1	43.1 ± 1	$59k \pm 15k$
TwoAlarms	seq	4.7	67.1	110,207
TenAlarms	seq	44.6 ± 11	311.4 ± 102	$641k \pm 159k$
	opt	41.8 ± 10	306.6 ± 80	$600k \pm 140k$

Checking one topology is feasible, but the procedure does not scale for full verification (more than 10^{126} possible topologies). [Parameterized Verification of Aggregation Protocols]

Models are still useful for simulation: extracted expected alarm times for different scenarios.

Verification: Alarm Function

For single, explicit topologies: Timed automata / UPPAAL.

Limited Collision				
Query	**ids**	**seconds**	**MB**	**States**
OneAlarm	-	1.4 ± 1	38.3 ± 1	$36k \pm 14k$
TwoAlarms	seq	0.5	24.1	19,528
TenAlarms	seq	17.3 ± 6	179.1 ± 61	$419k \pm 124k$
	opt	17.1 ± 6	182.2 ± 64	$412k \pm 124k$

Checking one topology is feasible, but the procedure does not scale for full verification (more than 10^{126} possible topologies). [Parameterized Verification of Aggregation Protocols]

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Verification: Alarm Function

For increased confidence: Does the collision resolution algorithm guarantee non-starvation?

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For increased confidence: Does the collision resolution algorithm guarantee non-starvation? Created an untimed model in PROMELA / SPIN.

- N: number of colliding components.
- I: set of IDs that may participate in the collision.
- Check all possible N-collision scenarios: vary IDs and timing.

Verification: Alarm Function

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- Check all possible N-collision scenarios: vary IDs and timing.

Results:

- Reproduced the hidden terminal problem.
- For $N = 2$: found a problem with IDs 0 and 128.
- For $N = \{3..10\}$: still not scaling to all IDs, used sampling (31744).

$\lvert I \rvert$	N	**sec.**	**MB**	**States**
255	2	49	1,610	1,235,970
H	10	3,393	6,390	6,242,610
L	10	4,271	10,685	10,439,545
Rnd	10	4,465	11,534	11,268,368
average		4,138	9,994	9,763,809

Lessons Learned

Generalized test procedures are useful for verification:

- Developers are already used to producing test specifications.
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Models are useful:

- For validation.
- As documentation.
- But still not very accesible for developers.

Formal verification shows potential to relieve the effort of testing.

Conclusions

- Formal methods are able to handle typical industrial scenarios (but require expert knowledge).
- The customers are confident early in the process that certification tests will be passed.
- Implementation is easier when based on a verified design.
- Other requirements can be simply tested.
- Still expensive: Almost as expensive as the certification test itself.
- Additional value: Formal methods not only improve confidence but helps structure development processes.
- Difficult technology transfer: SMEs prefer to scale out instead of up.

Outlook

- Check whether the source code of the implementation corresponds to the design models. Interrupt based implementations are hard to verify.
- Use the models to perform model-based testing.
- Investigate reuse strategies (new features, product lines).

Towards Successful Subcontracting for Software in Small to Medium-Sized Enterprises

RELAW Workshop, 2012-09-25

Bernd Westphal[1], Daniel Dietsch[1], Sergio Feo-Arenis[1], Andreas Podelski[1], Louis Pahlow[2], Jochen Morsbach[3], Barbara Sommer[3], Anke Fuchs[3], Christine Meierhöfer[3]

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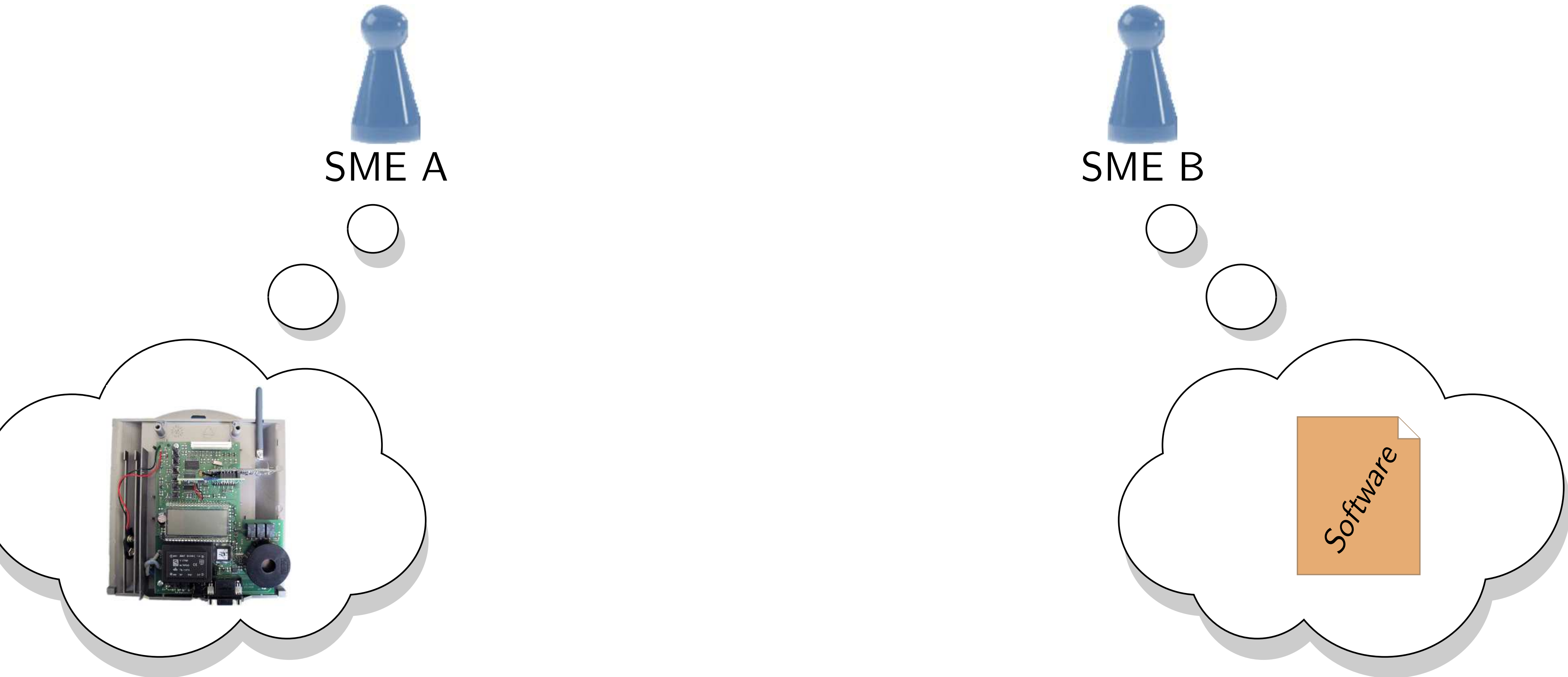
Outline

- Introduction
  - What is sub-contracting for software?
  - When is it succesful?
  - Why is it ofen not successful?
- The Salomo Approach:
  - Overview
  - Checkable Requirements, Checking Tool
  - Regulations in the Contract
- Related Work
- Conclusion and Further Work

Successful Subcontracting for Software in SMEs



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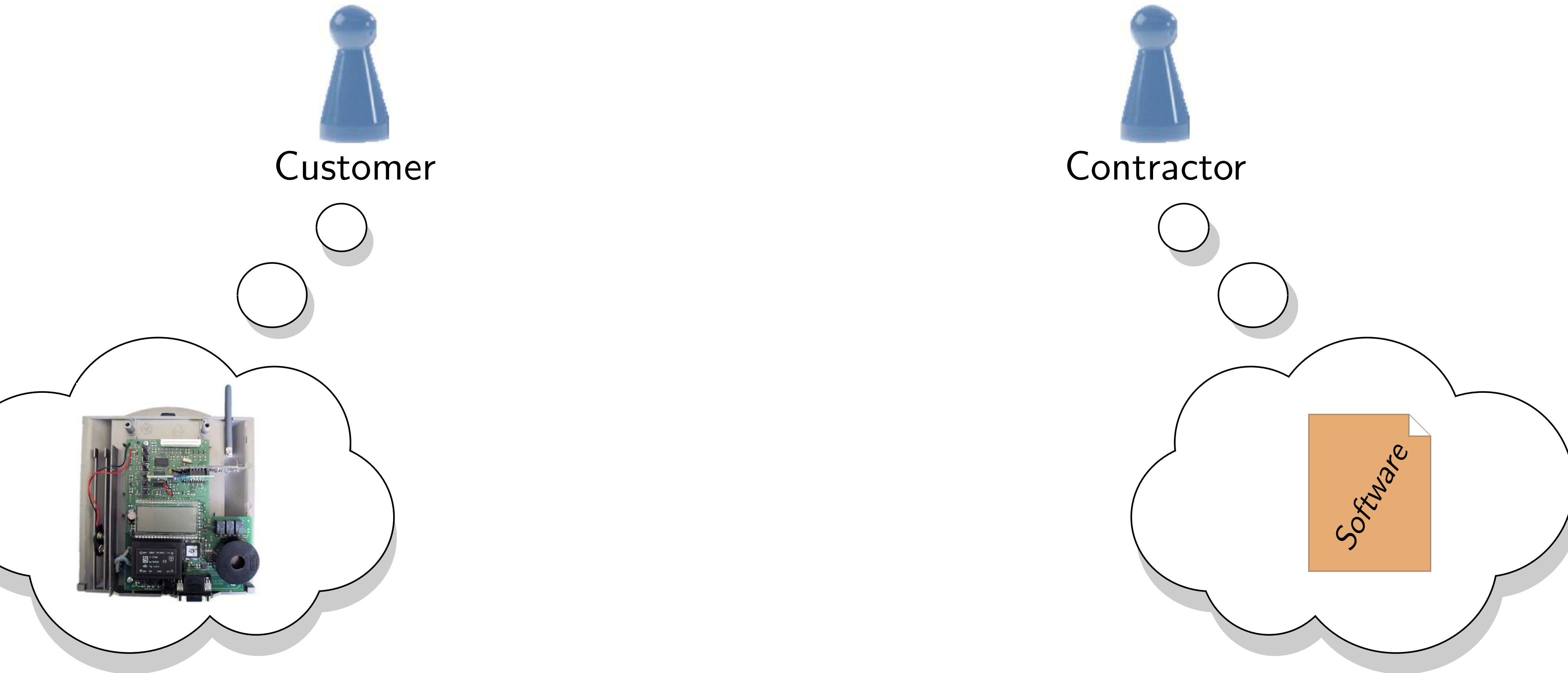

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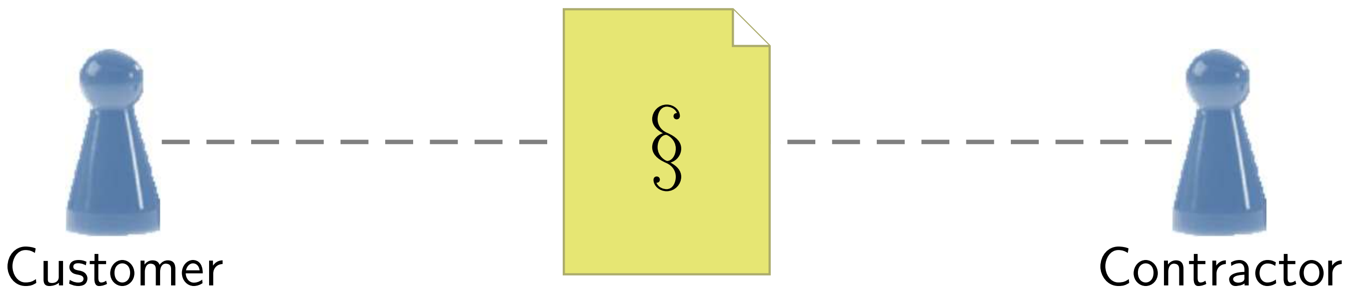

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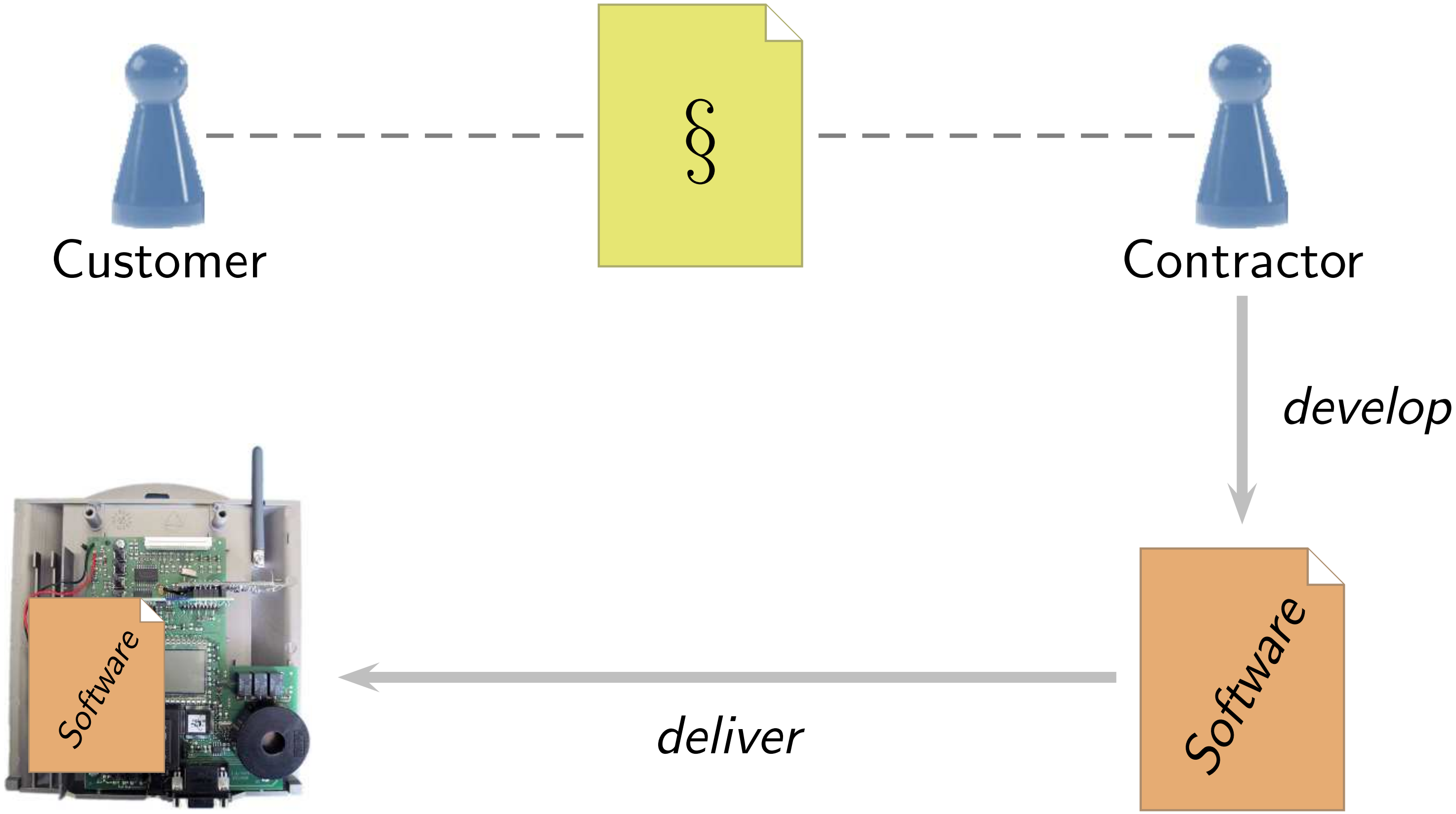

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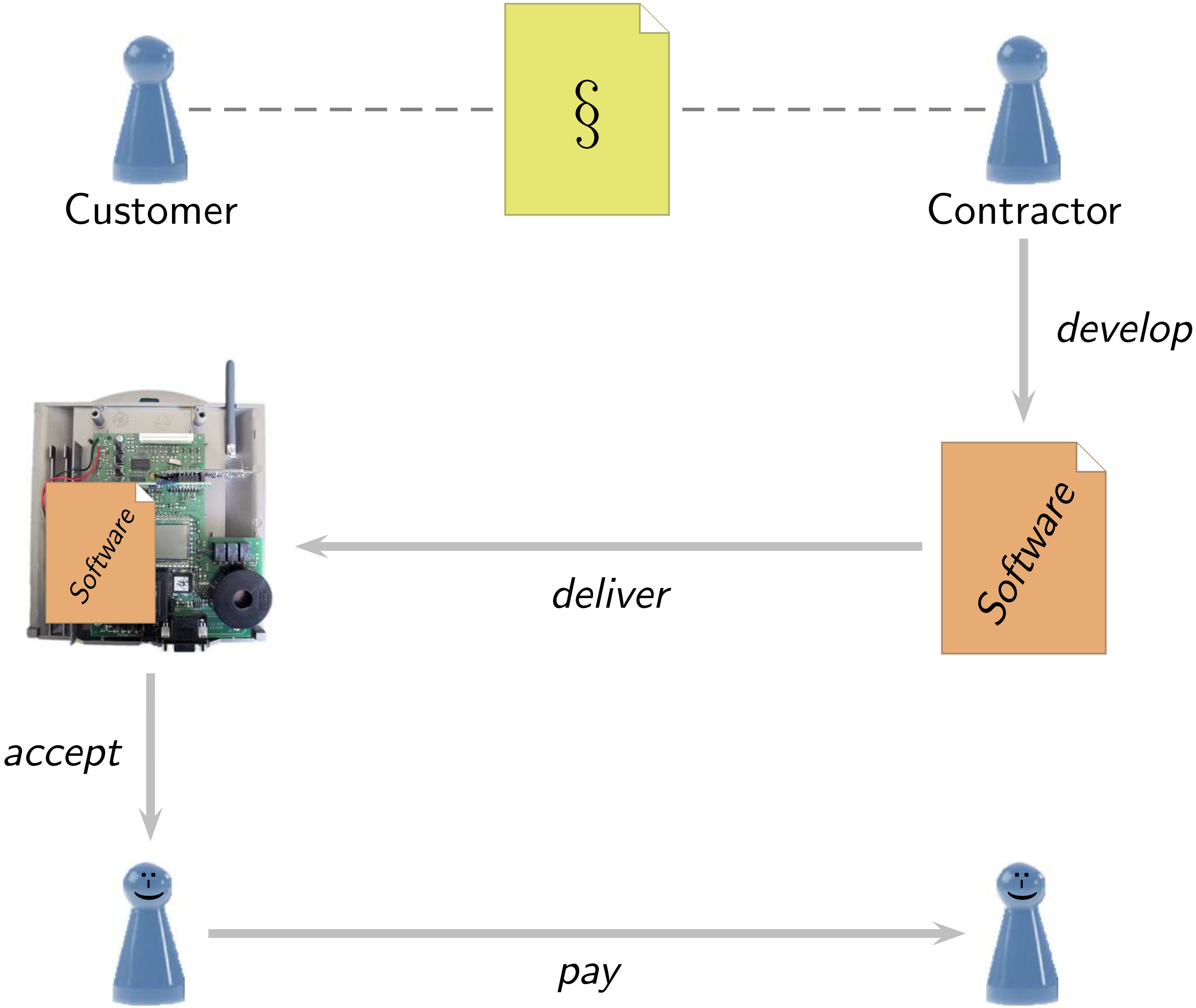
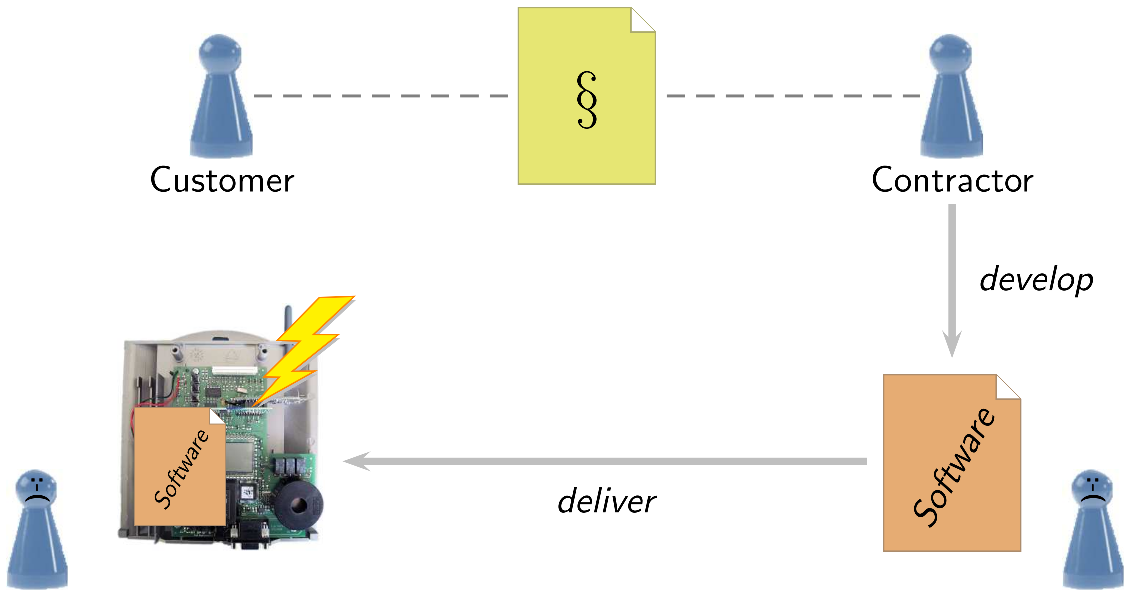


Subcontracting for Software in SMEs in Reality



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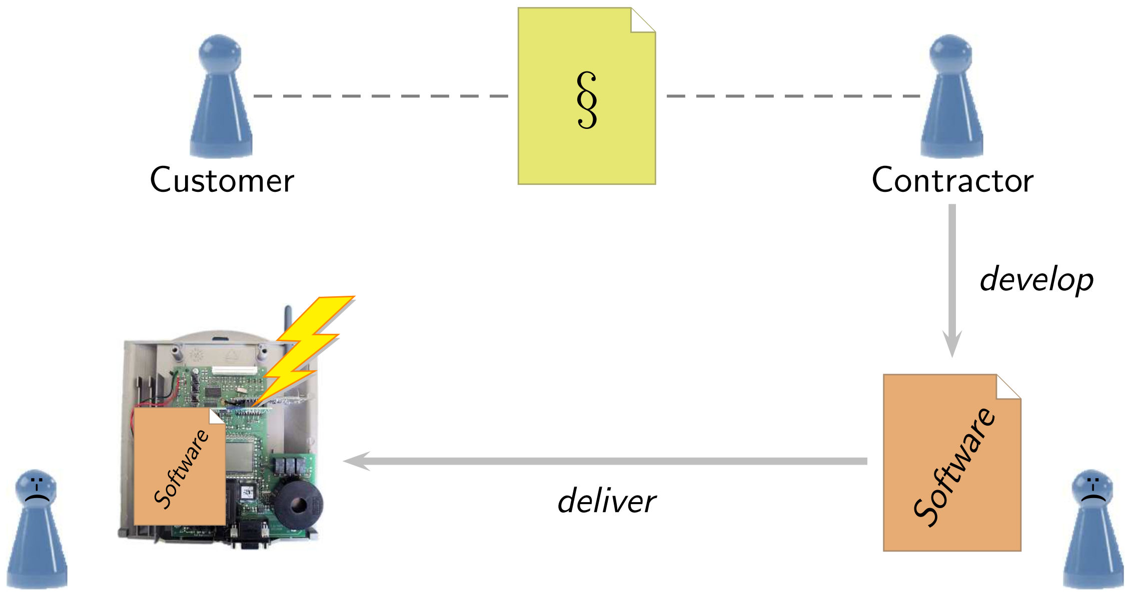

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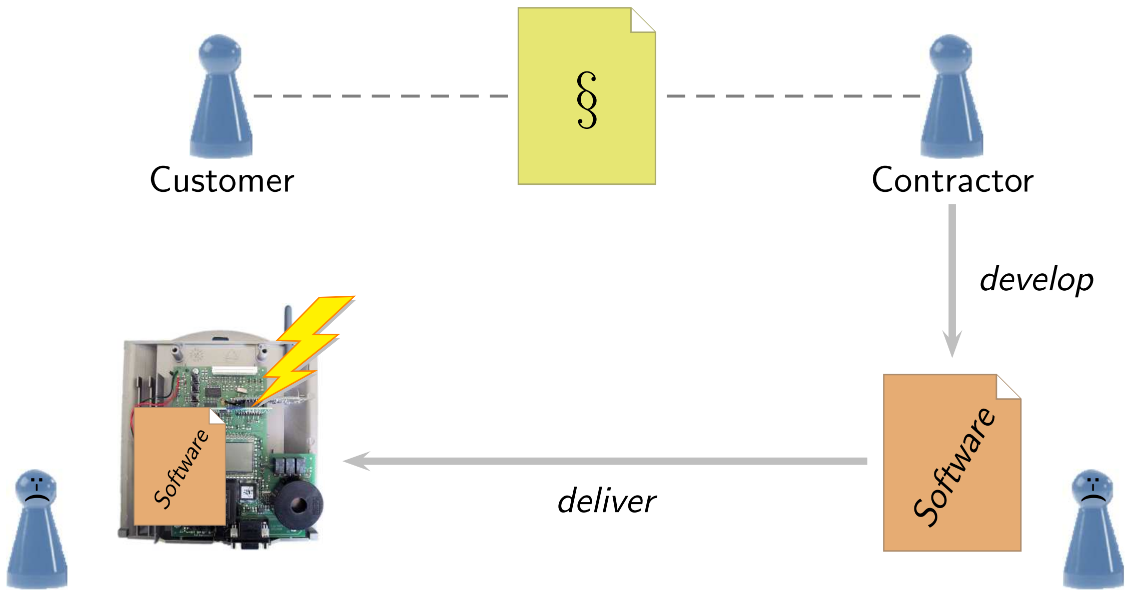
In addition, there is a **high uncertainty** about the outcome:

- given **unclear** requirements, an appointed **expert witness** may **confirm either interpretation**.

Subcontracting for Software in SMEs in Reality



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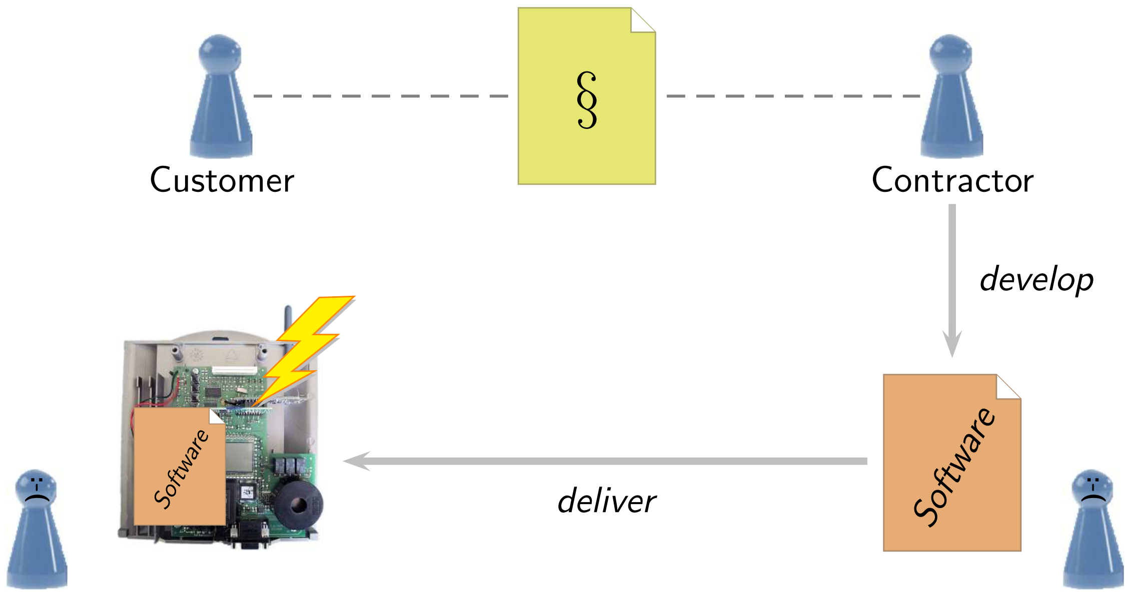

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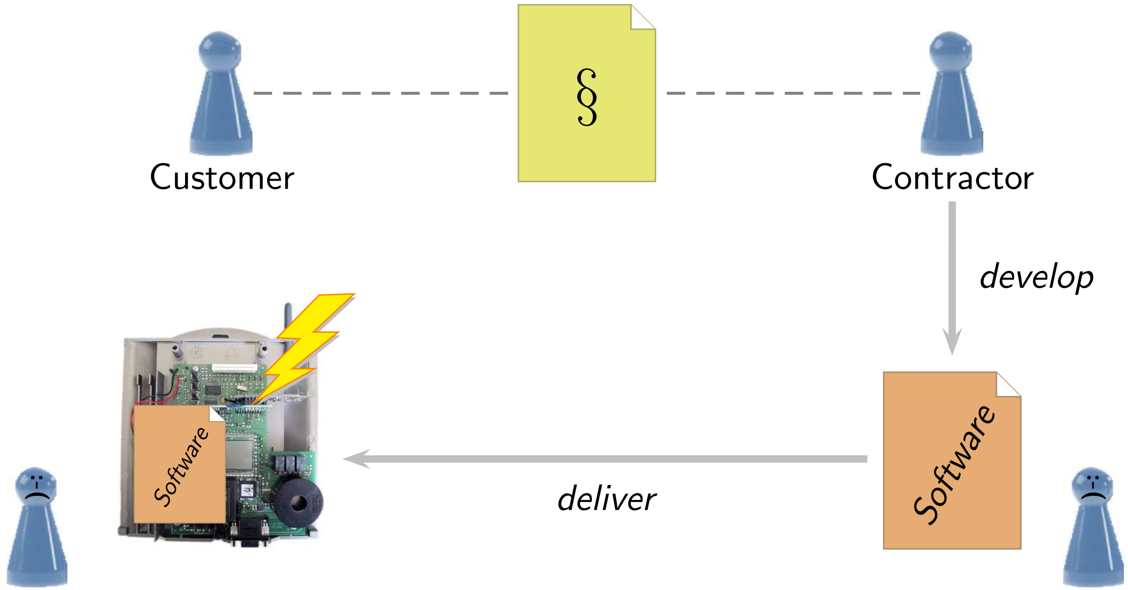

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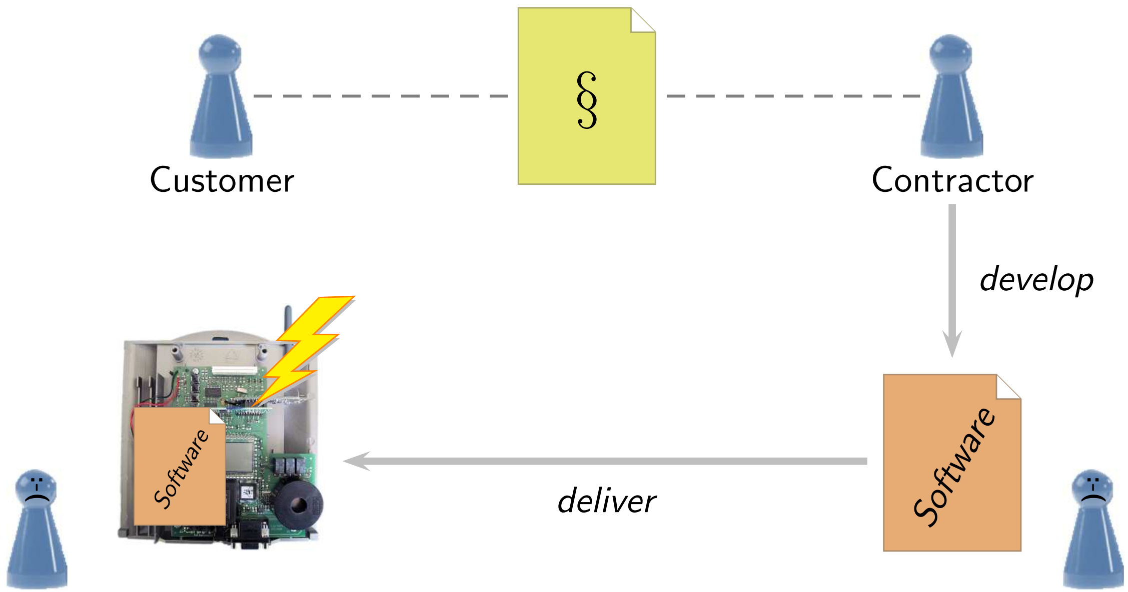

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Many SMEs conclude: subcontracting for software is too **risky** **due to** these three main sources of **uncertainty**.

Observation

- **(Legal) certainty** is crucial for subcontracting between SMEs:
  Outcomes of possible court judgements need to be **as clear as possible**.

- To **achieve legal certainty**, we need

(a) **clear and precise requirements**,
they avoid the 1st source of uncertainty.

(b) **clear and precise acceptance testing procedures**,
they avoid the 2nd source of uncertainty.

(c) **standardised legal contracts** which integrate (a) and (b),
they avoid the 3rd source of uncertainty.

The contract allows a judge to decide on (a) and (b),
and thus increases legal certainty.

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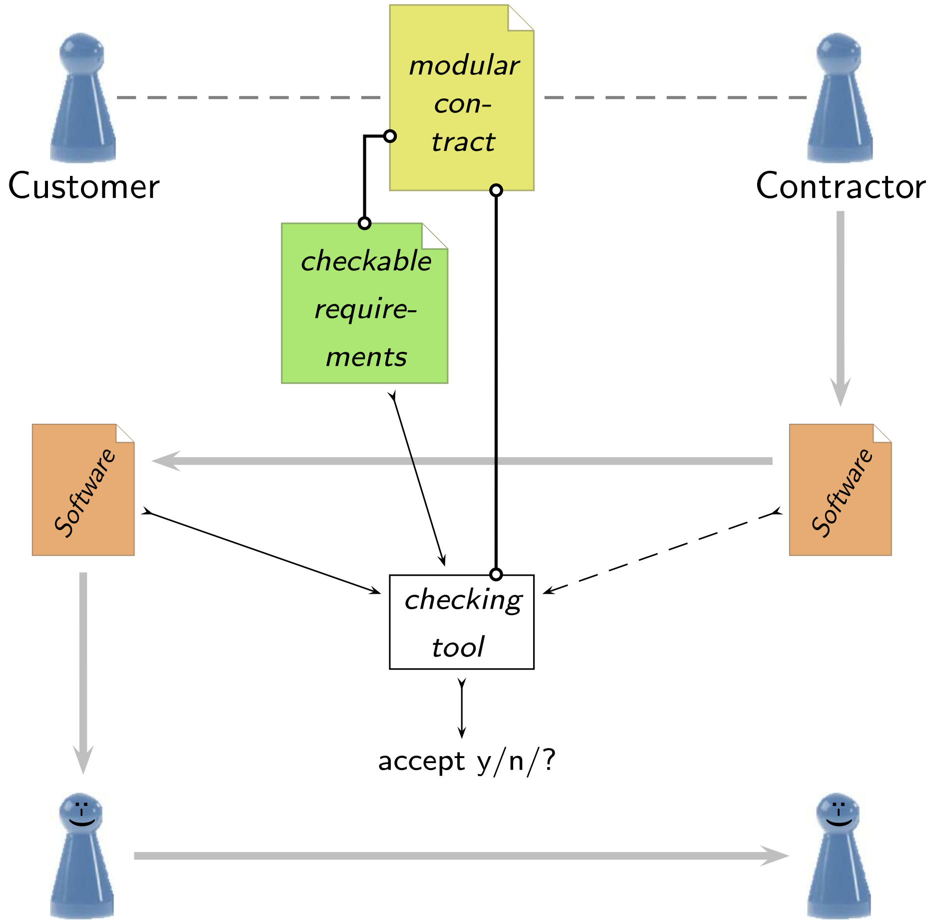
Towards (Legal) Certainty



Ingredients:

- new notion: **checkable requirement**,
- new notion: **checking tool**.
- a new, **modular** software development **contract**,

The **modular contract**

assumes: a subset of requirements is **designated** as **checkable requirements**,

includes: the **checkable requirements** in **machine-readable** form,

codifies: **agreement** that outcome of corresponding **checking tool** is — with few and exactly specified exceptions — **binding** for both parties,

provides: **legal certainty**.

Checkable Specification/Requirement, Checking Tool

- A **checkable specification** is a pair (φ, T) comprising a **program property** φ and a **backend** T.

- A **backend** maps a program p and a program property φ to a result $T(p, \varphi) \in \{\mathit{Yes}, \mathit{No}, \mathit{Unknown}\}$ such that the result is
  - Yes **only if** the program **has** the property,
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to a **checking tool result**

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- A requirement is called **checkable requirement** if and oly if
  a checkable specification can (mechanically) be derived from it.

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- **"Certification"**: expert reviews of programs

Regulations in the Contract

- The **modular software development contract**
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  - customisation by several **contractual modules**.

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  - consists of a **framework contract**, referred to by individual contract,
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- The **acceptance checking procedure** is regulated in two clauses:

(i) **checkable requirements** tested with and only with checking tool.

Exit option: if

- backend is evidently erroneous, or
- the parties agree to consider the result erroneous, or
- there is an "*Unknown*" among only "*Yes*"s and "*Unknown*"s,

then the clause for other requirements applies.

(ii) testing procedure for **other requirements** determined by customer.

Outline

- Introduction
  - What is sub-contracting for software?
  - When is it succesful?
  - Why is it ofen not successful?
- The Salomo Approach:
  - Overview
  - Checkable Requirements, Checking Tool
  - Regulations in the Contract
- Related Work
- Conclusion and Further Work

Related Work

- (Berenbach, Lo & Sherman, 2010)

  Scope limited to the time after the contract has been awarded, limited discussion regarding contract compliance check.

- (Governatori, Milosevic, & Sadiq, 2006) — formalise contract conditions

  Use FCL to formalise requirements business rules and tools which decide compliance as acceptance checking procedure.

- (Breaux, Antón, Spafford, 2009) — delegation

  We consider top-level obligations and verification sets without delegation.

- (Fanmuy, Fraga & Lloréns, 2012) — requirements verification

  Use requirements verification as acceptance checking procedure if creation of a requirements document is subject of a contract.

Conclusion and Further Work

- We tackle a main challenge of contracting for software: **legal uncertainty**.
- We outline a possible approach to resolve three reasons of uncertainty: a **modular legal contract** codifies the **mutual agreement** that **checkable requirements** are verified by **checking tool** exclusively.
- Both, contractor and customer have **strong interest** in obtaining positive checking results since positive results mean **certainty**.
- Our contract is well-suited for a **gradual introduction of formal methods** — any backend is supported as long as both parties agree.
- Formal methods effort promises **increased confidence** in software quality.

Further work:

- legally support traceability, change-requests.
- consider a concept of delegation similar to (Breaux et al., 2009),
- provide more backends.

Thanks.

http://www.salomo-projekt.de

Traces, Interpolants, and Automata: a New Approach to Automatic Software Verification

Jochen Hoenicke

University of Freiburg

joint work with Andreas Podelski and Matthias Heizmann

16 July 2015

Software Verification

- prove or disprove that a given program satisfies a given specification

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- prove or disprove that a given program satisfies a given specification
- problem is undecidable [Turing, 1936]

ULTIMATE

Automizer

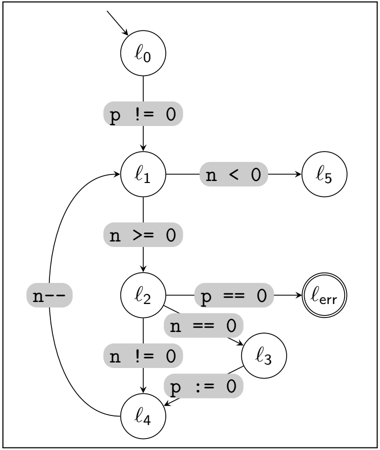
Example

```
ℓ0:  assume p != 0;

ℓ1:  while(n >= 0)
     {
ℓ2:      assert p != 0;

         if(n == 0)
         {
ℓ3:          p := 0;
         }
ℓ4:      n--;
     }
```

pseudocode



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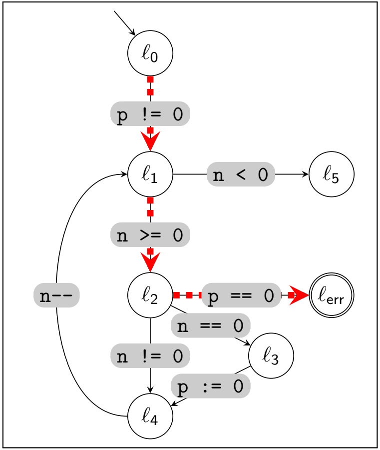
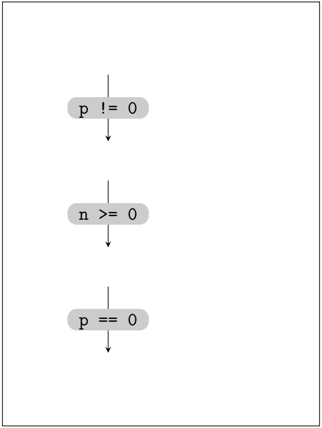


control flow graph

1. take trace π_1



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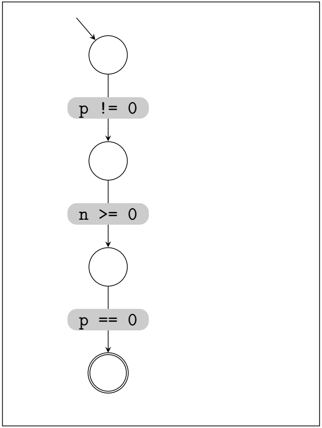


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assume p != 0;
assume n >= 0;
assert p != 0;
```

pseudocode of $\mathcal{P}_1$

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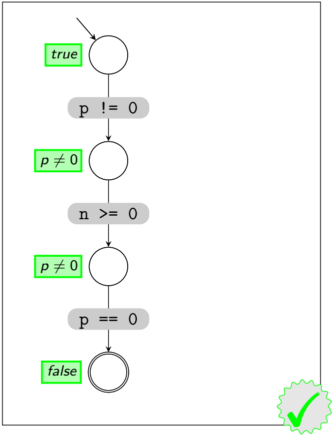

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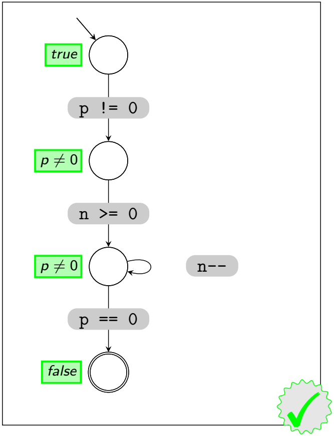
$\{p \neq 0\}$ `n--` $\{p \neq 0\}$ is valid Hoare triple



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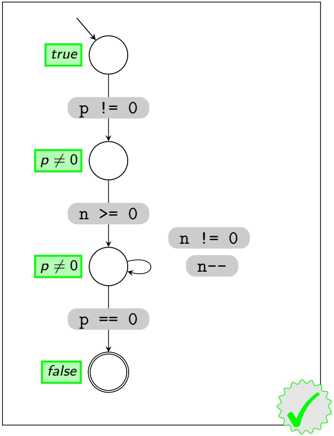

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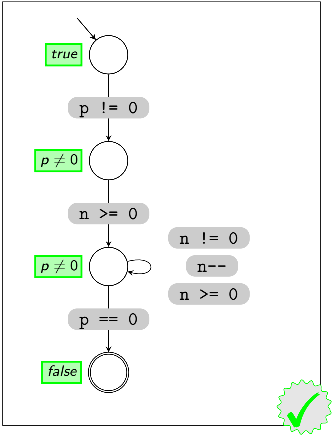

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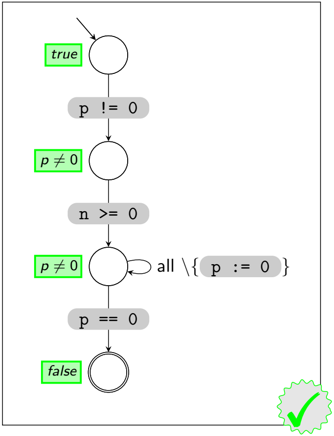

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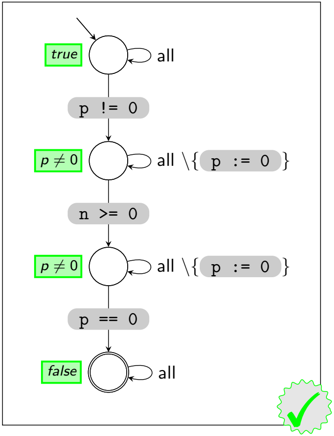

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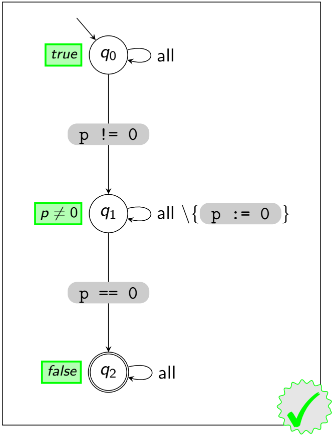

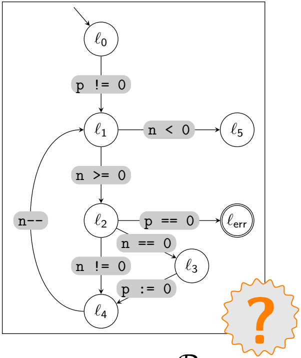

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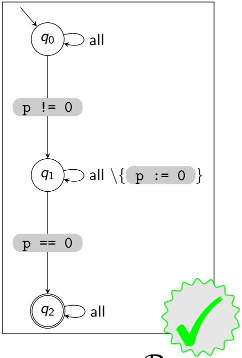

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New View on Programs

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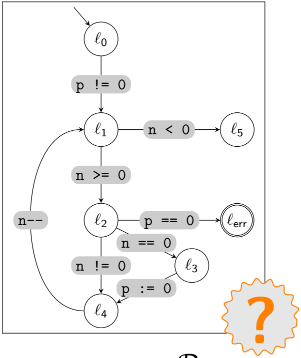
- Error trace of program: word accepted by this automaton



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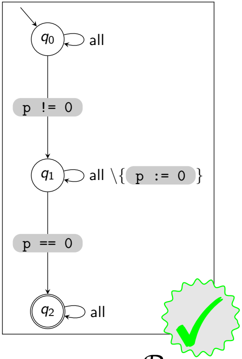

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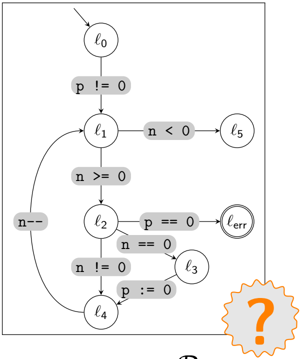

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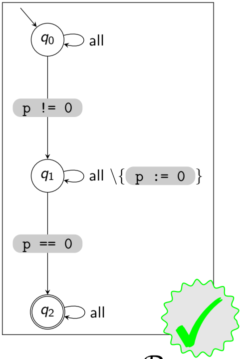
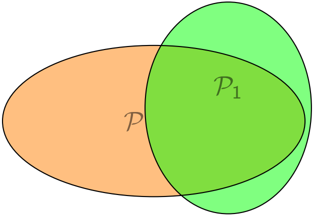
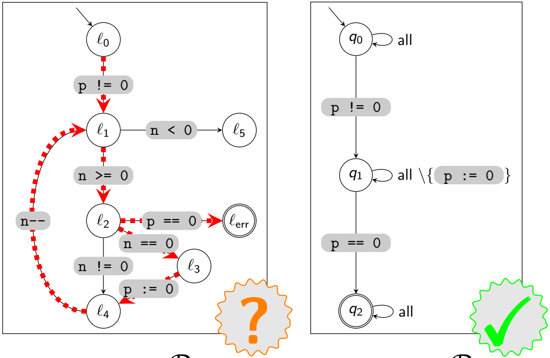


program $\mathcal{P}_1$

Consider only traces in set theoretic difference $\mathcal{P} \backslash \mathcal{P}_1$.





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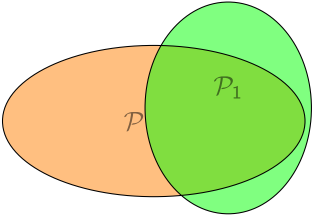
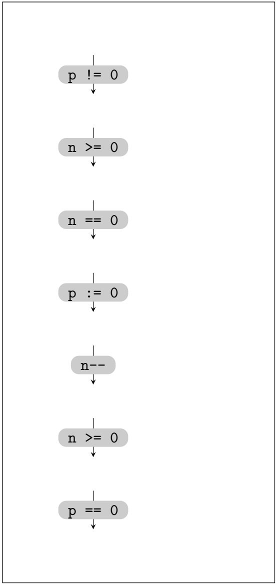


1. take trace π_2



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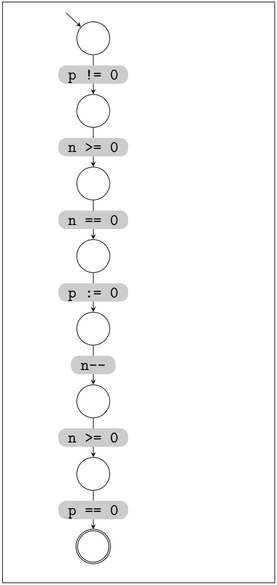

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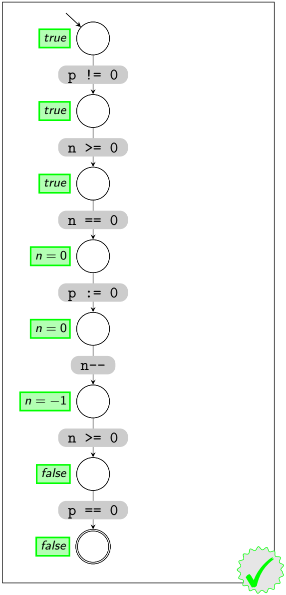

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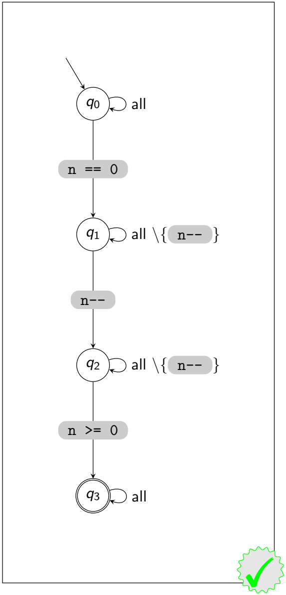
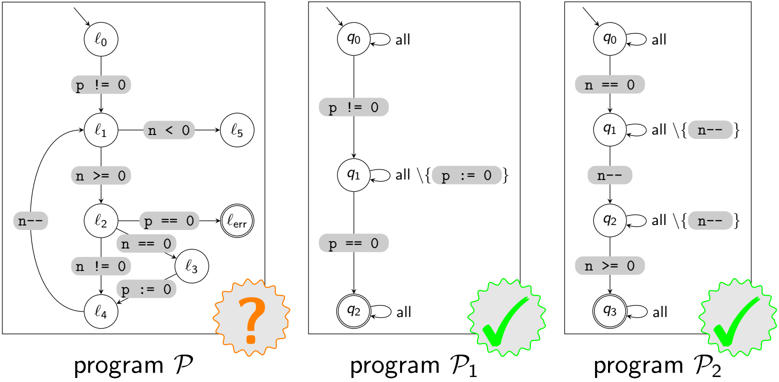
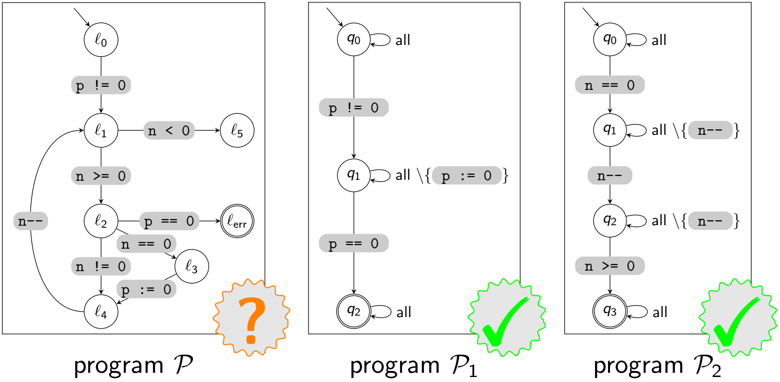


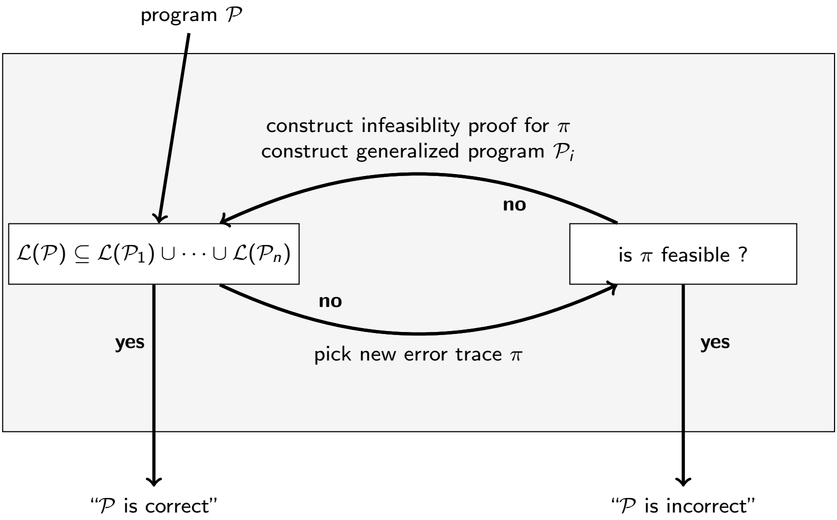


ℓ0
p != 0
ℓ1
n < 0
ℓ5
n >= 0
ℓ2
p == 0
ℓerr
n == 0
ℓ3
n != 0
p := 0
n--
ℓ4
?
program 𝒫
q0
all
p != 0
q1
all \{ p := 0 }
p == 0
q2
all
program 𝒫1
q0
all
n == 0
q1
all \{ n-- }
n--
q2
all \{ n-- }
n >= 0
q3
all
program 𝒫2



$$\mathcal{P} \subseteq \mathcal{P}_1 \cup \mathcal{P}_2$$

Verification Algorithm



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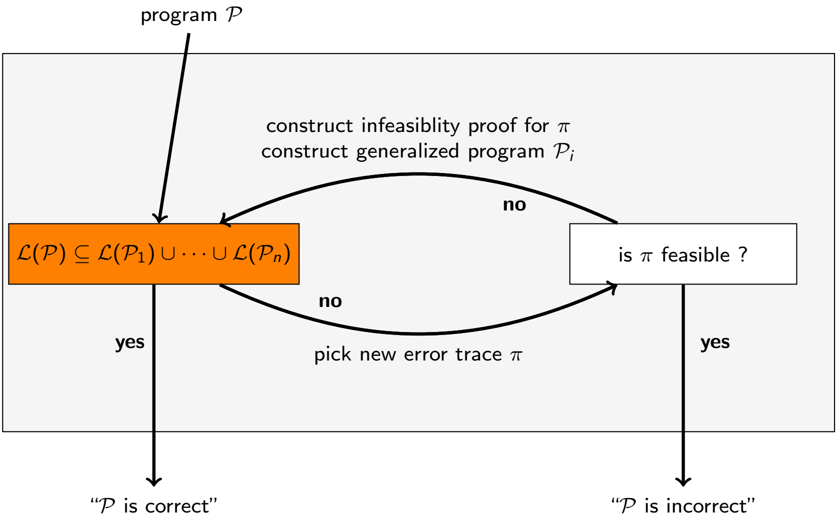

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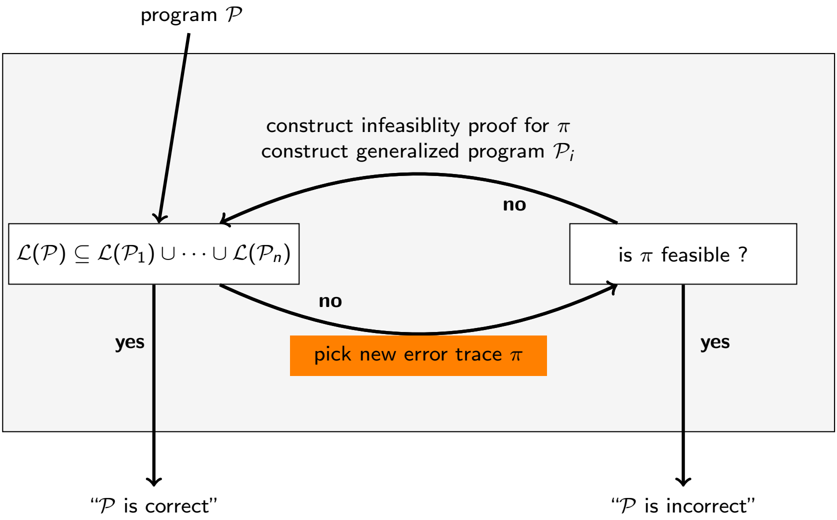

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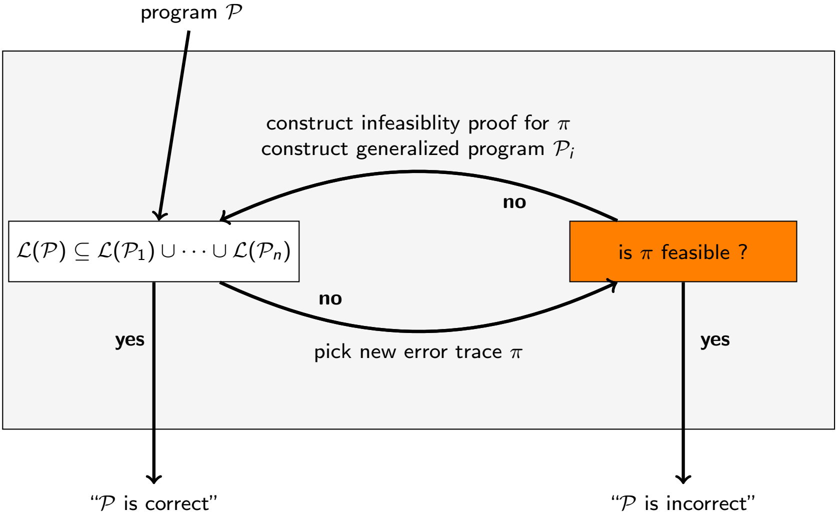

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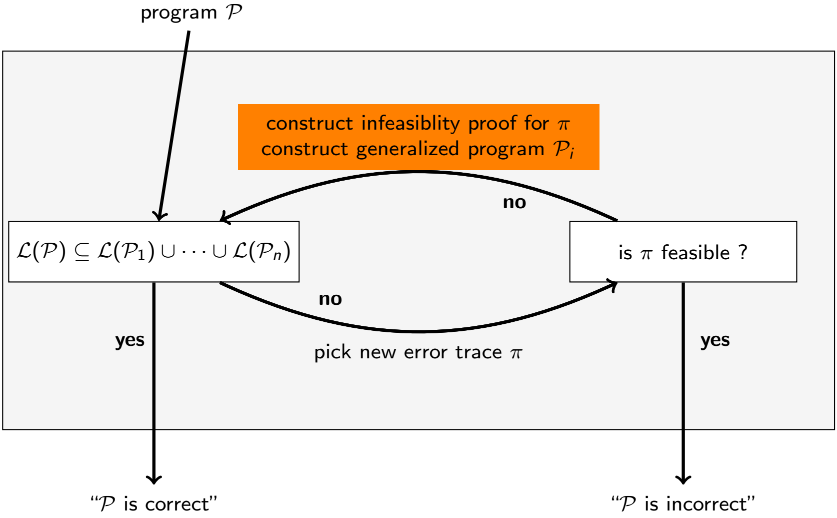


Interprocedural/Recursive Programs

Recursive Programs - Challenge 1: Control Flow

```
procedure m(x) returns (res)

ℓ0: if x>100

ℓ1:   res:=x-10
    else

ℓ2:   x_m := x+11

ℓ3:   call m

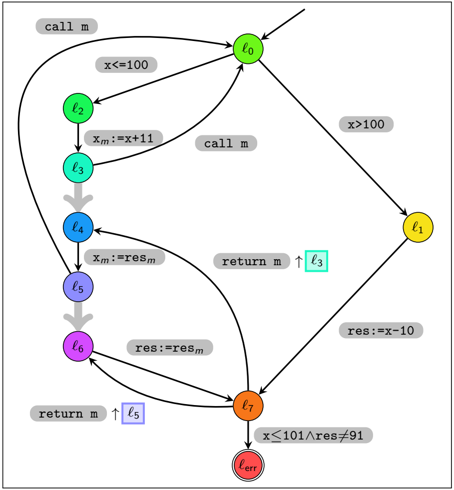
ℓ4:   x_m := res_m

ℓ5:   call m

ℓ6:   res := res_m

ℓ7: assert (x<=101 -> res=91)
    return m
```

McCarthy 91 function



control flow graph

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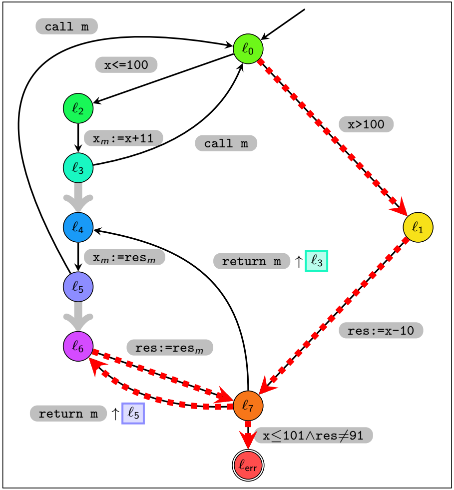
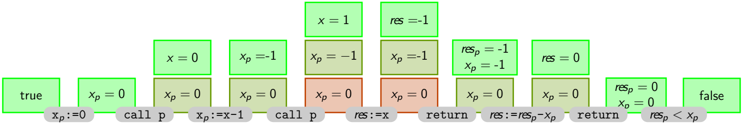


control flow graph

Recursive Programs - Challange 2: Local Annotations

What is an annotation for an interprocedural execution?

- state with a stack?
  $\rightsquigarrow$ locality of annotation is lost



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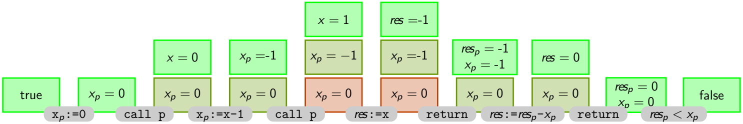
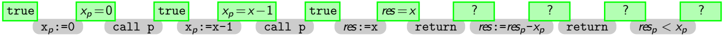


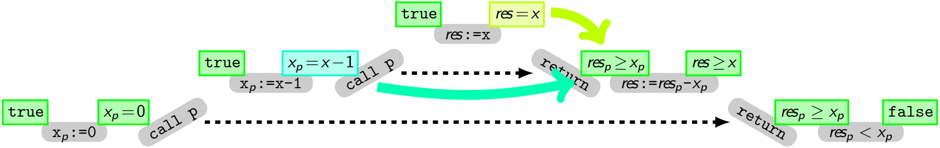
- only local valuations?
  $\rightsquigarrow$ call/return dependency lost,
  $\rightsquigarrow$ sequence of state assertions is not a proof



Recursive Programs - Challange 2: Local Annotations

What is an annotation for an interprocedural execution?

Idea: "Nested Interpolants"
Define sequence of state assertions with respect to nested trace.



Define ternary post operator for return statements

$$post(\, res = x,\ x_p = x-1,\ \texttt{return p}\,) \subseteq res_p \geq x_p$$

Termination Analysis

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- Challenge 1: counterexample to termination is infinite execution

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while (x > 0) {
    x--;
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  Solution: ranking functions (here: f(x)=x)

Ranking Function (for a Loop)

Function from program states to well-founded domain such that value is decreasing while executing the loop body.
Proof by contradiction for the absence of infinite executions.

Example: Bubble Sort

```
   program sort(int i, int a[])
ℓ1 while (i>0)
ℓ2      int j:=1
ℓ3      while(j<i)
             if (a[j]>a[i])
                  swap(a,i,j)
ℓ4           j++
ℓ5      i--
```

Example: Bubble Sort

```
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ℓ3       while(j<i)
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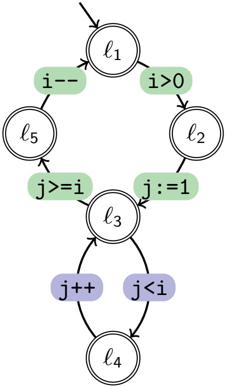

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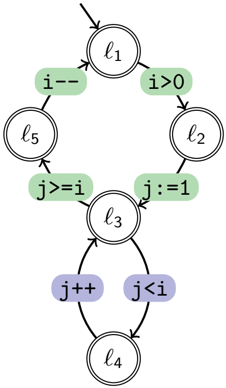
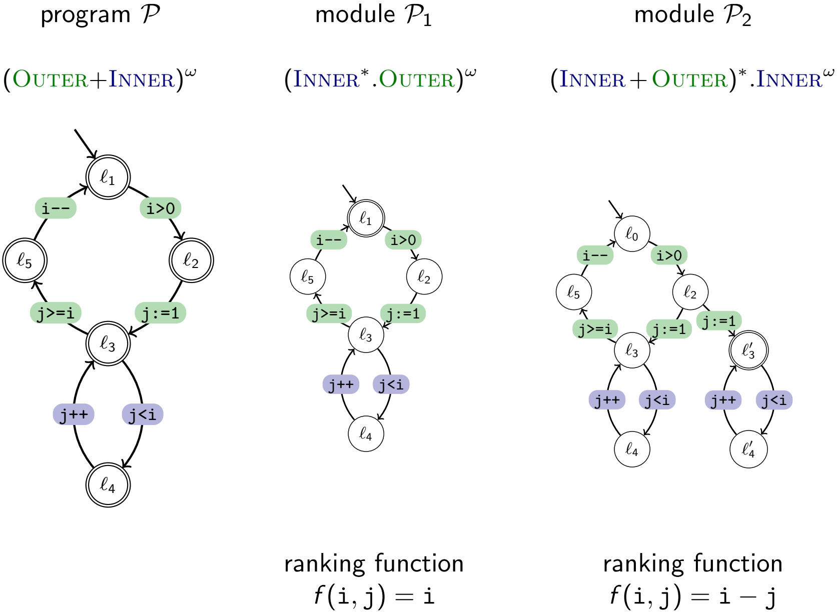
quadratic ranking function:

$$f(\mathtt{i},\mathtt{j}) = \mathtt{i}^2 - \mathtt{j}$$

lexicographic ranking function:

$$f(\mathtt{i},\mathtt{j}) = (\mathtt{i}, \mathtt{i} - \mathtt{j})$$




program $\mathcal{P}$
module $\mathcal{P}_1$
module $\mathcal{P}_2$
$(\text{OUTER}+\text{INNER})^\omega$
$(\text{INNER}^*.\text{OUTER})^\omega$
$(\text{INNER}+\text{OUTER})^*.\text{INNER}^\omega$
ℓ_1
ℓ_2
ℓ_3
ℓ_4
ℓ_5
ℓ_0
ℓ_3'
ℓ_4'
i--
i>0
j>=i
j:=1
j++
j<i
ranking function
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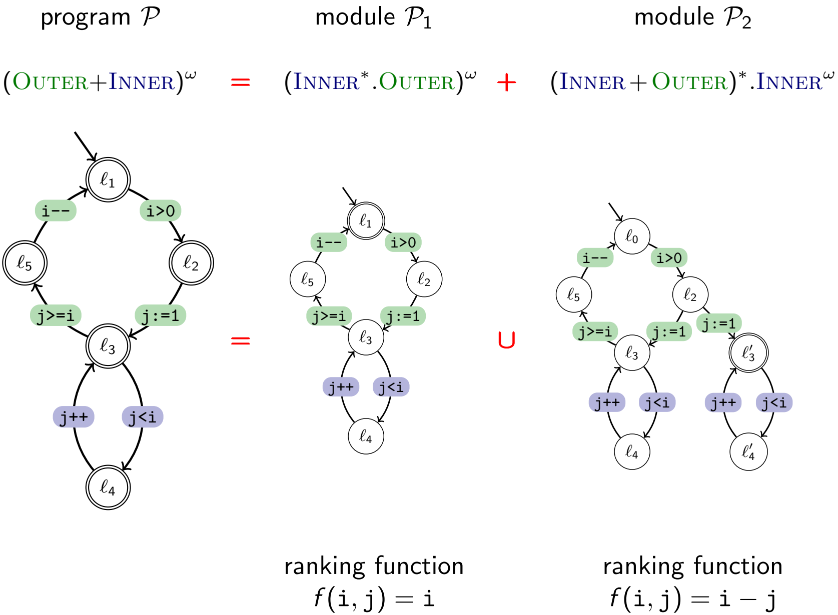
program $\mathcal{P}$
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ℓ_1
i--
i>0
ℓ_5
ℓ_2
j>=i
j:=1
ℓ_3
j++
j<i
ℓ_4
=
∪
ℓ_0
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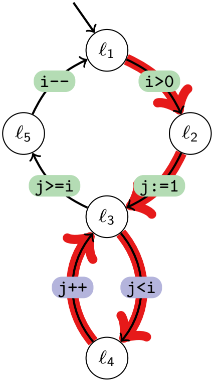

ℓ_1
i>0
i--
ℓ_5
ℓ_2
j>=i
j:=1
ℓ_3
j++
j<i
ℓ_4

From ω-Trace to Terminating Program – Example

input: ultimately periodic trace `i>0` `j:=1` (`j<i` `j++`)$^\omega$,

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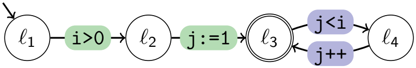

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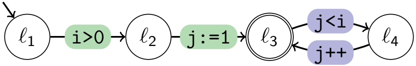

2. synthesize ranking function

$$f(i,j) = i - j$$

Colón, Sipma **Synthesis of Linear Ranking Functions** (TACAS 2001)

Podelski, Rybalchenko **A complete method for the synthesis of linear ranking functions** (VMCAI 2004)

Bradley, Manna, Sipma **Termination Analysis of Integer Linear Loops** (CONCUR 2005)

Bradley, Manna, Sipma **Linear ranking with reachability** (CAV 2005)

Bradley, Manna, Sipma **The polyranking principle** (ICALP 2005)

Ben-Amram, Genaim **Ranking functions for linear-constraint loops** (POPL 2013)

H., Hoenicke, Leike, Podelski **Linear Ranking for Linear Lasso Programs** (ATVA 2013)

Cook, Kroening, Rümmer, Wintersteiger **Ranking function synthesis for bit-vector relations** (FMSD 2013)

Leike, H. **Ranking Templates for Linear Loops** (TACAS 2014)

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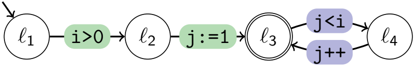

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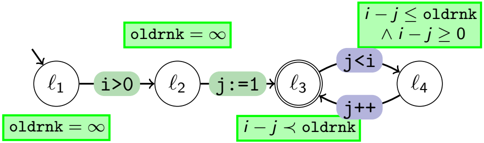

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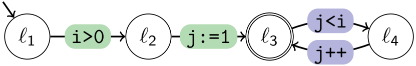

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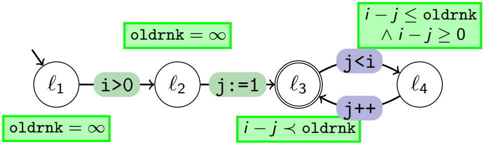
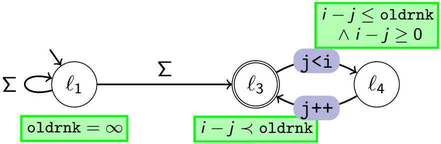


4. add additional transitions

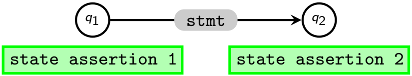


Generalization of Program with Rank Certificate

- Case 1: q_1 not accepting

Hoare triple { `state assertion 1` } `stmt` { `state assertion 2` }

automaton transition



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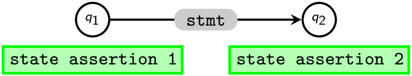
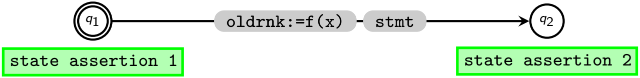


- Case 2: q_1 accepting

  Hoare triple { `state assertion 1` } `oldrnk:=f(x)` `stmt` { `state assertion 2` }

  automaton transition



Implemented in

Ultimate Büchi Automizer

`http://ultimate.informatik.uni-freiburg.de/BuchiAutomizer/`

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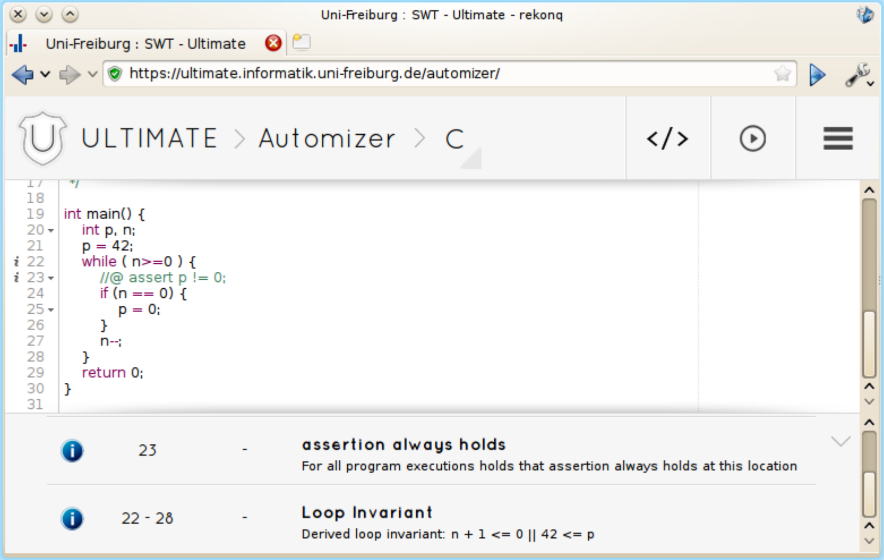
Programs with procedures and recursion? Büchi Nested Word Automata!

Results of the Competition on Software Verification 2015

Competition candidate	AProVE	Beagle	BLAST 2.7.3	Cascade	CBMC	CPAchecker	CPArec	ESBMC 1.24.1	FOREST	Forester	FuncTion	HIPTNT+	Lazy-CSeq	Map2Check	MU-CSeq	Perentie	Predator	SeaHorn	SMACK+Corral	Ultimate Automizer	Ultimate Kojak	Unbounded Lazy-CSeq
Representing Jury Member	Thomas Ströder	Dexi Wang	Vadim Mutilin	Wei Wang	Michael Tautschnig	Matthias Dangl	Ming-Hsien Tsai	Jeremy Morse	Pablo Sánchez	Ondrej Lengal	Caterina Urban	Ton-Chanh Le	Gennaro Parlato	Herbert Oliveira Rocha	Bernd Fischer	Franck Cassez	Tomas Vojnar	Arie Gurfinkel	Zvonimir Rakamaric	Matthias Heizmann	Alexander Nutz	Salvatore La Torre
Affiliation	Aachen, Germany	Beijing, China	Moscow, Russia	New York, USA	London, UK	Passau, Germany	Taipei, Taiwan	Bristol, UK	Cantabria, Spain	Brno, Czechia	Paris, France	Singapore, Singapore	Southampton, UK	Manaus, Brazil	Stellenbosch, South Africa	Sydney, Australia	Brno, Czechia	Pittsburgh, USA	Salt Lake City, USA	Freiburg, Germany	Freiburg, Germany	Southampton, UK
Arrays 86 tasks, max. score: 145	--	--	--	--	-134 2 500 s	2 62 s	--	-206 5.5 s	--	--	--	--	--	--	--	--	--	0 0.61 s	**48 400 s**	**2 6.4 s**	**2 5.9 s**	--
BitVectors 47 tasks, max. score: 83	--	4 58 s	--	52 16 000 s	**68 1 800 s**	**58 870 s**	--	**69 470 s**	--	--	--	--	--	--	--	--	--	-80 550 s	--	5 170 s	-62 120 s	--
Concurrency 1 003 tasks, max. score: 1 222	--	--	--	--	**1 039 78 000 s**	0 0 s	--	1 014 13 000 s	--	--	--	--	**1 222 5 600 s**	--	**1 222 16 000 s**	--	--	- 8 973 42 s	--	--	--	984 36 000 s
ControlFlow 1 927 tasks, max. score: 3 122	--	--	983 33 000 s	537 43 000 s	158 570 000 s	**2 317 47 000 s**	--	**1 968 59 000 s**	--	--	--	--	--	--	--	--	--	**2 169 30 000 s**	1 691 78 000 s	1 887 54 000 s	872 10 000 s	--
ControlFlowInteger 48 tasks, max. score: 78	--	--	51 3 300 s	38 11 000 s	62 1 300 s	77 1 800 s	--	78 87 s	--	--	--	--	--	--	--	--	--	77 440 s	61 200 s	78 930 s	43 1 000 s	--
ECA 1 140 tasks, max. score: 1 874	--	--	11 9 800 s	0 0 s	- 2 334 560 000 s	987 39 000 s	--	523 58 000 s	--	--	--	--	--	--	--	--	--	516 25 000 s	112 45 000 s	632 46 000 s	1 14 s	--
Loops 142 tasks, max. score: 235	--	--	-14 790 s	46 32 000 s	59 4 900 s	118 2 600 s	--	66 620 s	168 45 000 s	--	--	--	--	--	--	125 1 600 s	--	130 1 100 s	86 370 s	115 2 900 s	109 4 300 s	--
ProductLines 597 tasks, max. score: 929	--	--	637 19 000 s	0 0 s	399 1 900 s	901 4 100 s	--	917 430 s	--	--	--	--	--	--	--	--	--	913 3 500 s	917 32 000 s	554 3 300 s	87 5 000 s	--
DeviceDrivers64 1 650 tasks, max. score: 3 097	--	--	**2 736 11 000 s**	--	2 293 380 000 s	**2 572 39 000 s**	--	2 281 36 000 s	--	--	--	--	--	--	--	--	--	**2 657 16 000 s**	2 507 72 000 s	274 850 s	82 270 s	--
Floats 81 tasks, max. score: 140	--	--	--	--	**129 15 000 s**	**78 5 100 s**	--	**-12 5 300 s**	--	--	--	--	--	--	--	--	--	-164 5.9 s	--	--	--	--
HeapManipulation 80 tasks, max. score: 135	--	--	--	70 6 000 s	**100 13 000 s**	96 930 s	--	79 37 s	--	32 1.8 s	--	--	--	--	--	--	**111 140 s**	-37 14 s	**109 820 s**	84 460 s	84 420 s	--
MemorySafety 205 tasks, max. score: 361	--	--	--	**200 82 000 s**	-433 14 000 s	**326 5 700 s**	--	--	--	22 25 s	--	--	--	28 2 100 s	--	--	**221 460 s**	0 0 s	--	95 13 000 s	66 4 800 s	--
Recursive 24 tasks, max. score: 40	--	6 22 s	--	--	0 10 000 s	16 31 s	**18 140 s**	--	--	--	--	--	--	--	--	--	--	-88 2.3 s	**27 2 300 s**	**25 310**	10 220	--
Sequentialized 261 tasks, max. score: 364	--	--	--	--	-171 39 000 s	**130 11 000 s**	--	**193 9 600 s**	--	--	--	--	--	--	--	--	--	-59 5 800 s	--	**15 8 600 s**	-10 7 000 s	--
Simple 46 tasks, max. score: 68	--	--	32 4 200 s	--	51 16 000 s	**54 4 000 s**	--	29 990 s	--	--	--	--	--	--	--	--	--	**65 1 400 s**	**51 5 100 s**	0 1 800 s	3 140 s	--
Termination 393 tasks, max. score: 742	**610 5 400 s**	--	--	--	--	0 0 s	--	--	--	--	350 61 s	**545 300 s**	--	--	--	--	--	0 0 s	--	**565 8 600 s**	--	--
Overall 5 803 tasks, max. score: 9 562	--	--	--	--	**1 731 1 100 000 s**	**4 889 110 000 s**	--	- 2 161 130 000 s	--	--	--	--	--	--	--	--	--	- 6 228 53 000 s	--	**2 301 87 000 s**	231 23 000 s	--



http://ultimate.informatik.uni-freiburg.de/automizer

Future Work

- verification tasks $\leftrightarrow$ automata
- optimized inclusion check for Büchi automata
- differnt ω-automata in termination analysis

Thank you for your attention!