Real-Time Systems

Lecture 1: Introduction

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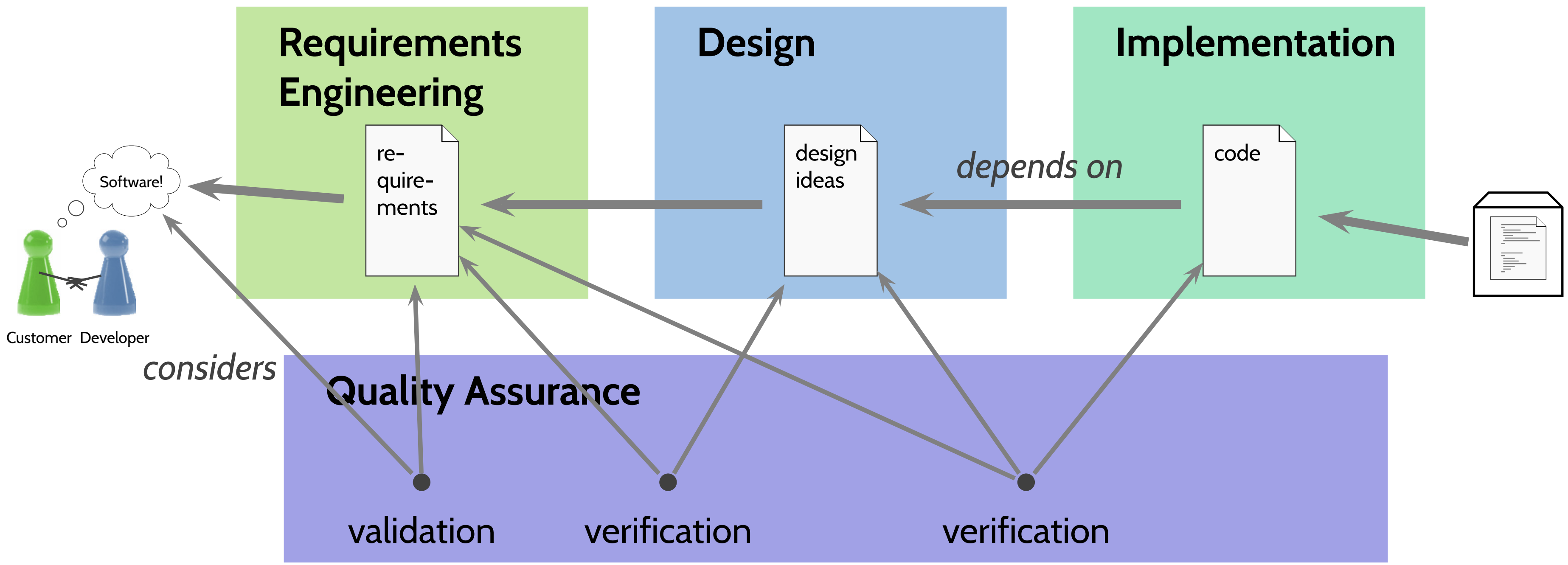
Content

- **Introduction**
  - a **software engineering** perspective
  - a **theoretical computer science** perspective
- **Real-Time Systems**
  - vs. **reactive systems**
  - vs. **hybrid systems**
  - **safety-critical systems**
  - **examples**
- **Lecture Content Overview**
  - and **non-content**
- **Formalia**
  - times/dates, procedures, exam
- **A Formal Model of Real-Time Behaviour**
  - **state variables** / observables
  - **evolution** / behaviour

Introduction: Software Engineering Perspective

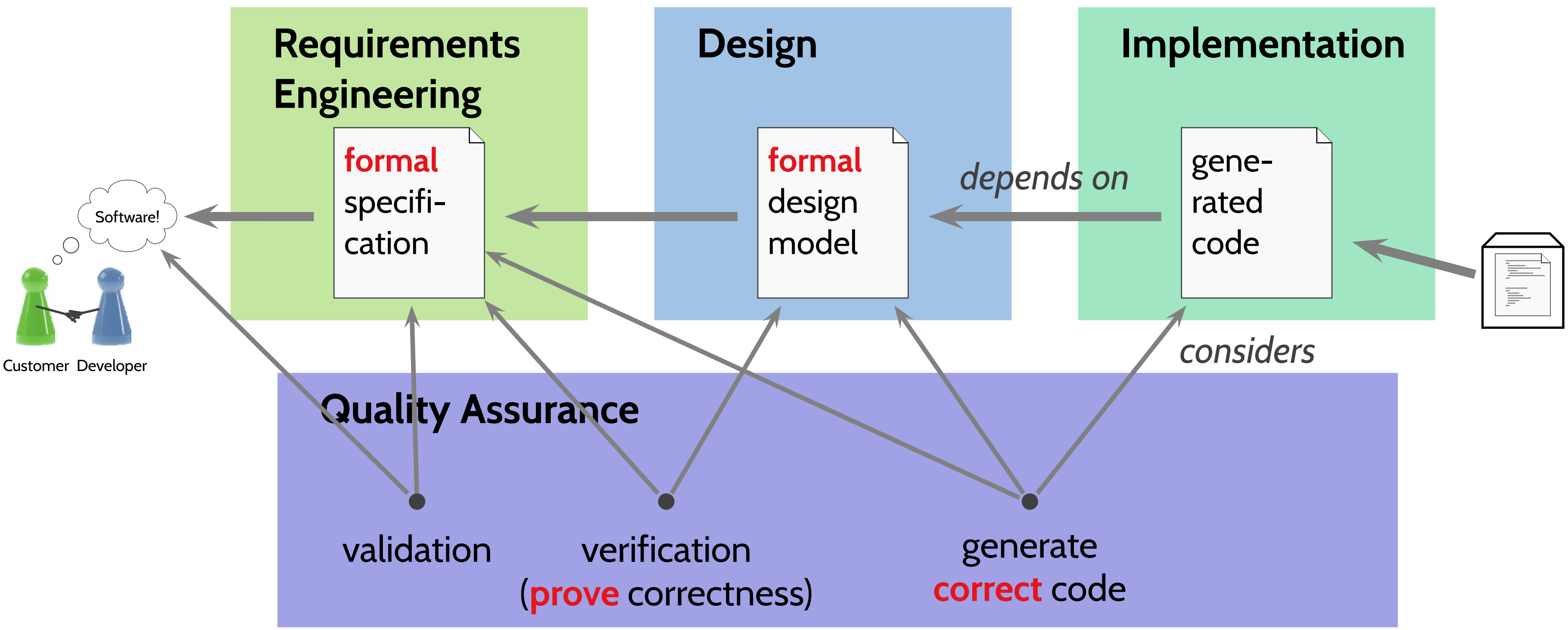
Recall: Software Engineering



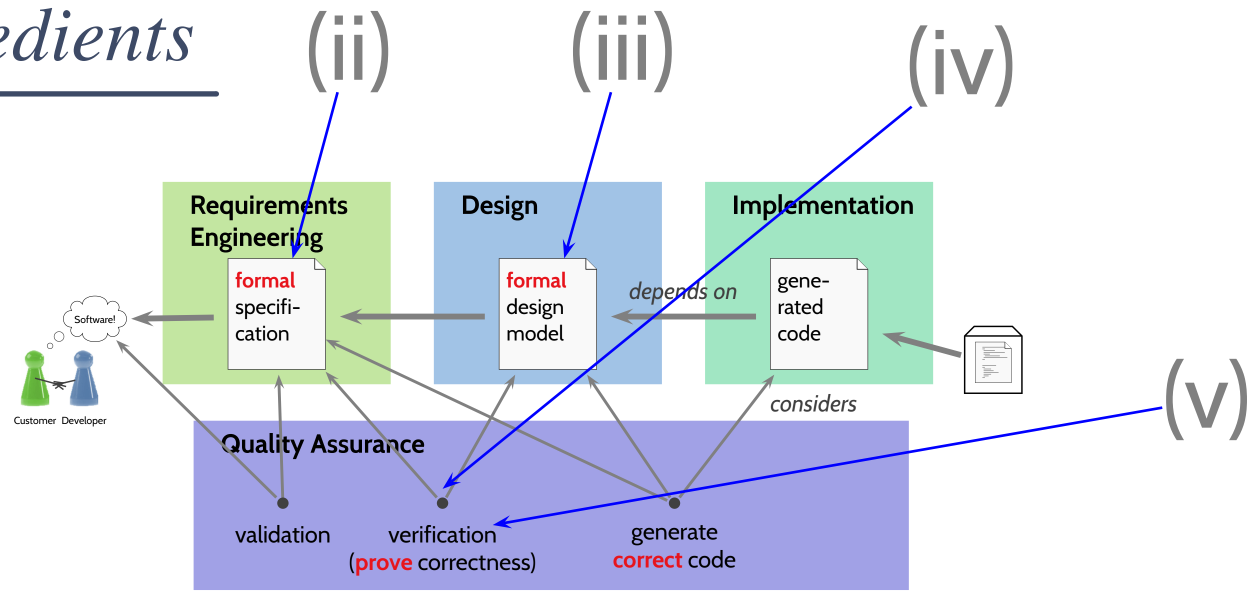
- misunderstandings / errors detected late in development can be expensive:
  - design and implementation may need to be re-done.
- misunderstandings / errors detected only during use can be fatal:
  - software malfunction may harm business goals, or even lead to people being hurt.

Recall: Formal Methods

- One approach to detect misunderstandings / errors early:
  - describe **requirements** precisely / formally / **mathemathically**
  - try to **prove** requirements to be consistent, complete, etc.
  - describe **design ideas** precisely / formally / **mathemathically**
  - try to **prove** that design satisfies requirements, i.e. that design is **correct**



Necessary Ingredients



To develop **software that is (provably) correct wrt. its requirements**, we need:

(i) a **formal model** of software **behaviour**

(ii) a **language*** to specifiy **requirements** on **behaviour**,
(to distinguish desired from undesired behaviour),

(iii) a **language*** to specify **behaviour** of **design ideas**,

(iv) a notion of **correctness**
(a relation between requirements and design specifications),

(v) and a **method** to **verify (or prove) correctness**
(that a given pair of requirements and design specifications are in correctness relation).

∗: at best concisely and conveniently, with adequate expressive power.

Example (Un-timed): Traffic Lights

- Choose **observables**:
  R: red light on, $\overline{R}$: red light off, Y: yellow light on, $\overline{Y}$: yellow light off,
  G: green light on. $\overline{G}$: green light off.
- **Model of (finite) behaviour**: Σ^*, where $\Sigma = (\{R, \overline{R}\} \times \{Y, \overline{Y}\} \times \{G, \overline{G}\})$.
  finite sequences of letters Σ — *alphabet*
  We write, e.g., RYG as shorthand for $(R, \overline{Y}, \overline{G})$.

  Example behaviours:
  - RYG, RYG, RYG
  - RYG, RYG, RYG
- **Requirements**:
  - Desired lights sequence: red, red-yellow, green, yellow, …
    Formalisation: $\mathsf{Req}_1 := (\mathsf{RYG}.\mathsf{RYG}.\mathsf{RYG}.\mathsf{RYG})^*$ } *regular expression*
  - Undesired configuration: red-green
    Formalisation: $\mathsf{Req}_2 := \overline{\Sigma^*.\mathsf{RYG}.\Sigma^*}$ *complement*
- **Design**:

  $\mathsf{Des}_0 :=$ 

- Define **notion of correctness**:
  A design Des is correct wrt. requirement Req if and only if $\mathcal{L}(\mathsf{Des}) \subseteq \mathcal{L}(\mathsf{Req})$.

Example (Un-timed): Traffic Lights

derived from: F. Welter-Schultes, CC0

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  We write, e.g., RYG as shorthand for $(R, \overline{Y}, \overline{G})$. (i)

  Example behaviours:

  - RYG, RYG, RYG
  - RYG, RYG, RYG

- **Requirements**:
  - Desired lights sequence: red, red-yellow, green, yellow, ...

    Formalisation: $\text{Req}_1 := (\text{RYG.RYG.RYG.RYG})^*$ (ii)
  - Undesired configuration: red-green

    Formalisation: $\text{Req}_2 := \overline{\Sigma^*.\text{RYG}.\Sigma^*}$

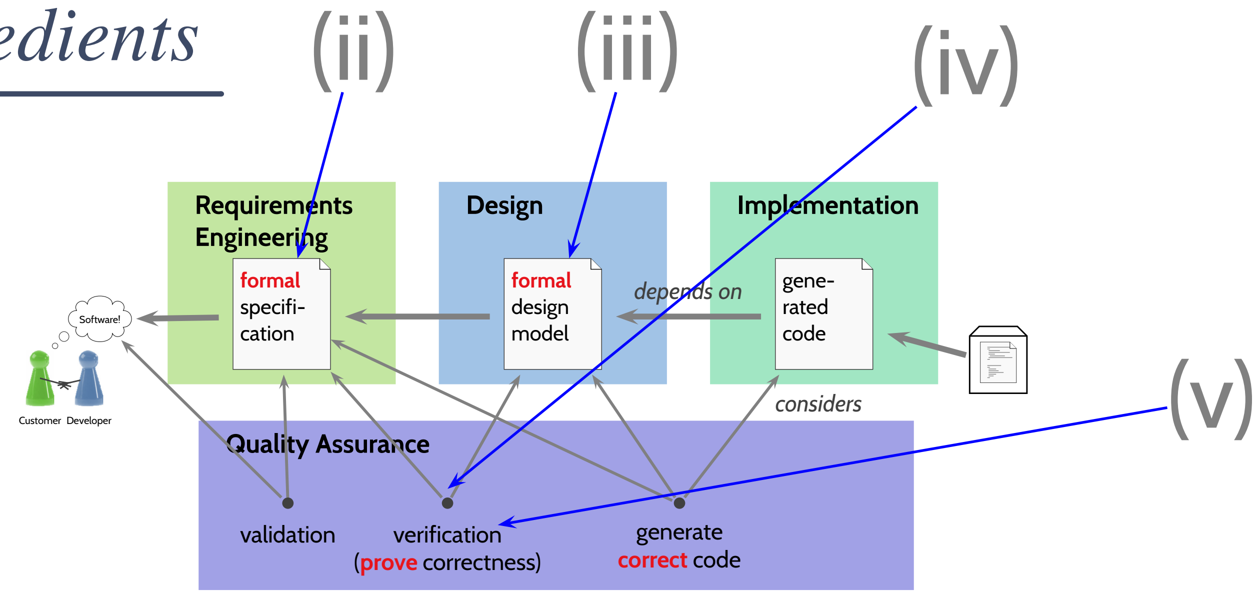
- **Design**:

  $\text{Des}_0 :=$ 

  (iii)

- Define **notion of correctness**:
  A design Des is correct wrt. requirement Req if and only if $\mathcal{L}(\text{Des}) \subseteq \mathcal{L}(\text{Req})$. (iv)
- Design Des_0 is correct wrt. requirements Req_1 and Req_2 (proof method: automata theory). (v)

Necessary Ingredients



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Example (Timed): Traffic Lights

- **Requirement**: yellow phases (RYG) should have a duration of 3 seconds on streets with speed limit 50 km/h.
- **How** do we **formally model** traffic lights behaviour **with time**?

  For example (informal):

  - red for 10 s
  - red-yellow for 2 s
  - green for 120 s
  - yellow for 3 s

- **How** do we **formalise** the **timed requirement** of 3 s?
- **How** do we **formally model** a **controller design with time**?
- **What** does it mean for a **timed design** to be **correct** wrt. a **timed requirement**?
- **How** do we **prove timed designs** correct wrt. **timed requirements**?

→ Lecture **"Real-Time Systems"**

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Introduction: Theoretical Computer Science Perspective

Logics and Automata for Timed Behaviour

Lectures like **Introduction to Theoretical Computer Science** ("Informatik 3") cover content such as

- **propositional logic**
  - syntax, semantics, decision problems (e.g., satisfiability is decidable)
- **finite automata**
  - syntax, language of an automaton
  - decision problems (e.g., language emptiness is decidable)
  - properties, e.g., finite automata are closed under intersection
- **Questions**: Are there logics whose models are timed behaviours?
  - Is satisfiability still decidable?
  - If not for the full logic, then for which fragment?
- **Questions**: If we equip finite automata with real-time clocks,
  - is language emptiness still decidable?
  - are the set of such timed automata still closed under intersection?
  - is it decidable whether a timed automaton satisfies a timed property?

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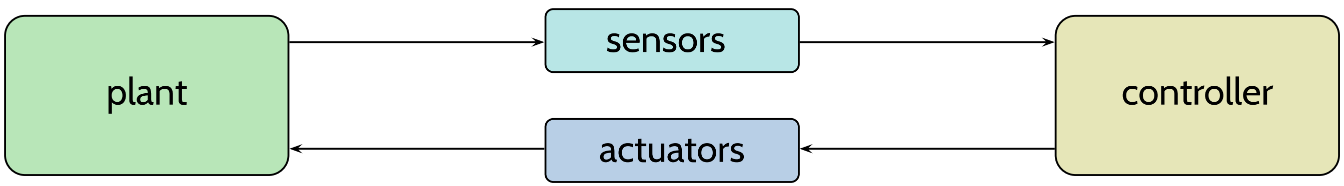
Reactive Systems

- A **reactive system** interacts with its environment
  by reacting to inputs from the environment with certain outputs.
  - Reactive systems usually **do not terminate**.
    For example, the traffic lights controller continues to run,
    unless there is a power outage or a scheduled maintenance.

- **Contrast**: terminating, transformational systems.
  For example: a sorting or searching function.

- **Reactive systems** can be partitioned into:

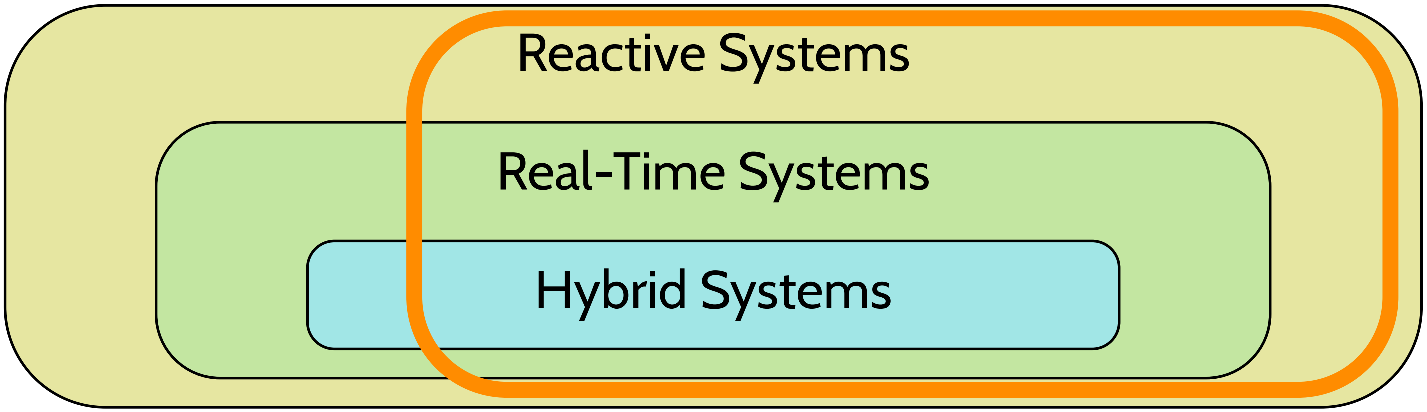


  - "In constructing a **real-time system** the aim is to control a physically existing environment, the **plant**, in such a way that the controlled plant satisfies all desired (timing) requirements."

Real-Time and Hybrid Systems

- A **Real-Time System** is a **reactive system** which,
  for certain inputs,
  has to compute the corresponding outputs **within given time bounds**.

- A **Hybrid System** is a **real-time system** consisting of continuous and discrete components. The continuous components are time-dependent (!) physical variables ranging over a continuous value set.



- A system is called **Safety Critical**
  if and only if a malfunction can cause loss of goods, money, or even life.

Another Definition *Douglass (1999)*

- "A **real-time** system is one
  that has **performance deadlines** on its computations and actions."
- Sometimes distinguished:
  - "**Hard deadlines**: performance requirements
    that **absolutely must** be met each and every event or time mark." (→ **this lecture**)

    "(Early / late data can be bad data.)"
  - "**Soft deadlines**: for instance about **average** response times."

    "(Early / late data is still good data.)"
- **Design Goal**:

  A **timely system**, i.e. one which is meeting its performance requirements.
- **Note**: **performance** can in general be measured by any unit of quantities:
  - (discrete) number of steps or processor instructions,
  - (discrete or continuous) number of seconds, (→ **this lecture**)
  - etc.

Example: Airbag Controller

Controller requirement: "When a crash is detected, fire the airbag."

- When firing **too early**: airbag ineffective.
- When firing **too late**: additional threat.

Say, 300ms (plus/minus small ε) after a crash is the right™ time to fire.

Then the **precise requirement** is

"When a crash is detected at time t, fire the airbag at $t + 300ms \pm \varepsilon$."

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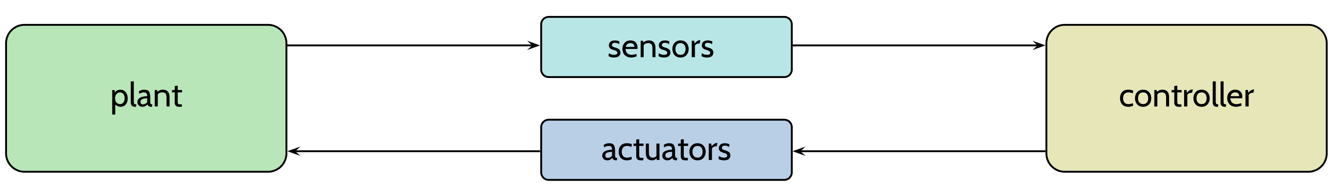
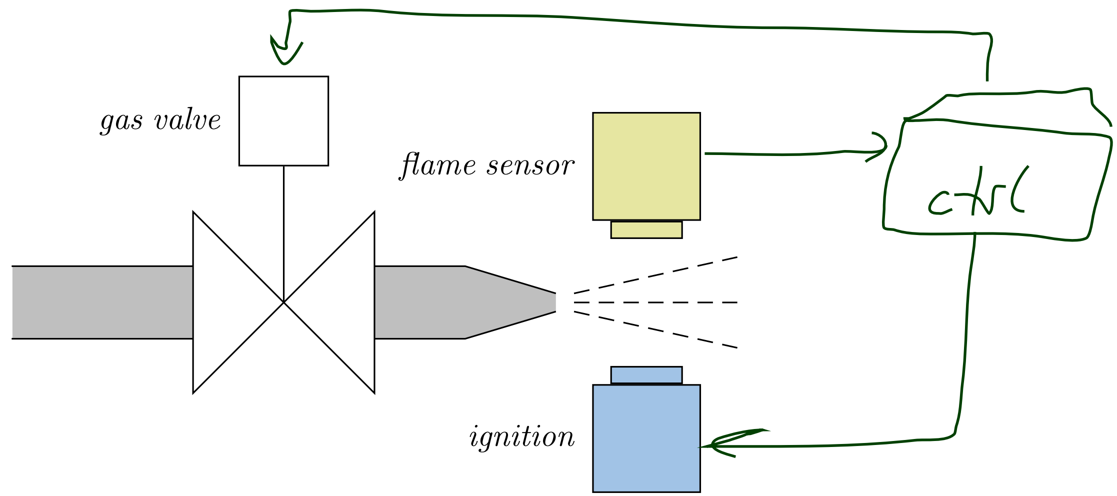
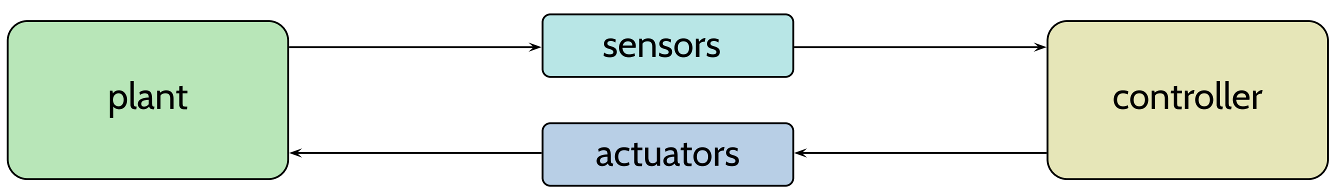
What is the plant, what is the controller?



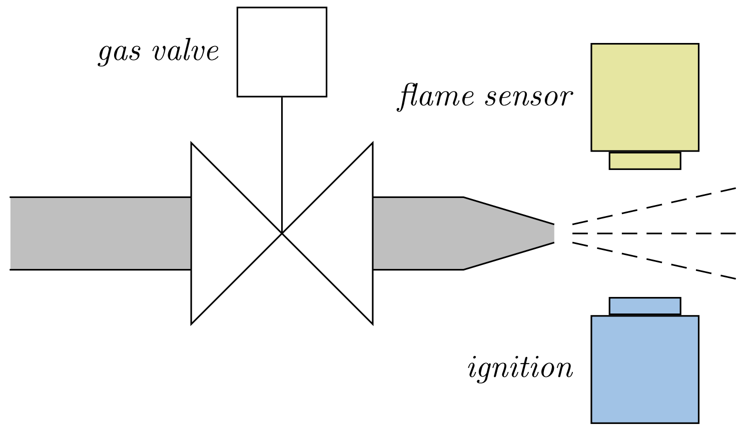
Example: Gas Burner



Where is the plant, where is the controller?



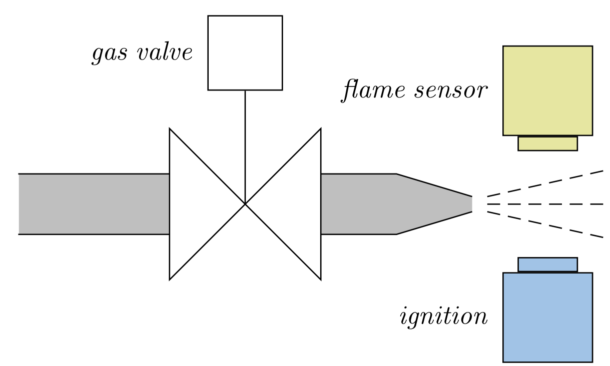
Example: Gas Burner



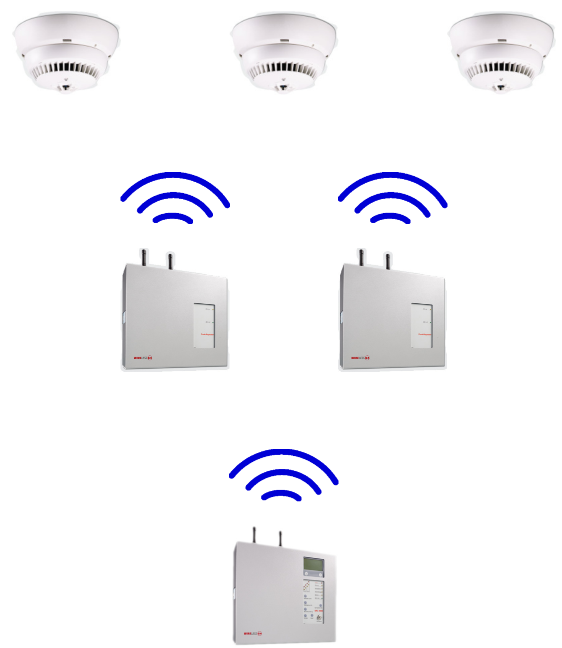
- A situation where the **gas valve is open** but there is **no flame** is called **leakage**.
- **Leakage** is practically unavoidable:
  - for ignition, first open valve,
  - then ignite the available gas;
  - ignition may fail…
- **Leakage** is **safety critical**:
  Igniting large amounts of leaked gas may lead to a dangerous explosion.
- **Requirement**: Leakage phases should have a limited duration.

Sketch of the Methodology: Gas Burner Example

- **Requirements**
  - At most 5% of any at least 60s long interval amounts to leakage.
- **Reflective Design**
  - Time intervals with leakage last at most 1s.
  - After each leak, wait 30s before opening valve again.
- **Constructive Design**
  - PLC Automaton:
    (open valve for 0.5s;
    ignite;
    if no flame after 0.1s close valve)
- **Implementation**
  - IEC 61131-3 program



Example: Wireless Fire Alarm System



(Arenis et al., 2016)

- Wireless fire alarm systems are regulated by **European Norm EN-54, Part 25**.
- EN 54-25 states the following **requirements**:

(i) The loss of the ability of the system to transmit a signal from a component to the central unit is detected in **less than 300 seconds** and displayed at the central unit **within 100 seconds** thereafter.

(ii) Out of exactly **ten alarms** occurring **simultaneously**, the first should be displayed at the central unit **within 10 seconds** and all others **within 100 seconds**.

(iii) There must be **no spurious displays** of events at the central unit.

(iv) The above requirements must hold as well in the presence of **radio interference** by other users of the frequency band. Radio interference by other users of the frequency band is simulated by a **jamming device** specified in the standard.

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Content Overview

Content

Introduction

- **Observables and Evolutions**

- **Duration Calculus** (DC)
- Semantical Correctness Proofs
- DC Decidability
- DC Implementables

- **PLC-Automata**

$$obs : \text{Time} \rightarrow \mathscr{D}(obs)$$

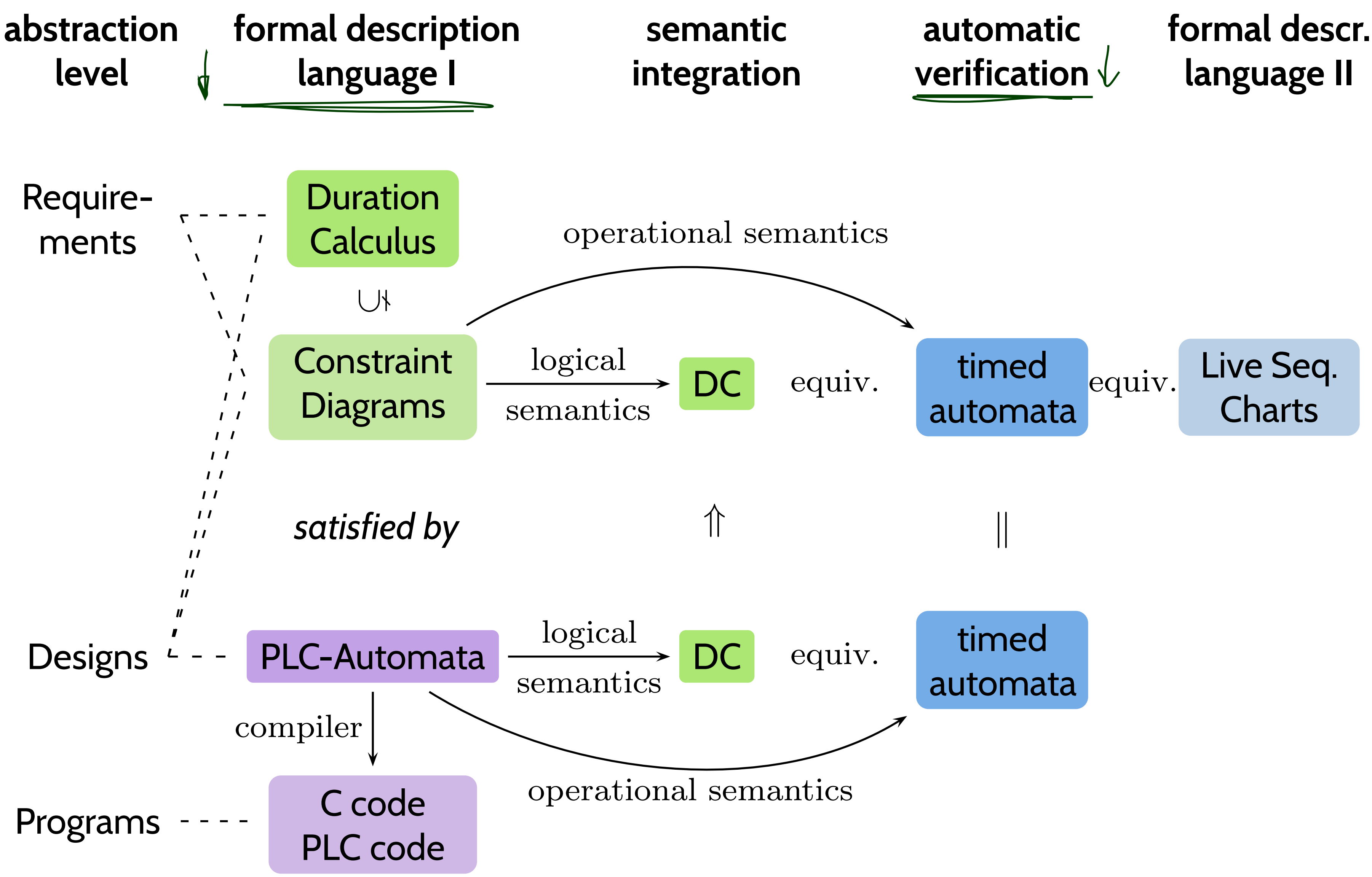
- **Timed Automata** (TA), Uppaal
- Networks of Timed Automata
- Region/Zone-Abstraction
- TA model-checking
- Extended Timed Automata
- Undecidability Results

$$\langle obs_0, \nu_0 \rangle, t_0 \xrightarrow{\lambda_0} \langle obs_1, \nu_1 \rangle, t_1 \ldots$$

- **Automatic Verification**...

  ...whether a TA satisfies a DC formula, observer-based
- **Recent Results**:
  - **Timed Sequence Diagrams**, or **Quasi-equal Clocks**, or **Automatic Code Generation**, or …

Tying It All Together



Non-Content

- **Worst Case Execution Time**
  - Over-simplified airbag controller program:

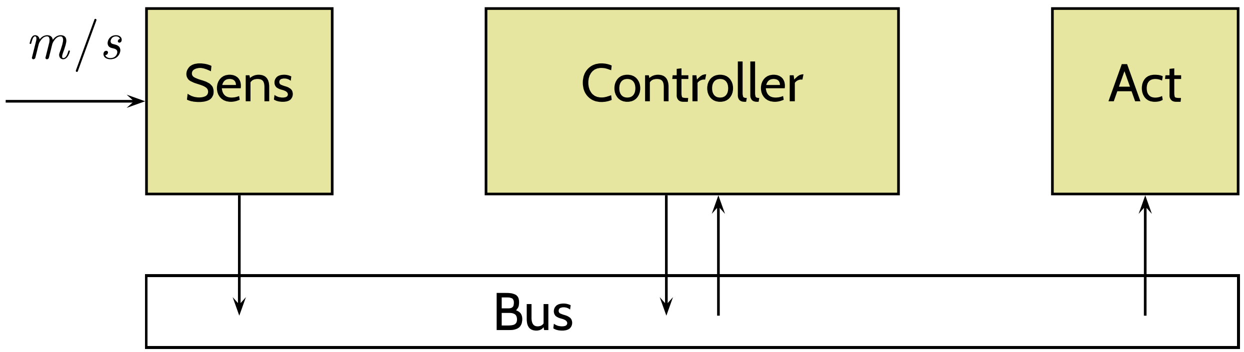
```
while (true) do
   poll_sensors();
   if (crash) tmr.start(300ms);
   if (tmr.elapsed()) fire := 1;
   update_actuators();
od
```

  - The execution of `poll_sensors()` and `update_actuators()` also **takes time**! (And we have to consider it!)

  - **Not in lecture**:
    How to determine the WCET of, for instance, C code.
    (A science of its own.)

Scheduling

- A bit less over-simplified airbag controller:



- **Not in lecture**: Specialised methods to determine...
  - ...whether the bus provides sufficient bandwidth.
  - ...whether the Real-Time OS controlling CPU 'Controller' schedules the airbag control code in time.
  - ...how to distribute tasks over multiple CPUs.
  - etc.

(Also a science of its own.)

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Formalia

Formalia: Event

- **Lecturer: Dr. Bernd Westphal**
- **Support: Liridon Musliu**

- **Homepage:**

  `http://swt.informatik.uni-freiburg.de/teaching/WS2017-18/rtsys`

- **ILIAS course**: see homepage.

- **Location:**
  - Tuesday, Thursday: here

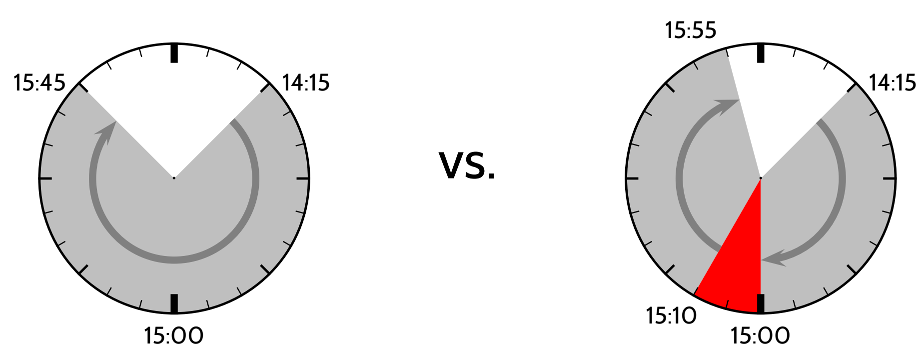
Formalia: Dates/Times, Break

- **Schedule:**

Thursday, week N:	14:00–16:00 **lecture**		(exercises M **online**)
Tuesday, week $N+1$:	14:00–16:00 **lecture**		
Thursday, week $N+1$:	14:00–16:00 **lecture**		
Monday, week $N+2$:	14:00		(exercises M **early turn-in**)
Tuesday, week $N+2$:	14:00		(exercises M **late turn-in**)
Tuesday, week $N+2$:	14:00–16:00 **tutorial**		
Thursday, week $N+2$:	14:00–16:00 **lecture**		(exercises $M+1$ **online**)

With a prefix of lectures, with public holidays; see homepage for details.

- **Break:**
  - Unless a majority objects **now**,
    we'll have a **10 min. break** in the middle of each event from now on.



Formalia: Lectures

- **Course language:** **English**
  (slides/writing, presentation, questions/discussions)

- **Presentation:**
  half slides/half on-screen **hand-writing** – for reasons

- **Script/Media:**
  - **slides** without annotations on **homepage**,
    trying to put them there **before** the lecture
  - **slides** with annotations on **homepage**, 2-up for printing,
    typically **soon after** the lecture
  - **recordings** in **ILIAS** course with max. 1 week delay.

- **Interaction:**
  absence often moaned but **it takes two**,
  so please ask/comment immediately

Formalia: Exercises and Tutorials

- **Schedule/Submission:**
  - **Recall**: exercises **online** on Thursday before (or soon after) lecture, regular **turn in** on corresponding tutorial day until **14:00 local time**
  - should work in groups of **max. 3**, clearly give **names** on submission
  - please submit **electronically** ~~by Mail to me (cf. homepage)~~, ILIAS !
    some LaTeX styles on homepage; paper submissions are tolerated
- **Didactical aim:**
  - deal more extensively with notions from lecture (easy)
  - explore corner cases or alternatives (medium)
  - evaluate/appreciate approaches (difficult)
  - additional **difficulty**: imprecise/unclear tasks – by intention
- **True aim: most complicated** rating system **ever**, namely two ratings
  - Good-will ("reasonable solution with knowledge **before** tutorial")
  - Evil/Exam ("reasonable solution with knowledge **after** tutorial")

10% **bonus** for **early** submission.

Formalia: Exam

- **Exam Admission:**

  50% of the maximum possible non-bonus **good-will points** in total are **sufficient** for admission to exam

- **Exam Form:** (oral or written) not yet decided

Formalia: Evaluation

Speaking of **grading and examination**...

- **Mid-term Evaluation:**
  We will have a **mid-term evaluation**[1], but we're **always** interested in comments/hints/proposals concerning form or content.

[1] that is, students are asked to evaluate lecture, lecturer, and tutor...

Formalia: Questions

- **Questions:**

  - **“online”**:

    (i) ask immediately or in the break

  - **“offline”**:

    (i) try to solve yourself

    (ii) discuss with colleagues

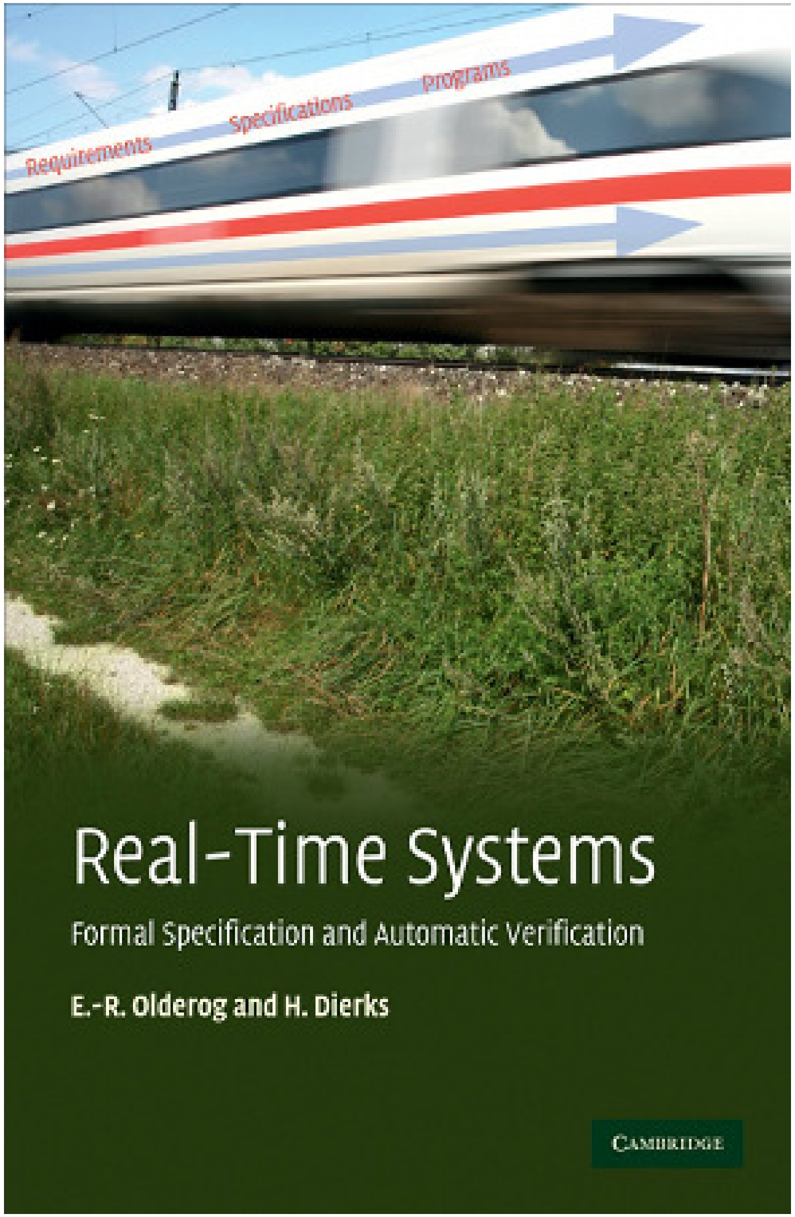
    (iii)

      - **Exercises**: contact tutor via ILIAS forum or by mail
      - **Rest**: contact lecturer by mail (cf. homepage)
        or just drop by: Building 52, Room 00-020

Speaking of questions:

Any questions so far...?

Formalia: Literature *(offered as eBook by UB)*



Tell Them What You've Told Them...

- **Real-Time Systems**...
  - ...have to compute outputs for certain inputs within (**quantitative!**) **time bounds**,
  - ...are often **safety critical**, then construction requires a high degree of precision.
  - (discrete) **reactive system**: without time (other lecture),
  - **hybrid system**: other continous components than clocks (other lecture).
- **The lecture** presents approaches for the **precise development** of real-time sytems,
  - logic-based: **Duration Calculus**
  - automata-based: **Timed Automata**
- **Non-content**: (other lectures)
  - Real-time operating systems,
  - Scheduling,
  - Worst-case execution time, etc..

References

References

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