Real-Time Systems

Lecture 1: Introduction

2017-10-17

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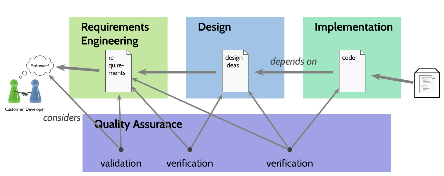
Content

Introduction: Software Engineering Perspective

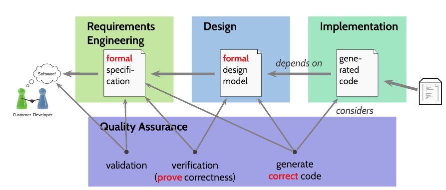
Recall: Software Engineering



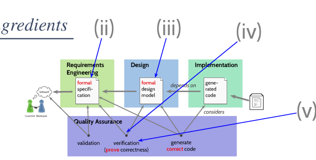
- **misunderstandings** / **errors** detected **late in development** can be **expensive**:
  - design and implementation may need to be **re-done**.
- **misunderstandings** / **errors** detected only **during use** can be **fatal**:
  - software malfunction may **harm business goals**, or even lead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

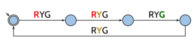
(v) and a **method** to **verify (or prove) correctness**
(that a given pair of requirements and design specifications are in correctness relation).

*: 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 $\Sigma = (\{R, \overline{R}\} \times \{Y, \overline{Y}\} \times \{G, \overline{G}\})$.
  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: $\text{Req}_1 := (\text{RYG}.\text{RYG}.\text{RYG}.\text{RYG})^*$
  - Undesired configuration: red-green
    Formalisation: $\text{Req}_2 := \overline{\Sigma^*.\textbf{RYG}.\Sigma^*}$
- **Design**:

Des₀ :=



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

finite sequences of letters Σ
alphabet
regular expression
complement

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  } (i)
- **Requirements**:
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  (ii)
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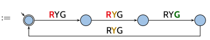
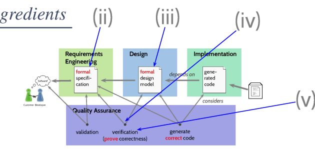


} (iii)

- 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"**

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: 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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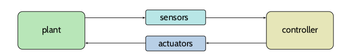
Reactive Systems

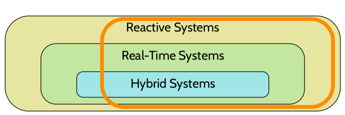
- A reactive system interacts with its environment by reacting to inputs from the environment with certain outputs.
  - Reactive systems usually do not terminate.
    For example, the traffic lights controller continues to run, unless there is a power outage or a scheduled maintenance.
- Contrast: terminating,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

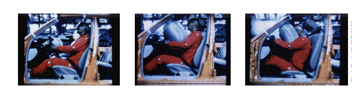


- A system is called Safety Critical if and only if a malfunction can cause loss of goods, money, or even life.

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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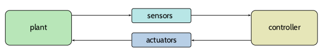
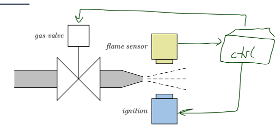
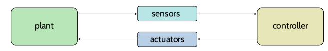
What is the plant, what is the controller?



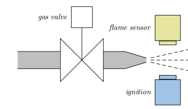
Example: Gas Burner



Where is the plant, where is the controller?



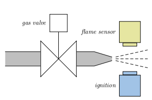
Example: Gas Burner



- 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

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

(Arenis et al., 2016)

(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**

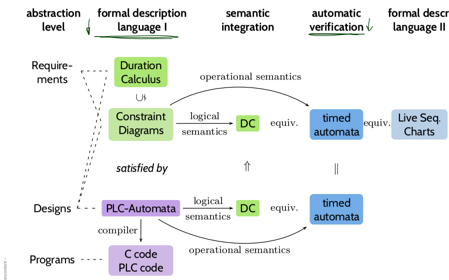
$obs : \text{Time} \to \mathscr{D}(obs)$

- **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:

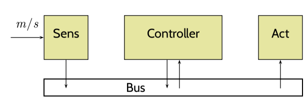
```
while (true) do
   poll_sensors();
   if (crash) tmr.start(300ms);
   if (tmr.elapsed()) fire := 1;
   update_actuators();
od
```

- 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.)

Non-Content

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

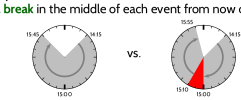
Formalia: Dates/Times, Break

- **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 — 10% (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

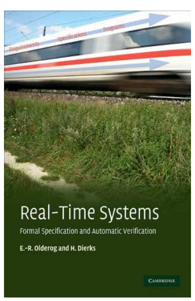
- **Questions:**
  - **"online"**:
    (i) ask immediately or in the break
  - **"offline"**:
    (i) try to solve yourself
    (ii) discuss with colleagues
    (iii)
      - **Exercises**: contact tutor via ILIAS forum or by mail
      - **Rest**: contact lecturer by mail (cf. homepage) or just drop by: Building 52, Room 00-020

Formalia

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

Arenis, S. F., Westphal, B., Dietsch, D., Muñiz, M., Andisha, A. S., and Podelski, A. (2016). Ready for testing: ensuring conformance to industrial standards through formal verification. *Formal Asp. Comput.*, 28(3):499–527.

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