27. Rich Components with A/P-Quality Contracts

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Obligatory Literature

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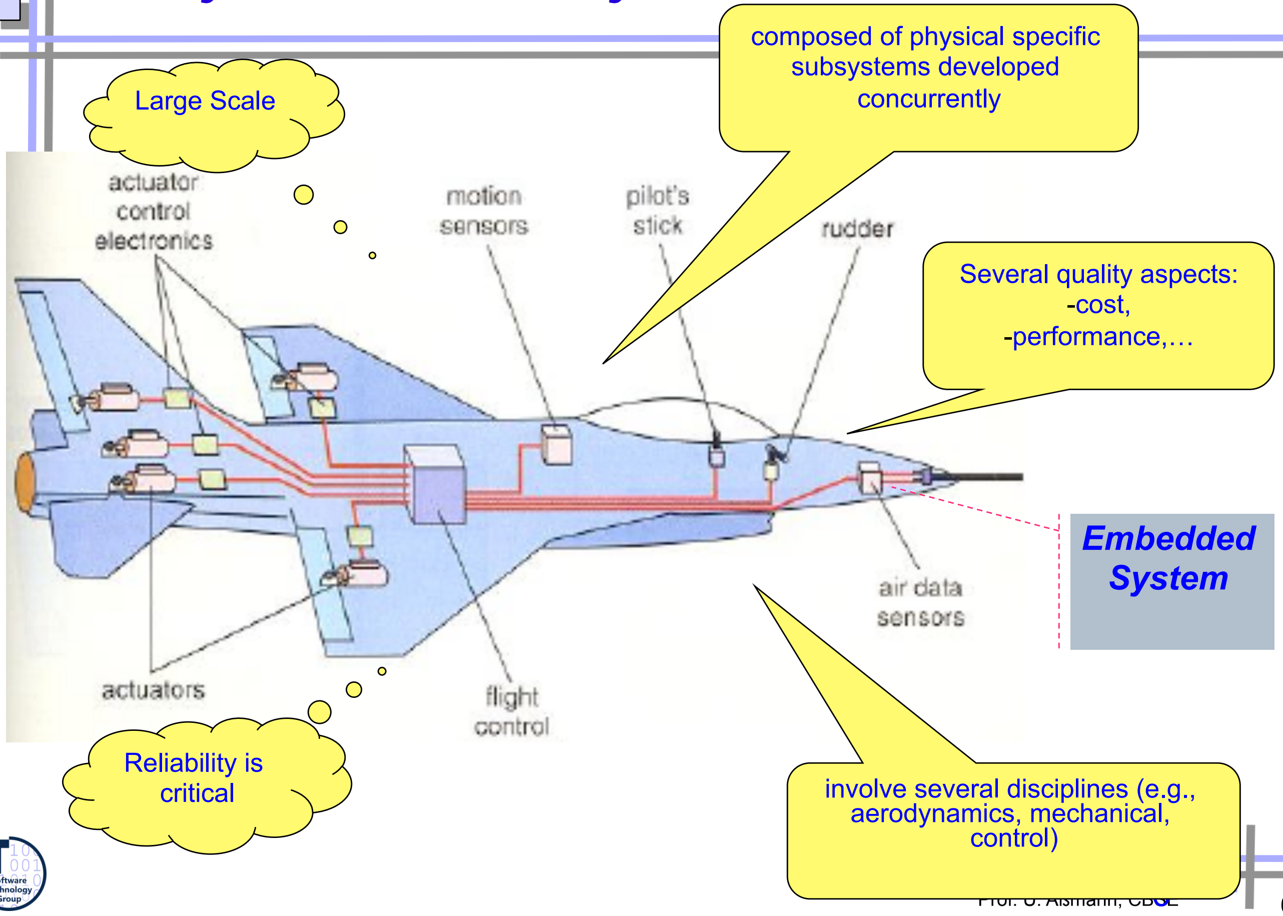
27.1. CBSE for Embedded Systems

Today's Embedded Systems



Götting Autonomous Transport Systems

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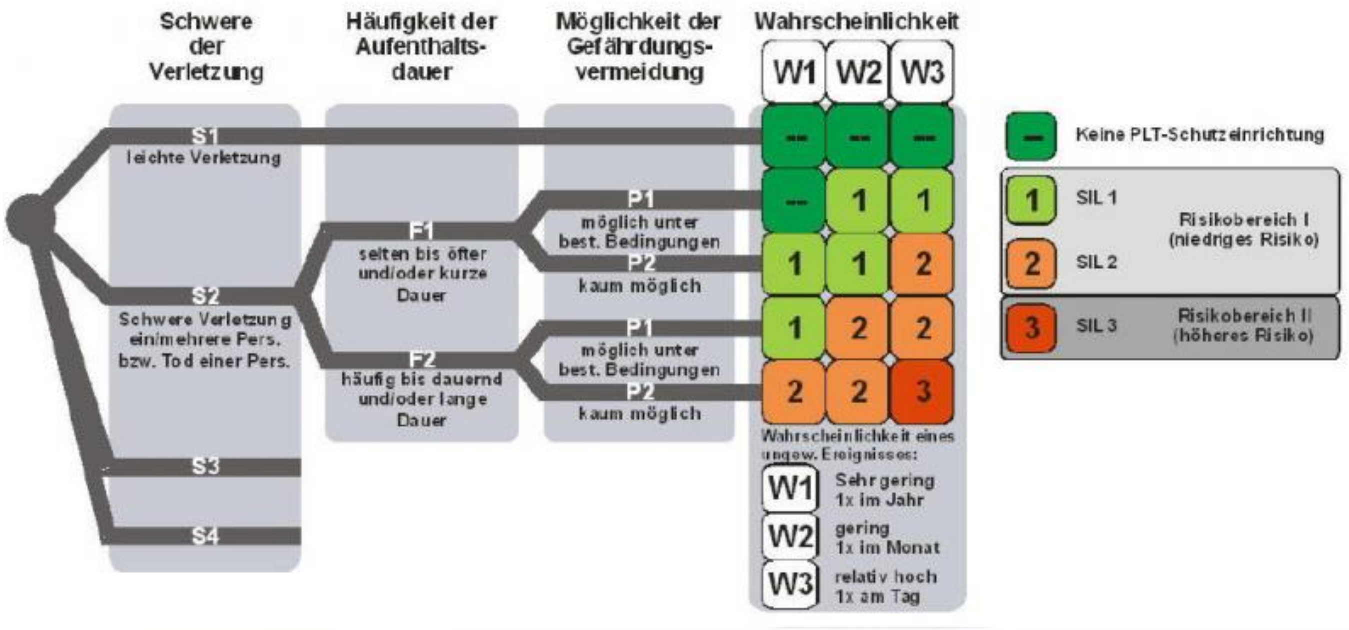
Risk Graph from Götting Autonomous Transport



Schwere der Verletzung
Häufigkeit der Aufenthalts-dauer
Möglichkeit der Gefährdungs-vermeidung
Wahrscheinlichkeit
W1 W2 W3
S1
leichte Verletzung
S2
Schwere Verletzung ein/mehrere Pers. bzw. Tod einer Pers.
S3
S4
F1
selten bis öfter und/oder kurze Dauer
F2
häufig bis dauernd und/oder lange Dauer
P1
möglich unter best. Bedingungen
P2
kaum möglich
-- -- --
-- 1 1
1 1 2
1 2 2
2 2 3
Wahrscheinlichkeit eines ungew. Ereignisses:
W1 Sehr gering 1x im Jahr
W2 gering 1x im Monat
W3 relativ hoch 1x am Tag
Keine PLT-Schutzeinrichtung
SIL 1
SIL 2
Risikobereich I (niedriges Risiko)
SIL 3
Risikobereich II (höheres Risiko)

http://www.goetting.de/dateien/galerienbilder/risikograph.jpg

Quality Requirements (Real-time, Safety, Energy, Dynamics)

- **Informal Quality Requirements** are specified in the *software requirements specification (SRS, Pflichtenheft)*
- **Informal Real-Time Requirement:** *The gate is closed when a train traverses the gate region, provided there is a minimal time distance of 40 seconds between two approaching trains.*
  - Hard Real-time: definite deadline specified after which system fails
  - Soft Real-time: deadline specified after which quality of system's delivery degradates
- **Informal Safety Requirement:** *If the robot's arm fails, the robot will still reach its power plug to recharge.*
- **Informal Energy Requirement:** *If the robot's energy sinks under 25% of the capacity of the battery, it will still reach its power plug to recharge.*
- **Informal Dynamic Movement Requirement:** *If the car's energy sinks under 5% of the capacity of the battery, it will still be able to break and stop.*

Vision: Modular Verification of Behavior of Embedded Systems

- Usually, Embedded Software is hand-made, verification is hard
- But fly-by-wire and drive-by-wire need verification

- Challenge 1: Quality requirements can be formalized and proven
  - How to formalize them?
  - How to prove them?
- Challenge 2: Proof can be computed in modules, proof is modular and can be reused as a proof component in another proof
  - Contracts serve this purpose: they prove assertions about components and subsystems
  - Whenever an implementation of a component is exchanged for a new variant, the new variant must be proven to be **conformant** to the old contract. Then the old global proof still holds
  - This is a CBSE challenge!

27.2. SPEEDS HRC (Heterogeneous Rich Components)

.. Further developed in the EU project CESAR

.. Now called CESAR Component Model (CCM)

Rich Component Models

- A **rich component** defines contracts in several *views* with regard to different *viewpoints*
  - A contract for functional behavior (functional view)
  - Several quality contracts, e.g.,
    - Real-time behavior (real-time view)
    - Energy consumption (energy view)
    - Safety modes (safety view)
    - Movements (dynamics view)
  - Used for component-based software for embedded systems
- The **contract** (about the observable behavior) of a component is described by state machines in the specific view (**interface automata**)
  - The interface automata encode infinite, regular path sets (traces)
  - They can be intersected, unioned, composed; they are decidable
  - Contracts can be proven
- Instead of an automaton in a contract, temporal logic can be used and compiled to automata (**temporal logic contract**)

Assumptions about Automata-Based Contracts

- A component has one thread of control
- A component is always in a finite set of states
- The behavior of a component can be described by a protocol automaton (interface automaton)
  - Compatibility is decidable
- A **hybrid automaton** is an automaton in which states and transitions can be annotated in different views
  - A **real-time automaton** is a hybrid automaton with real-time annotations
  - A **safety automaton** is a hybrid automaton with safety annotations
  - A **dynamics automaton** is a hybrid automaton with dynamics equations (physical movement, electricity movement)
  - An **energy automaton** is a hybrid automaton with energy consumption annotations

A/P Quality Contracts for CBSE

- [Gössler/Sifakis, Heinecke/Damm]
- **Composability** gives guarantees that a component property is preserved across composition/integration
- **Compositionality** deduces global semantic properties (of the composite, the composed system) from the properties of its components
- An **A/P-contract** is an if-then rule: under the **assumption A**, the component will deliver **promise P** (aka **guarantee G**)

Assertion

Contract = (assumption, promise)

Assertion

= IF assumption THEN promise

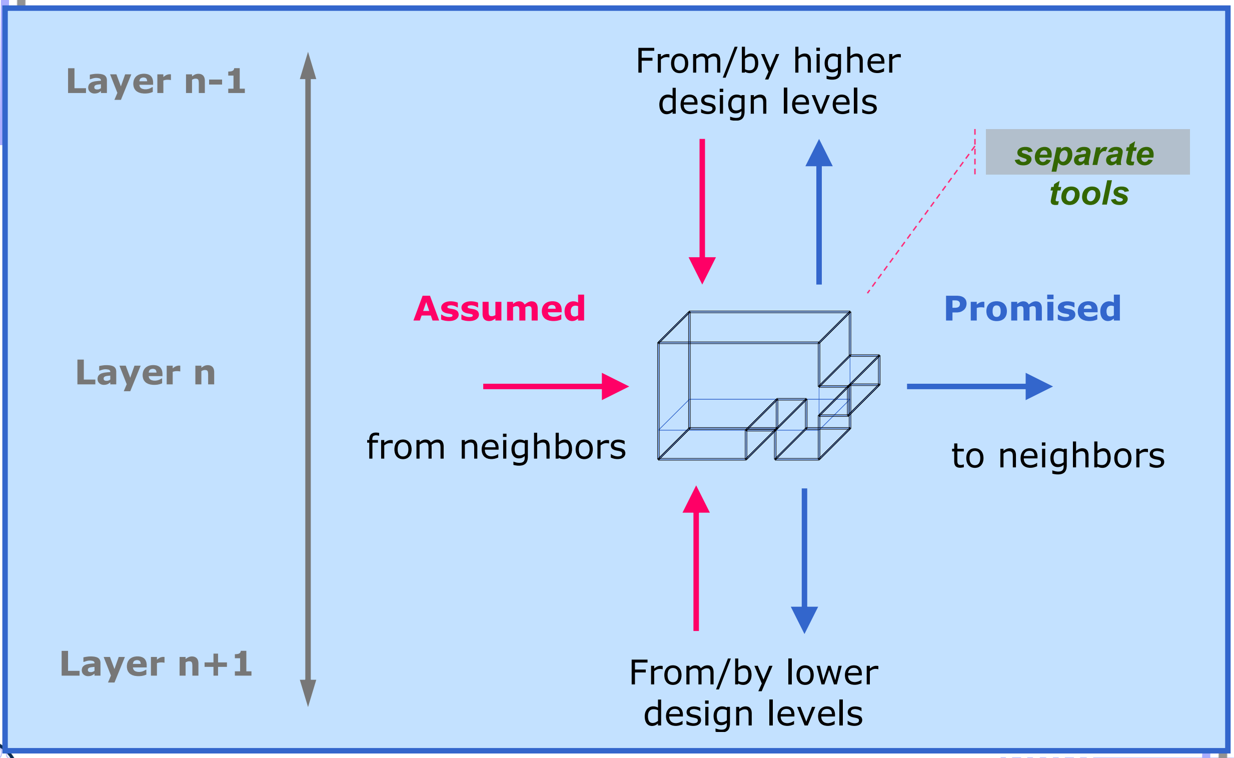
- An **A/P-quality contract** is an A/P-contract in which hybrid automata form the assumptions and promises

A/P-quality contract based component models are composable and compositional.

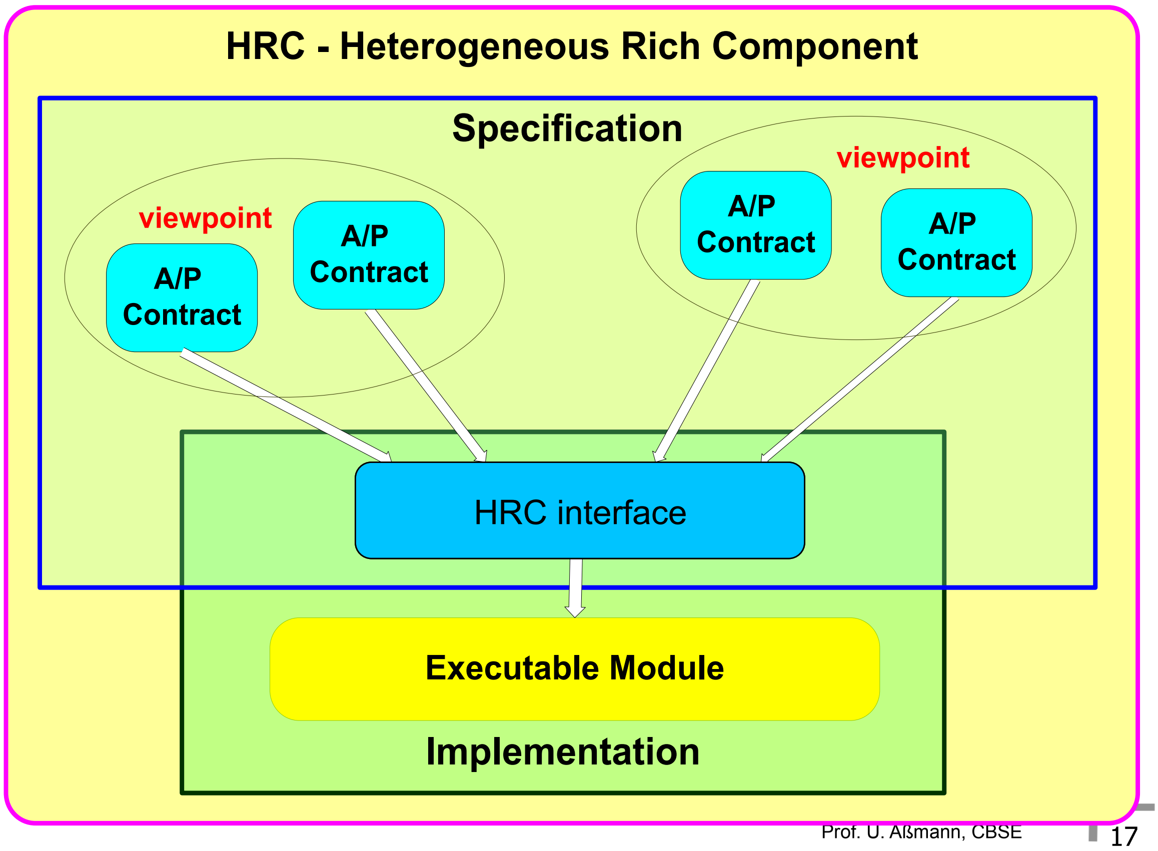
Semantics of Assertions and Contracts

- The semantics of an assertion A is the *regular set of traces (paths),* to which the interface automaton expands (unrolled automaton)
  - Every state of the trace assigns a value to the ports of a component
- [[A]] := { p | p is path of A }
- An assumption A is stronger (bigger) than an assumption B, if its semantics contains the semantics of B:
- [[A]] > [[B]] := { p | p is path of B } ⊆ { q | q is path of A }
- The semantics of contract C is formed of promise G unioned with the complement of A (either A, then G; or not A)
- [[C]] = [[(A,G)]] := compl([[A]]) ∪ [[G]]
- The semantics is computable with regular trace set composition

EU IP SPEEDS – Speculative and Exploratory Design in Systems Engineering



HRC – SPEEDS's View of a Component
An A/P-quality contract based component model



Semantics of View Composition

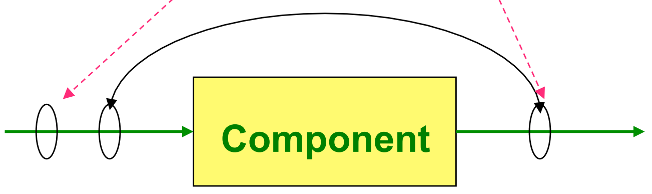
- HRC is a view-based component model with 4 views:
  - Functional
  - Real-time
  - Safety
  - Dynamics (movement)
- If a component has several contracts in several views, their trace sets are intersected, meaning that the component fulfils all of them
  - Semantics is set intersection on trace sets

Basic Elements of HRC A/P-Contracts

Given behaviors

Behaviors component must produce

Contract = (assumption, promise)

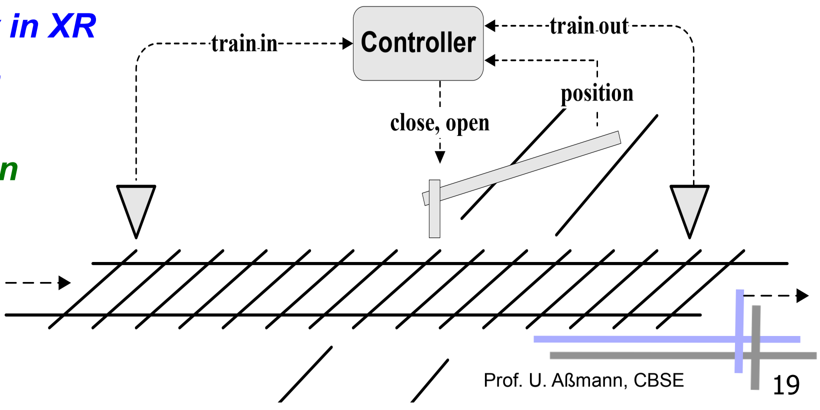


Assumption in natural language for a railway crossing XR:

- *Minimal delay of 50 sec. between successive trains*
- *At startup no train is already in XR*
- *Trains move in one direction*

Promise in natural language:

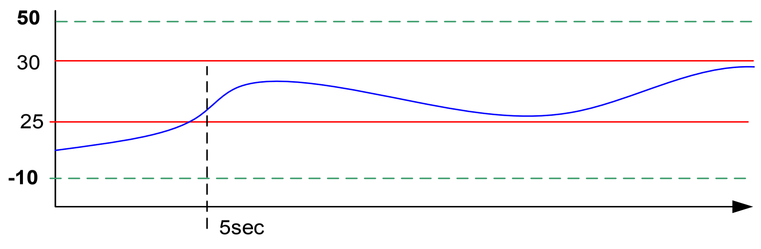
- *Gate closed as long as a train is in XR*
- *Gate open whenever XR is empty for more than 10 sec*



Assertions Describe Behavior

- An *assertion* specifies a subset of the possible component behaviors
- A finite automaton specifying an infinite set of regular paths

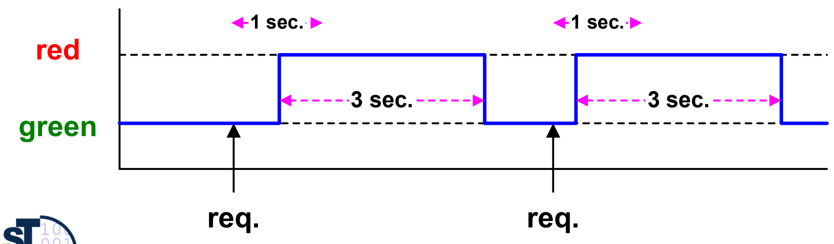
Contract = (assumption, promise)



Contract over continuous variable:

temp: [-10°,50°]

'after 5 sec. 25≤temp≤30'



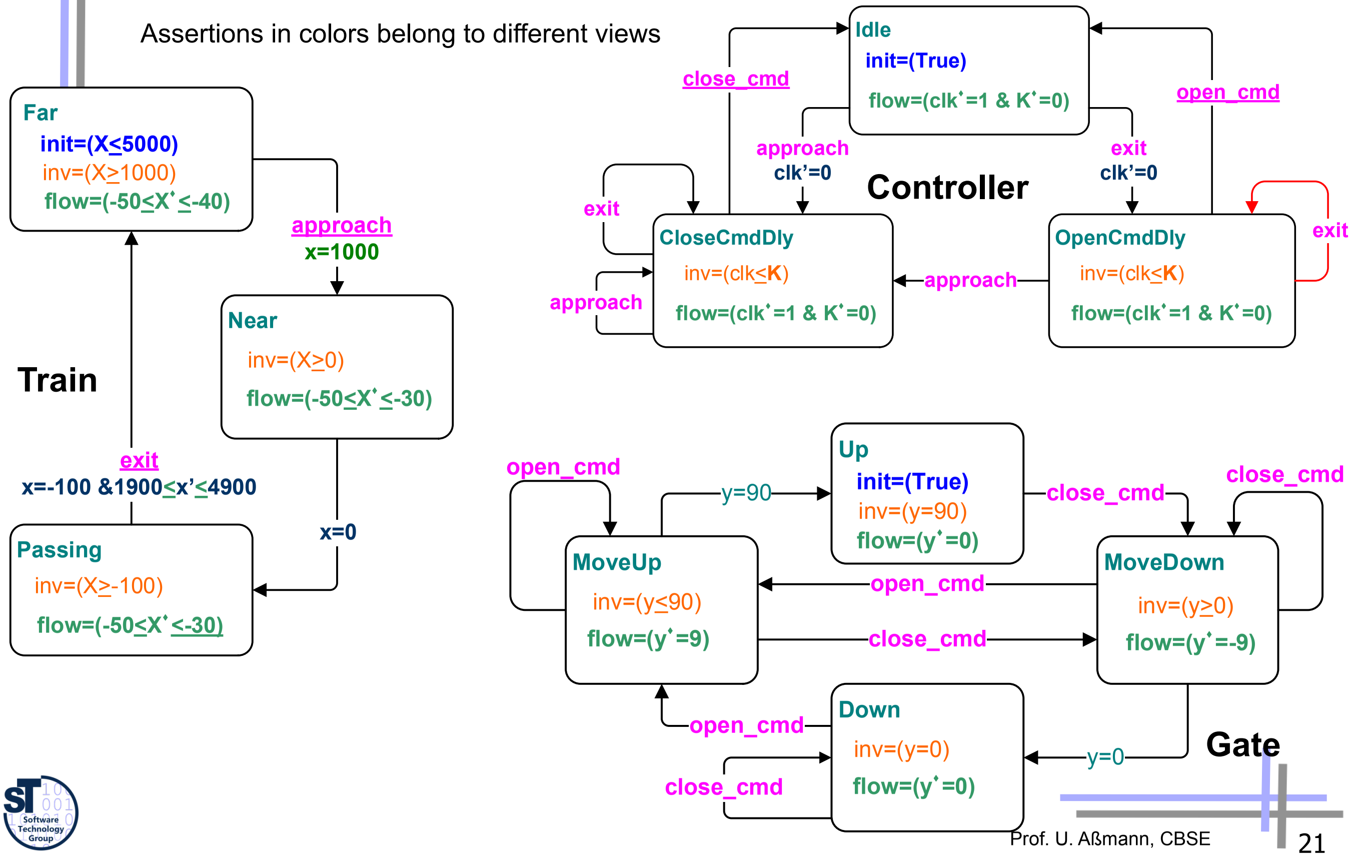
Contract over discrete variable:

lights :{*red, green*}, *req*: *event*

'lights initially green, and after each 'req', within 1sec, become red for 3 sec. then back green'

Hybrid Automata – Automata Representing Assertions

Assertions in colors belong to different views



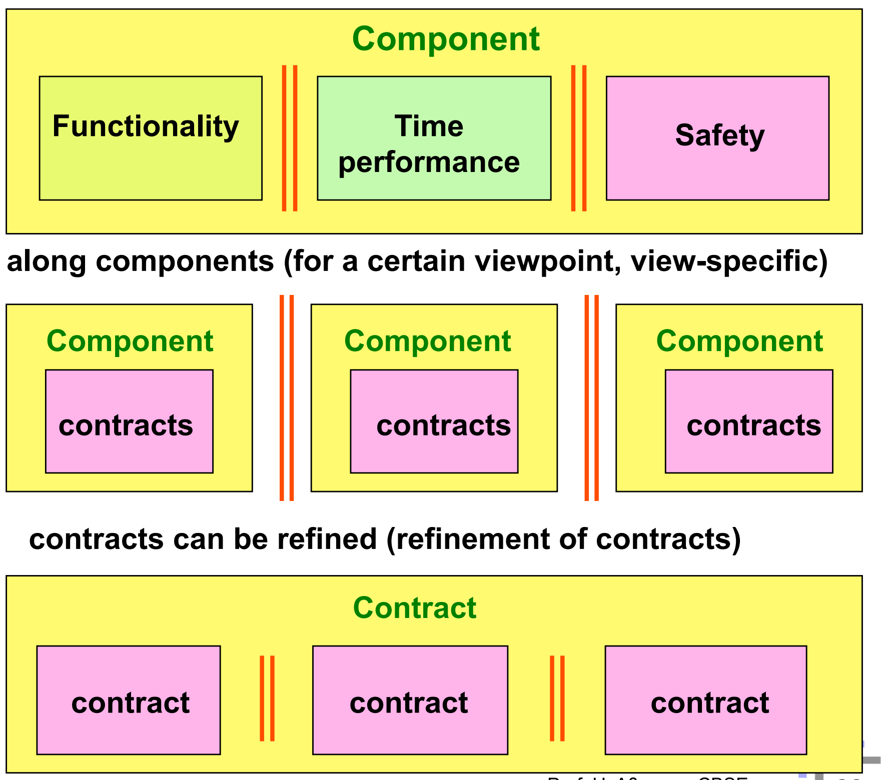
Contract Analysis

- is based on algebra of contracts
- For HRC contracts, the following properties can be proven:
- Refinement
- Consistency,
- Compatibility,
- Dominance,
- Simulation,
- Satisfiability

Within one component (same interface): contracts are intersected

along components (for a certain viewpoint, view-specific)

contracts can be refined (refinement of contracts)

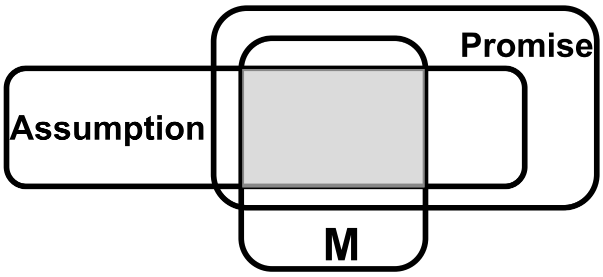


Basic Relations on Contracts: Satisfaction

- **Satisfaction** (implementation conformance) couples implementations to contracts.
- Given contract: C=(A,G), implementation M
- **Satisfaction: (M satisfies C)**

  $\mathbf{M \models C \Leftrightarrow_{def} A \cap M \subseteq G}$

(promise G is stronger than intersection of A and M)



Reasoning with Venn diagrams: smaller means weaker;
Inclusion means implication

Basic Relations on Contracts: Refinement

Refinement: **Given contract: C=(A,G) C'=(A',G'), *implementation M, C refines C':***

$\mathbf{C \sqsubseteq C' \Leftrightarrow_{def} (\neg A \cup G) \subseteq (\neg A' \cup G')}$

Basic Relations on Contracts: Dominance

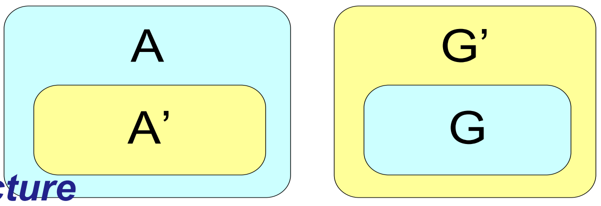
Dominance (contract conformance): **Given contract: C=(A,G) C'= (A',G'),** ***implementation M, C dominates C':***

$C<C' \Leftrightarrow_{def} A' \subseteq A$ and $G \subseteq G'$

C=>C' iff A'<=A and G<=G'

**(A is stronger (bigger) than A' and G' is stronger (bigger) than G;
A' is weaker (smaller) than A and G is weaker (smaller) than G')**

Dominance implies refinement. The dominance operator is *contravariant in A and G,* i.e, when assumption A "grows", the promise G "shrinks"



***Example*:**

- **C: A= *daylight*   G= *video & IR-picture***
- **C': A'= *anytime*   G'= *only IR-picture***
- ***Daylight ⊆ anytime, video&IR-picture ⊆ IR-picture***

Claim: $M \models C$ and $C<C' \Rightarrow M \models C'$

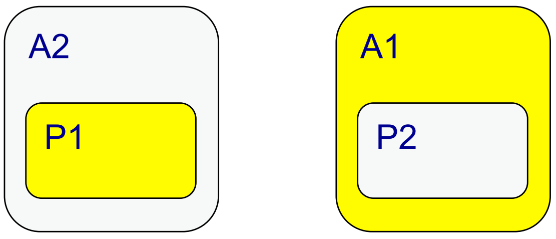
(if M satisfies C, and C dominates C', then M satisfies C')

Compatibility of Contracts

- **Compatibility** is a relation between two or more contracts *C1* .. *Cn*
- Two contracts *C1* and *C2* are **compatible** whenever the promises of one guarantee that the assumptions of the other are satisfied
  - When composing their implementations, the assumptions will not be violated
  - The corresponding components "fit" well together
- *C1* = (*A1*,*P1*) and *C2* = (*A2*,*P2*) are **compatible** if

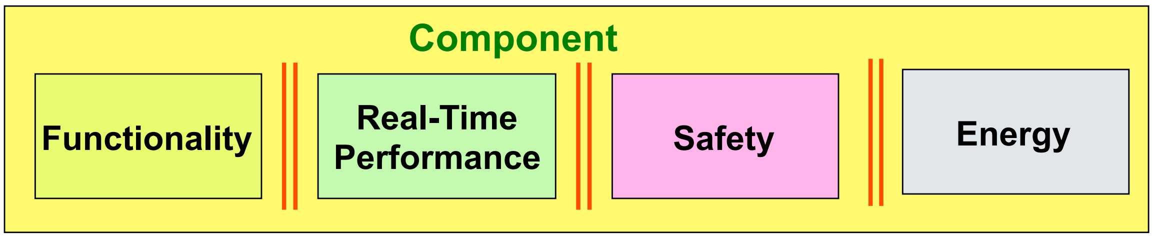
$C1<\text{-}>C2 \Leftrightarrow_{def} P1 \subseteq A2$ and $P2 \subseteq A1$

- **C1 is compatible to C2 if C1.P is weaker than C2.A, and C2.P weaker than C1.A**

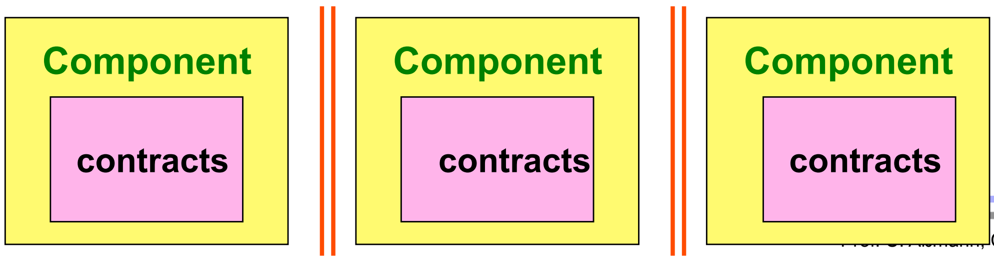


Composition of Contracts

- within a component (same interface), contracts in different views can be **synchronized**
  - The real-time assertions can be coupled with functional, real-time, safety, and energy view

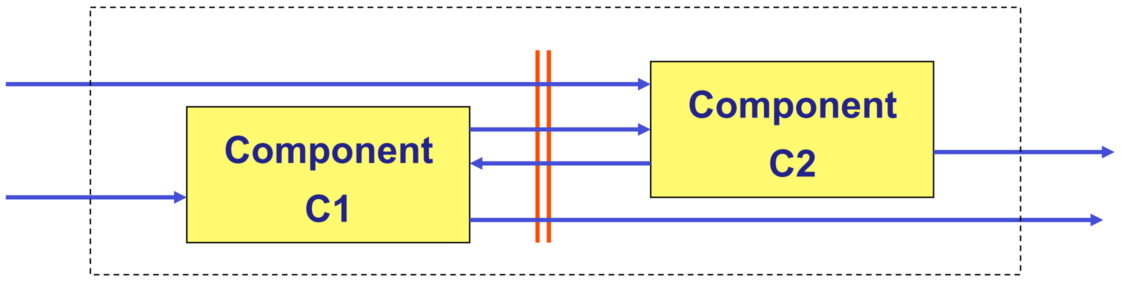


- along components – contracts of a certain viewpoint can be composed (with parallel composition)



Parallel Composition of Contracts (of Separate Components)

- Given contracts $C_1=(A_1,G_1)$, $C_2=(A_2,G_2)$, implementation M
- **Parallel composition operator** for contracts
- $C_1||C_2 := (A,G)$
- where: $A = (A1 \cap A2) \cup \neg(G_1 \cap G_2)$, $G = G_1 \cap G_2$



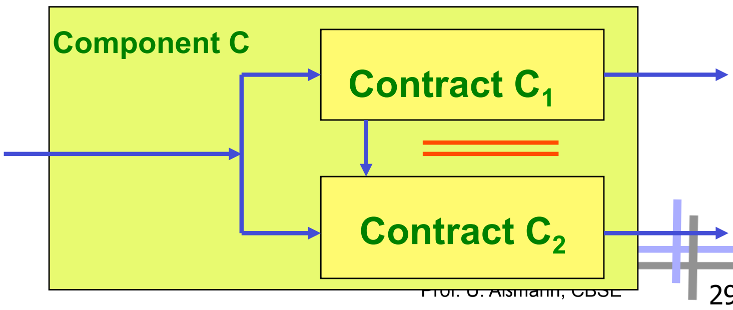
Composite Components

Given contracts C1=(A1,G1), C2=(A2,G2), the following operators can be defined. They are all reduced to operations on hybrid automata:

- **Greatest Lower Bound:** $C_1 \sqcap C_2 =_{def} (A_1 \cup A_2, G_1 \cap G_2)$
  The weaker consequence, stronger assumption
- **Least Upper Bound:** $C_1 \sqcup C_2 =_{def} (A_1 \cap A_2, G_1 \cup G_2)$
  The stronger consequence, weaker assumption
- **Complement:** $\neg C =_{def} (\neg A, \neg G)$

- **Fusion:** $[[C1,C2]]_p = [C1]_p \sqcap [C2]_p \sqcap [C1||C2]_p$

$C=(A,G),\ p \in P \Rightarrow_{def} [C]_p = (\forall pA, \exists pG)$



Assertions Expression – Formal Language: Temporal Logic

- **In practice, Hybrid Automata are too low level to be used by normal engineers**
  - **Alternatively, temporal logics like (Metric) LTL do better**

"The gate is closed when a train traverses GR (gate region)."

(EnterGR → ClosedUExitGR)

- **But for normal properties, logic is still too difficult and rejected by the engineers:**

P occurs within (Q,R)

((Q ∧ ¬R ∧ O¬R) ∧ ◊R) → (¬R)U(O(P ∧ ¬R)))

"Between the time an elevator is called at a floor and the time it opens its doors at that floor the elevator can pass that floor at most twice."

**((call ∧ ◊Open) → (Move U (Open ∨ (Pass U (Open
∨ (Move U (Open ∨ (Pass U (Open
∨ (Move U Open)))))))))**

Assertions by Contract Patterns

- A ***contract pattern (pattern rule)*** is an English-like template sentence embedded with parameters' placeholders, e.g.:

  inv [Q] while [P] after [N] steps

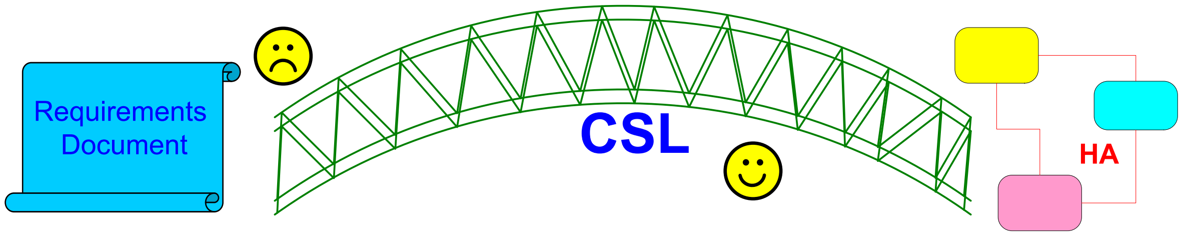
  represents a fixed property up to parameters' instantiation. (in the speak of the course, it is an English generic fragment of English)
- The semantics of a pattern is a template automaton (generic contract), which is instantiated by the parameters
  - A binding composition program translates the English sentence to a template automaton by binding its slots
- In the SafeAir project previous to SPEEDS, a contract patterns library was developed by OFFIS (Oldenburg), but the library grew up to ~400 patterns, and was not manageable

***idea acceptable by users (format, less) but patterns can be very complex, like*:**

inv [P] triggers [Q] unless [S] within [B] after_reaching [R]

27.3 CSL (Contracts Specification Language) based on A/P-contract-patterns

- CSL is a domain-specific language (DSL) intended to provide a friendly formal specification means
  - Translated into Hybrid Automata (assumptions and promises)
  - Template sentences from requirement specifications can be translated into interface automata
- CSL introduces events and time intervals in contract patterns
- CSL is a ECA language with real-time assertions



CSL – Component Specification

➢ The CSL/HRC grammar defines interfaces with contracts of assumptions and promises.

```
CSL ::= 'HRC' HRC-Id
      'Interface'
        'controlled': VariableDeclaration
        'uncontrolled': VariableDeclaration
      'Contracts'
      { Viewpoint-id 'contract' Contract-id *
          'Assumption': Assertion
          'Promise': Assertion                }
```

CSL Metamodel

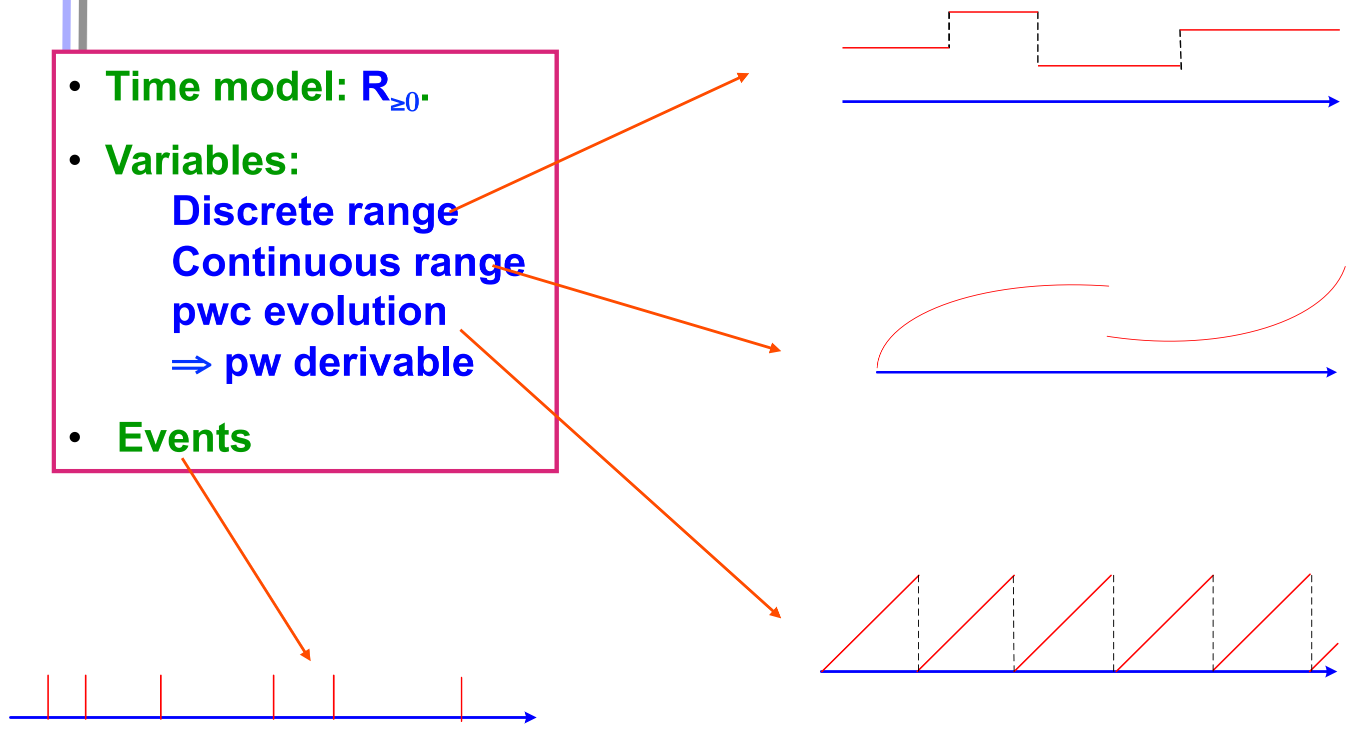
➢ [HRC-MM] is done in MOF and OCL
  - executable in MOF-IDE (Netbeans),
  - checked on well-formedness by OCL checkers

➢ Variables, assumptions

➢ More information about MOF-based metamodels and how to use them in tools -> Course Softwarewerkzeuge (WS)

```
Viewpoint-id 'contract' Contract-id
    'Assumption:' Assertion*
     'Promise:' Assertion*
```

CSL Time Model & Variables



- **Time model: R$_{\geq 0}$.**
- **Variables:**
  - **Discrete range**
  - **Continuous range**
  - **pwc evolution**
  - **⇒ pw derivable**
- **Events**

CSL – Contract Specification with Generic Text Fragments

➢ CSL uses generic programming for assertions

Assertion ::= (Text ‘[‘ slot:Parameter ‘]’)*
Text ::= char *

- An ***assertion*** is expressed by a ***contract pattern***, a generic text fragment embedded with parameters (slots):
  - Parameter slots are ***conditions, events, intervals***.
  - Hedge symbols [ ] to demarcate slots

Example: “Whenever the request button is pressed a car should arrive at the station within 3 minutes”

Whenever [car-request] occurs [car-arrives] occurs within [3min]

Contract Specification Process in HRC-CSL

Steps to Derive HRC-CSL-Contracts:

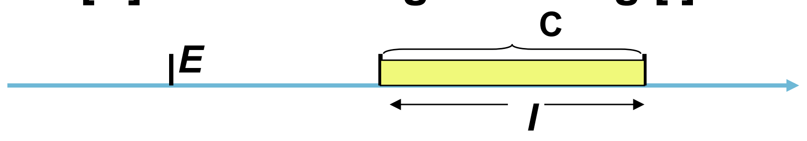
- Start with the informal requirement
  - Identify what has to be guaranteed by the component under consideration and what cannot be controlled and hence should be guaranteed by the environment:
  - Informal promise(s), Informal assumption(s)
- Identify the related interface: inputs / outputs
- Specify parts of the informal requirements in terms of inputs and outputs of the component
- Select an appropriate contract pattern from the contract pattern library and substitute its parameter slots

Ex.: Instantiation of a Contract Pattern

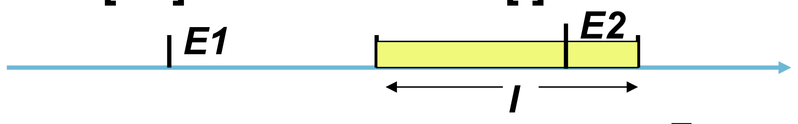
- **Informal Requirement:**
  “Whenever the request button is pressed a car should arrive at the station within 3 minutes.”
- **Contract Pattern**:
  Whenever [E: event] occurs [E2: event] occurs within [I: interval]
- **Instantiated Contract**:
  Whenever *req-button-pressed* occurs *car-arrives-at-station* occurs within *3 min*
- Compiles to an hybrid automaton (here: real-time automaton)

More Contract Patterns

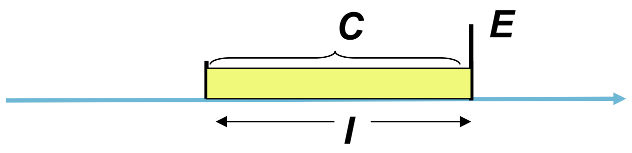
- **whenever [E] occurs [C] holds during following [I]**



- **whenever [E1] occurs [E2] occurs within [I]**



- **[C] during [I] raises [E]**



Temporal/Continuous expressions for parameters (Events, Conditions, Intervals)

Example: Formalization of Informal Requirement with a Contract Pattern

- Assertion:
  - Whenever the request button is pressed a car should arrives at the station within 3 minutes
- Instantiated in CSL:
  - *Whenever* [request-button-press] *occurs* [car-arrives-at-station] *holds within* [3min]

Contract with

- Assumption:
  - [40 seconds minimal delay between trains]
  - whenever [train_in] occurs [~train_in] holds during following (0,40]
- Promise:
  - The gate is closed when a train traverses gate region.
  - [gate is closed when a train traverses gate region]
  - whenever [train_in] occurs [position==closed] holds during following [train_in, train_out]

Contract Pattern Parameters (Slots) and Their Typing

Conditions:

- Boolean variables C
- *x ~ exp* -- *K=8, x>5, y'= -3y*^{2} *+7, x<y*
- Exp. $C_1 \vee C_2$ $C_1 \wedge C_2$ $\neg C$ $C_1 \rightarrow C_2$

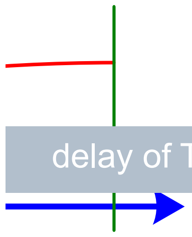
A condition must hold true along an interval

Events:

- Primitive: *a b c* *Startup*
- Condition change: *tr*(C) *fs*(C)
- Time delay: *dly*(T)
- Exp.: $e_1 \wedge e_2$, $e_1 \vee e_2$, $e_1 - e_2$, *e when C* $e_1;e_2$

Intervals:

- Designated by two occurrences of events a, b; all forms:
  [a,b], [a,b), (a,b], (a,b)



delay of T time units

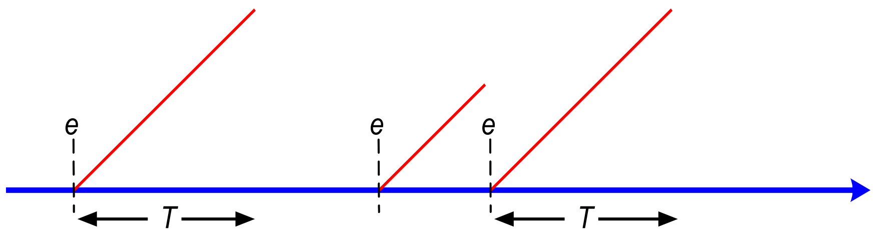
first e_2 after e_1

e_1 occurs, but not e_2

|C| = |*tr*(C),*fs*(C)|

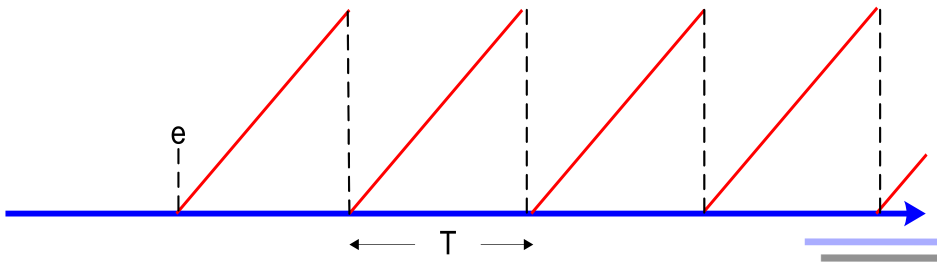
Timers

Timer(T) at e



➢ e+T ≡ *tr*(c=T) where c=Timer(T) at e

PeriodicTimer(T) at e



CSL Examples with Timers

“Dispatching commands will be refused during first 5 seconds after a car arrives at station”

- *Whenever* [car-arrives] *occurs*
  [dispatch-cmd] *implies* [refuse-msg] *during following* [5sec]

„40 sec. minimal delay between trains”

- *Whenever* [Tin] *occurs* [Tin] *does not occur during following* (40 sec]

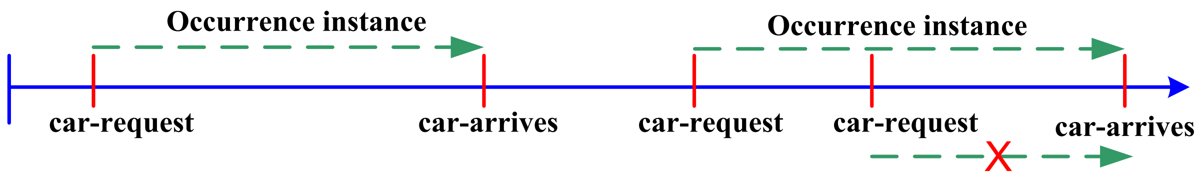
„Between the time an elevator is called at a floor and the time it stops at that floor the elevator can pass that floor at most twice.“

- [PassFloor[m]] *occurs at most* [2] *times*
  during (CallAtFloor[m], StopAtFloor[m])

Pattern Occurrence Types

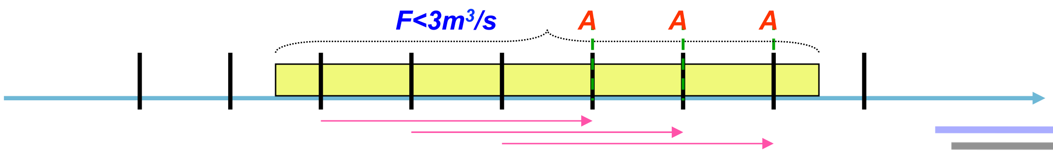
Iterative occurrences of events – non interleaving occurrence's instances

Whenever **[car-request]** ***occurs*** **[car-arrives]** ***occurs within*** **[3min]**



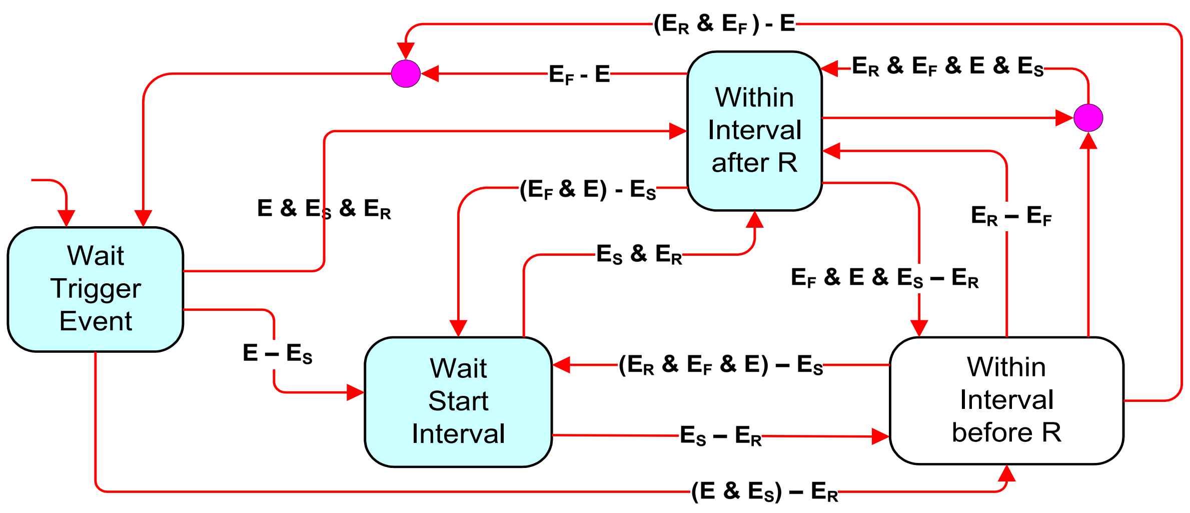
Flowing occurrences of events - interleaving occurrence's instances

[F<3] during [3 Sec] raises [AlarmSignal]



Automaton Representation of Iterative Occurences of Events

whenever [E] occurs [E_R] occurs within [E_S,E_F]



More HRC Patterns for Contract Specification

- E: Event, SC: State Condition, I: Interval, N: integer
- **Pattern Group “Validity over Duration”**
- **P1 (hold)**: whenever [E] occurs [SC] holds during following [I]
- **P2 (implication)**: whenever [E1] occurs [E2] implies [E3] during following [I]
- **P3 (absence)**: whenever [E1] occurs [E2] does not occur during following [I]
- **P4 (implication)**: whenever [E] occurs [E/SC] occurs within [I]
- **P5**: [SC] during [I] raises [E]
- **P6**: [E1] occurs [N] times during [I] raises [E2]
- **P7**: [E] occurs at most [N] times during [I]
- **P8**: [SC] during [I] implies [SC1] during [I1] then [SC2] during [I2]

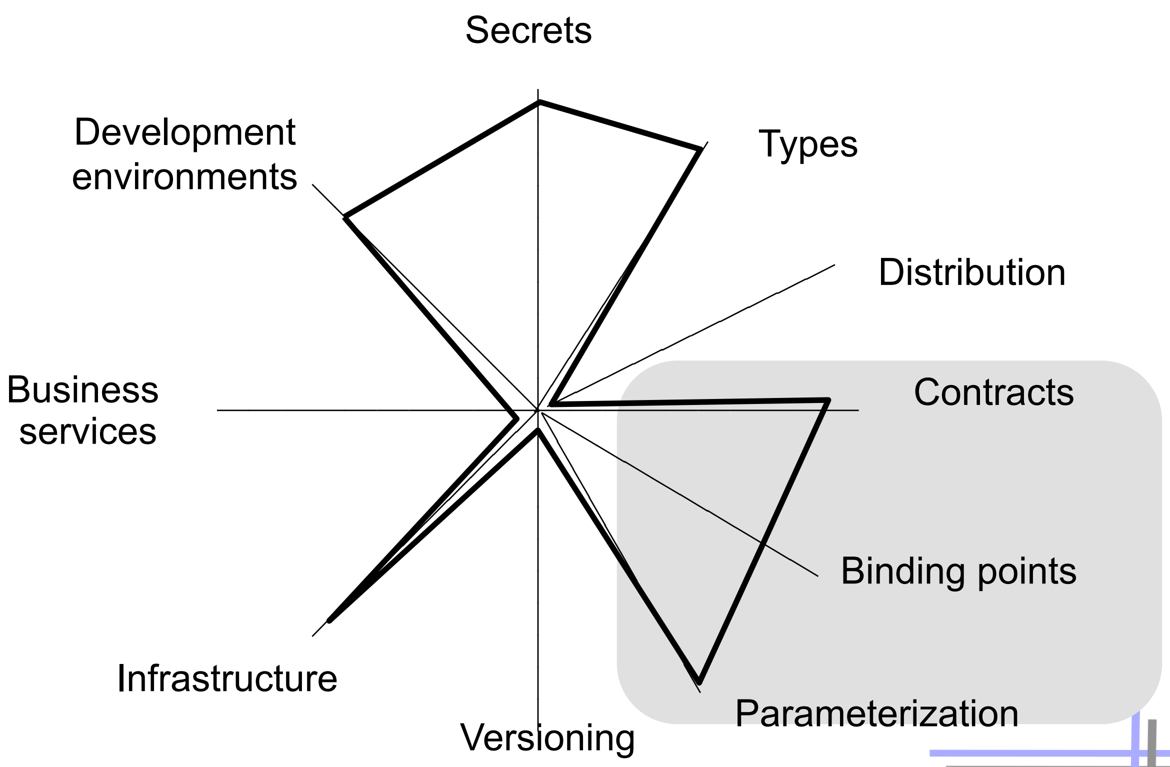
27.4. Self-Adaptive Systems

- For future networked embedded systems and cyber-physical systems, we need **verifiable, compositional** component models supporting **self-adaptivity**.
- Self-adaptivity can be achieved by dynamic product families with variants that are preconfigured, verified, and dynamically reconfigured:
  - **Contract negotation** (dynamic reconfiguration between quality A/P-automata)
  - Polymorphic classes with **quality-based polymorphism**: the polymorphic dispatch relies on quality types, quality predicates
  - **Autotuning** with code rewriting and optimization
- More in research projects at the Chair

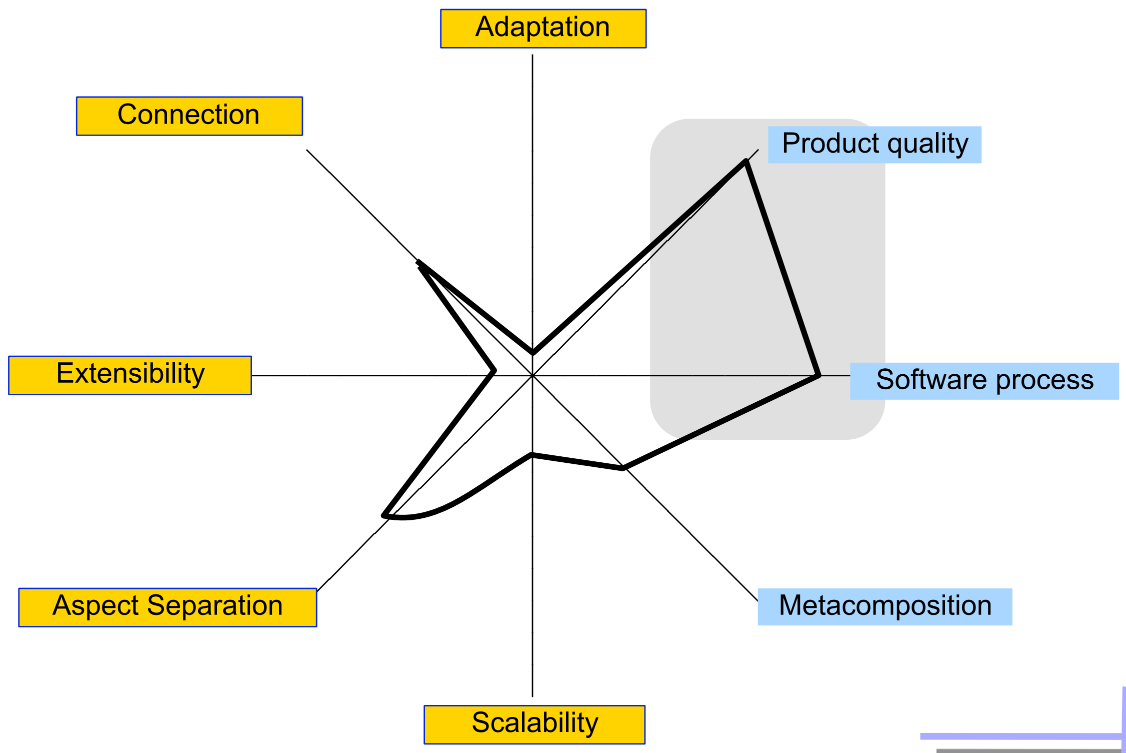
27.5 HRC as Composition System

- HRC is an interesting combination of a black-box component model in *different views*
- It could be one of the first COTS component models with viewpoints, but the standarization is unclear at the moment

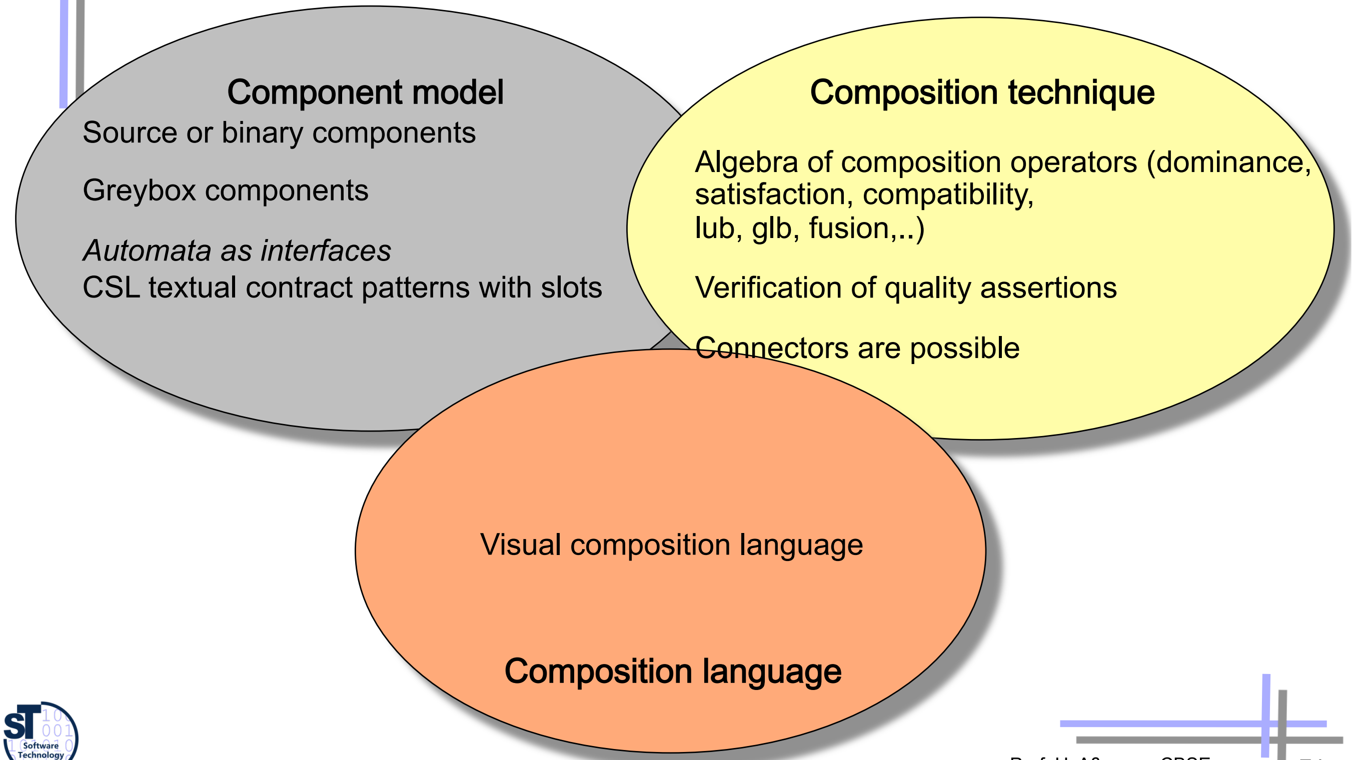
Evaluation of HRC Component Model



HRC – Composition Technique and Language



HRC as Composition System


Component model
Source or binary components
Greybox components
Automata as interfaces
CSL textual contract patterns with slots
Composition technique
Algebra of composition operators (dominance, satisfaction, compatibility, lub, glb, fusion,..)
Verification of quality assertions
Connectors are possible
Visual composition language
Composition language