27. Rich Components with A/P-Quality Contracts

1. CBSE for Embedded Systems
2. SPEEDS Heterogeneous Rich Components
3. Contract specification language CSL
4. Self-Adaptive Systems
5. HRC as Composition System

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Obligatory Literature

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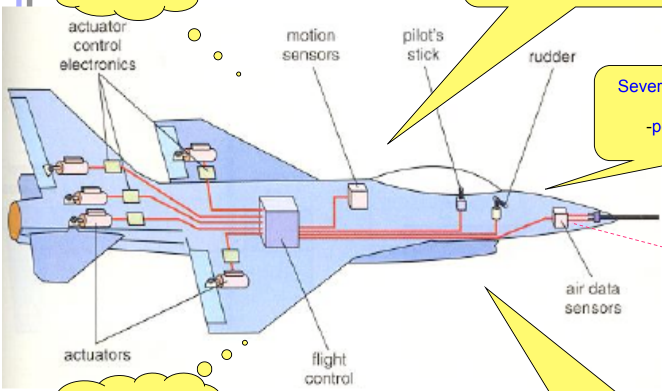
27.1. CBSE for Embedded Systems

Today's embedded systems

Large Scale

composed of physical specific subsystems developed concurrently

Several quality aspects:
-cost,
-performance,…



The kind of considered system

Reliability is critical

involve several disciplines (e.g., aerodynamics, mechanical, control)

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)

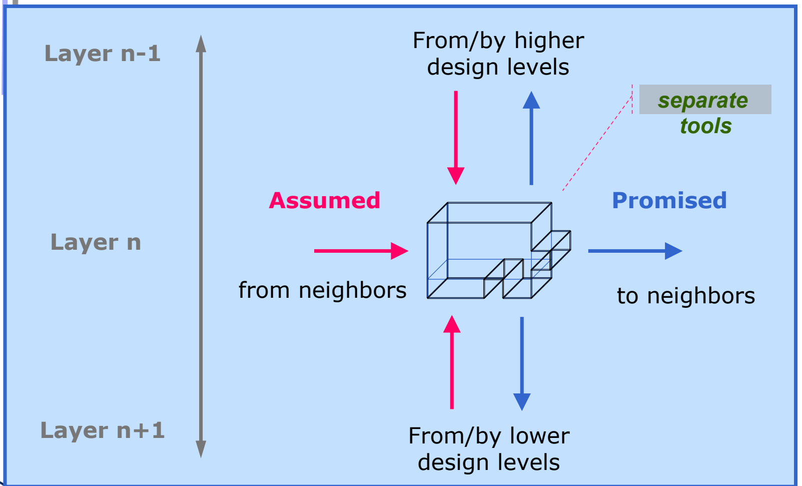
Assumptions about Automata-Based Contracts

- 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

Rich Component Models

- Used for component-based software for embedded systems
- 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)
- 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**)

EU IP SPEEDS – Speculative and Exploratory Design in Systems Engineering



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)

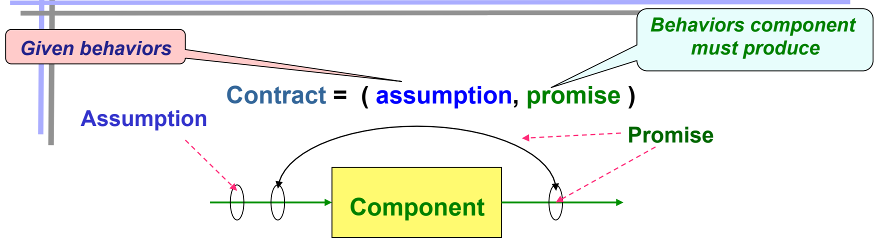
Assertion

= 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.

Basic Elements of HRC A/P-Contracts

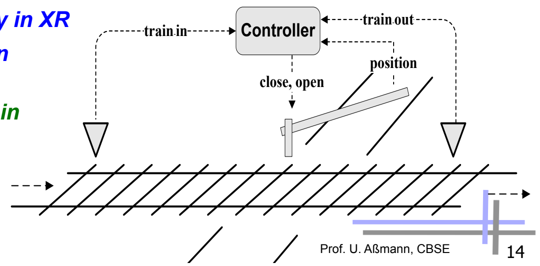


Assumption in natural language for a railway crossing XR:

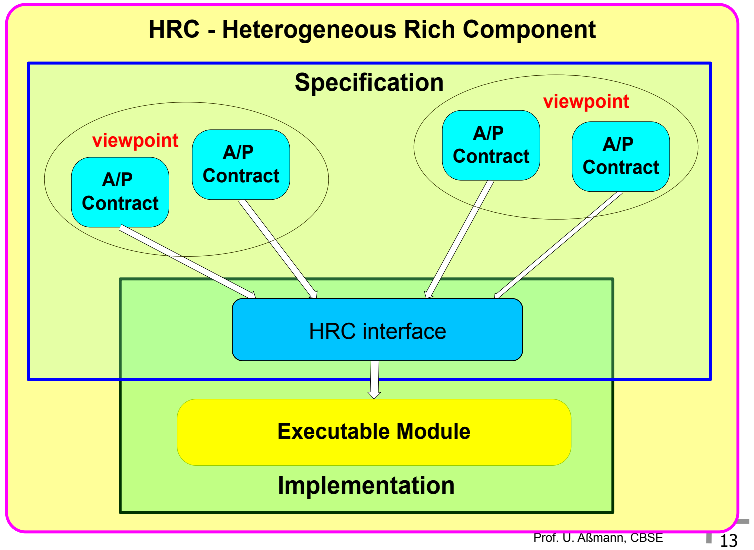
- *Minimal delay of 50 sec. between successive trains*
- *At startup no train is already in XR*
- *Trains move in one direction*

Promise in natural language:

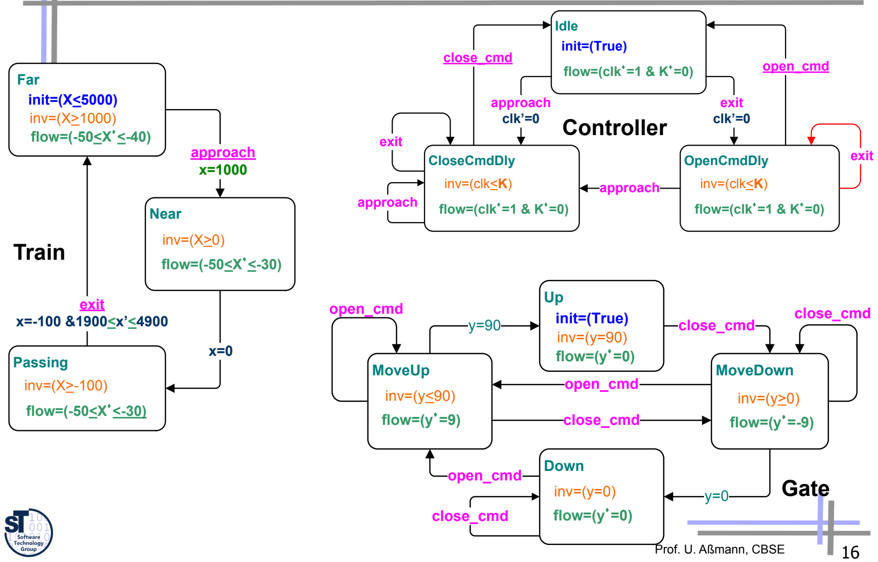
- *Gate closed as long as a train is in XR*
- *Gate open whenever XR is empty for more than 10 sec*



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



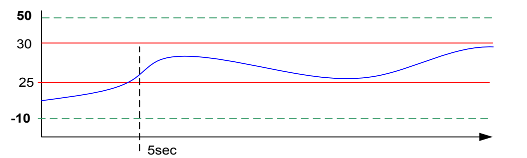
Hybrid Automata – Automata Representing Assertions



Assertions Describe Behavior

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

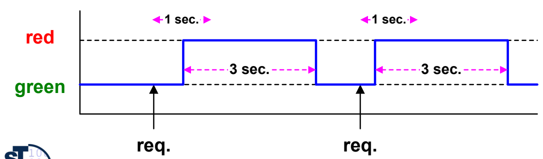
Contract = (assumption, promise)



Contract over continuous variable:

***temp*: [-10°,50°]**

'after 5 sec. 25≤temp≤30'



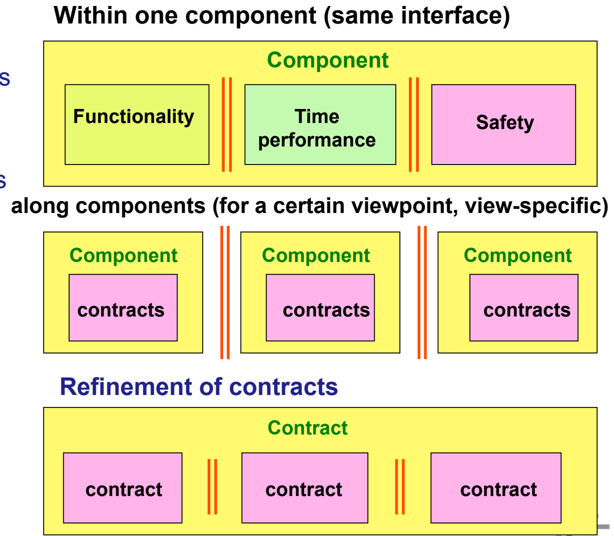
Contract over discrete variable:

lights :{red, green}, req: event

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

Contract Analysis

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

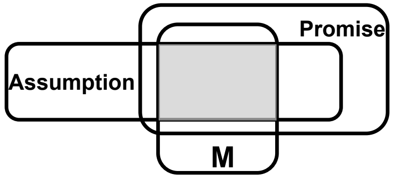


Basic Relations on Contracts

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

  M|=C ⇔$_{def}$ A∩M⊆ 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

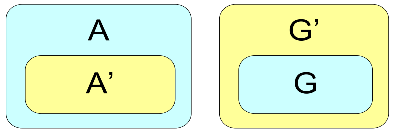
Given contract: C=(A,G) C'=(A',G'), *implementation M*

- ***Dominance: (C dominates C') :***

  C<C'⇔$_{def}$ A'⊆A and G⊆G'

(A is stronger than A' and G' is stronger than G; A' is weaker than A and G is weaker than G')

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|=C and C<C' ⇒ M|=C'

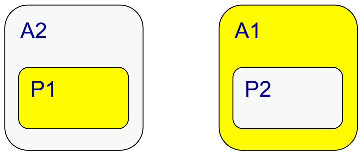
(if M satisfies C, and C dominates C', then M satisfies C')

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

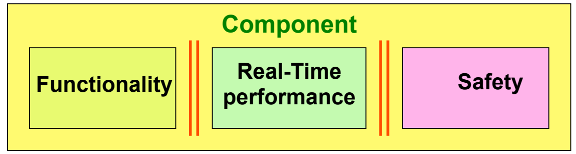
C1<->C2⇔$_{def}$ P1⊆A2 and P2⊆A1

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

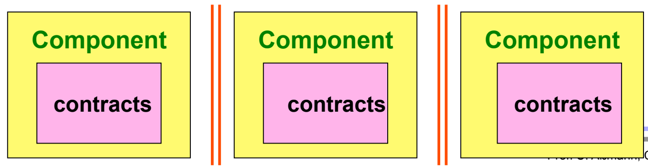


Composition of Contracts

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

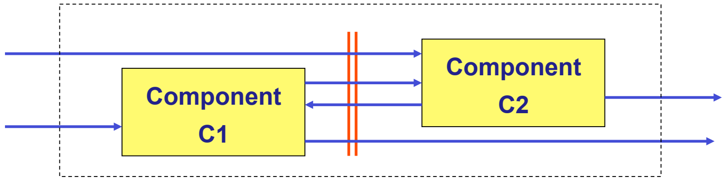


- along components – contracts of a certain viewpoint can be composed



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** of contracts $C_1||C_2 = (A,G) :=$
- where: $A = (A1 \cap A2) \cup \neg(G_1 \cap G_2)$, $G = G_1 \cap G_2$

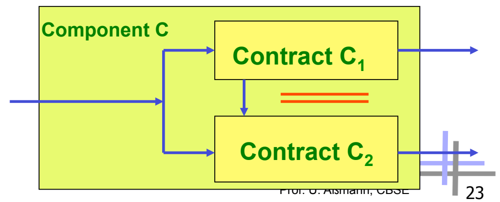


Algebra of Contracts

Given contracts $C_1=(A_1,G_1)$, $C_2=(A_2,G_2)$, the following operations can be defined:

- **Greatest Lower Bound:** $C_1 \sqcap C_2 =_{def} (A_1 \cup A_2, G_1 \cap G_2)$
- **Least Upper Bound:** $C_1 \sqcup C_2 =_{def} (A_1 \cap A_2, G_1 \cup G_2)$
- **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 formal’ (too low level) to be used by normal engineers.**
  - **Alternative options like (Metric) LTL were examined and 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

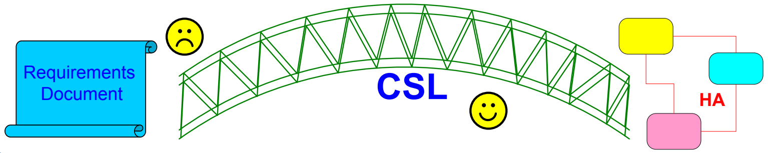
- A ***contract pattern (pattern rule)*** is an English-like template sentence embedded with parameters' placeholders, e.g.:
  inv [Q] while [P] after [N] steps

  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
  - Parameters are instantiated by state expressions
  - Semantics over discrete time model

***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 <u>friendly</u> 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.

HRC *{HRC-Id}*
Interface
controlled: *{variables declaration}*
uncontrolled: *{variables declaration}*
Contracts
{ *{viewpoint-id}* **contract** *{contract-id}* *
Assumption: *{assertion}*
Promise: *{assertion}* }

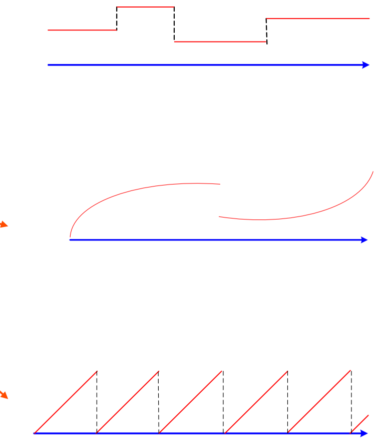
CSL Metamodel

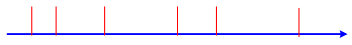
- [HRC-MM] is done in MOF and OCL
  - executable in MOF-IDE (Netbeans),
  - checked on well-formedness by OCL checkers
- Variables, assumptions
- More information about MOF-based metamodels and how to use them in tools -> Course Softwarewerkzeuge (WS)

{*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 ']')*

- 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 Contracts:

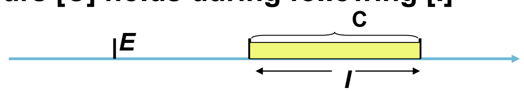
- Start with the informal requirement
  - Identify what has to be guaranteed by the component under consideration and what cannot be controlled and hence should be guaranteed by the environment:
  - Informal promise(s), Informal assumption(s)
- Identify the related interface: inputs / outputs
- Specify 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

Instantiation of a Contract Pattern

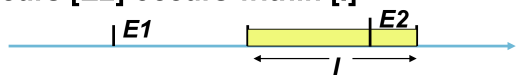
- *Whenever the request button is pressed a car should arrive at the station within 3 minutes*
- **Contract Pattern**:
  Whenever [E: event] occurs [E2: event] occurs within [I: interval]
- **Instantiated Contract**:
  Whenever *req-button-pressed* occurs *car-arrives-at-station* occurs within *3 min*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

More Contract Patterns

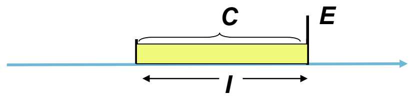
- **whenever [E] occurs [C] holds during following [I]**



- **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]
- And 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'= -3y² +7, x<y***
- **Exp.** $C_1 \vee C_2$ $C_1 \wedge C_2$ $\neg C$ $C_1 \rightarrow C_2$

Events:

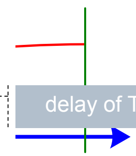
- **Primitive:** ***a b c*** ***Startup***
- **Condition change:** ***tr*(C)** ***fs*(C)**
- **Time delay:** ***dly*(T)**
- **Exp.:** $e_1 \wedge e_2$, $e_1 \vee e_2$, $e_1 - e_2$, *e when C* $e_1;e_2$

Intervals:

- **Designated by occurrences of events, a, b; all forms:**

  [a,b], [a,b), (a,b], (a,b)

A condition must hold true along an interval



delay of T time units

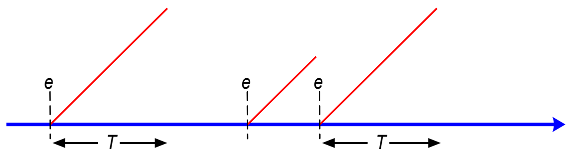
first e_2 after e_1

e_1 occurs, but not e_2

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

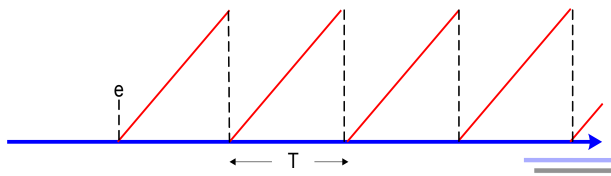
Timers

Timer(T) at e



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

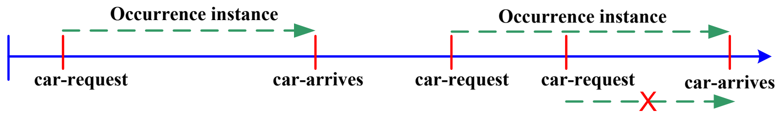
PeriodicTimer(T) at e



Pattern Occurrence Types

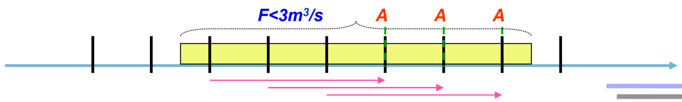
Iterative occurrences of events – non interleaving occurrence's instances

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



Flowing occurrences of events - interleaving occurrence's instances

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



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.

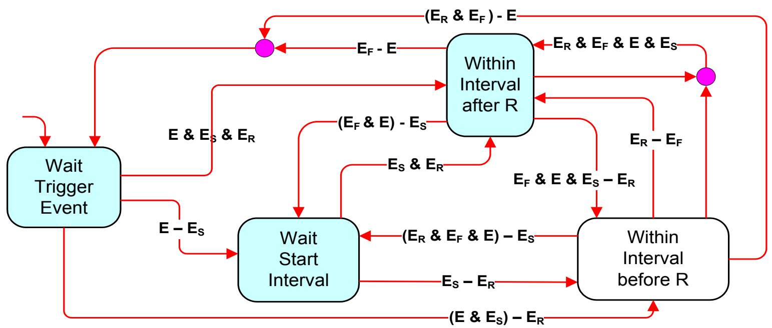
- [PassFloor[m]] *occurs at most* [2] *times*
  during (CallAtFloor[m], StopAtFloor[m])

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]

Automaton Representation of Iterative Occurences of Events

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



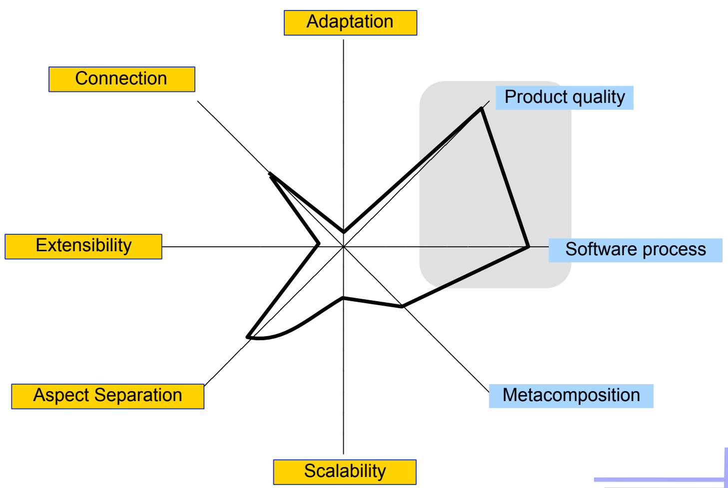
27.5 HRC as Composition System

- 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

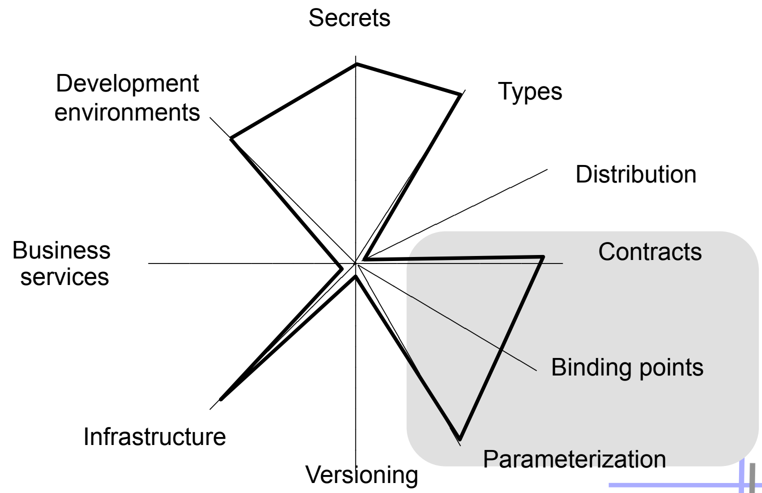
27.4. Self-Adaptive Systems

- 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

HRC – Composition Technique and Language



Evaluation of HRC Component Model



HRC as Composition System