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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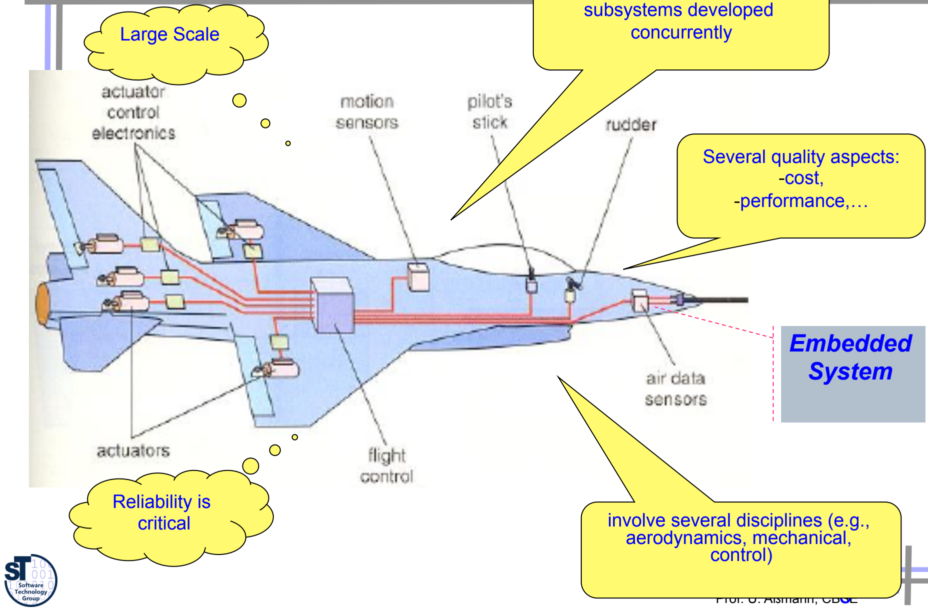
27.1. CBSE for Embedded Systems

Today's Embedded Systems



Götting Autonomous Transport Systems

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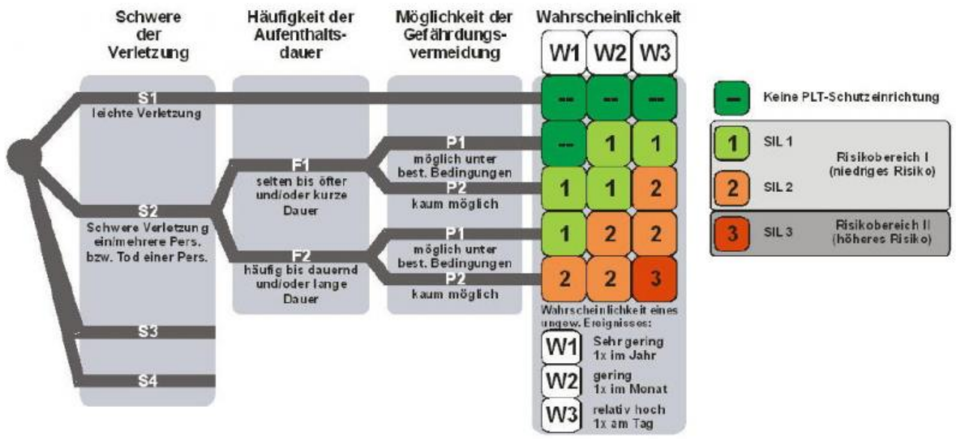
Risk Graph from Götting Autonomous Transport



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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

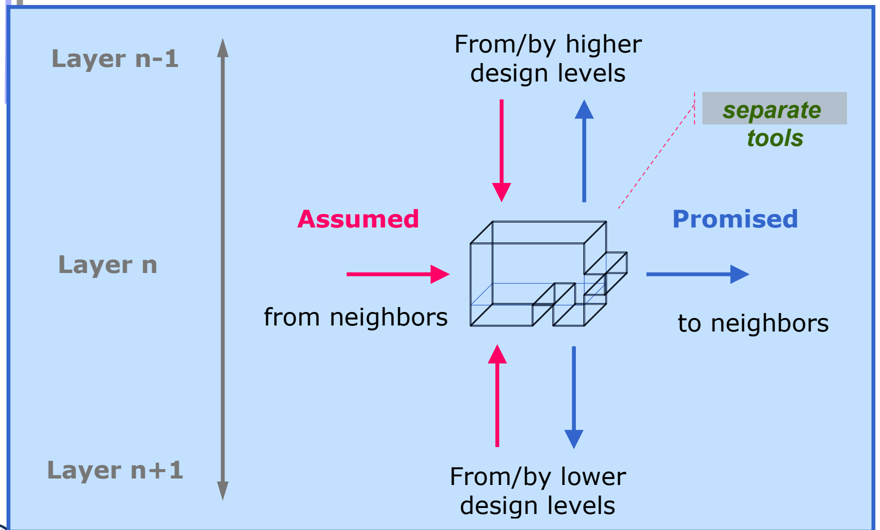
- An **A/P-quality contract** is an A/P-contract in which hybrid automata form the assumptions and promises

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

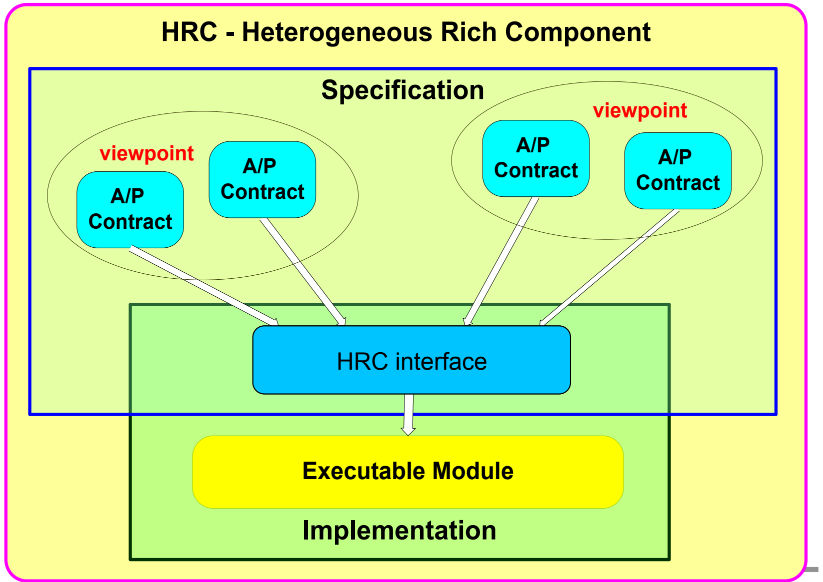
Semantics of Assertions and Contracts

- 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

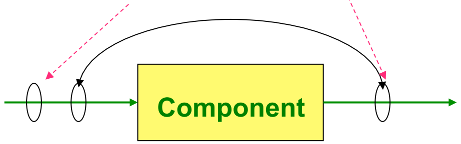
- HRC is a view-based component model with 4 views:
  - Functional
  - Real-time
  - Safety
  - Dynamics (movement)
- If a component has several contracts in several views, their trace sets are intersected, meaning that the component fulfils all of them
  - Semantics is set intersection on trace sets

Basic Elements of HRC A/P-Contracts

Given behaviors

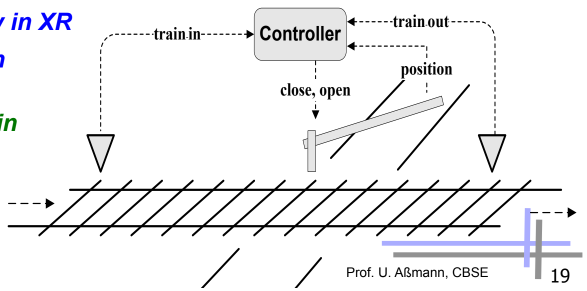
Behaviors component must produce

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*

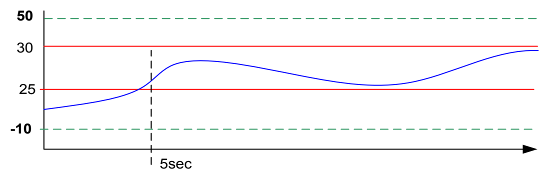
Promise in natural language:
- *Gate closed as long as a train is in XR*
- *Gate open whenever XR is empty for more than 10 sec*



Assertions Describe Behavior

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

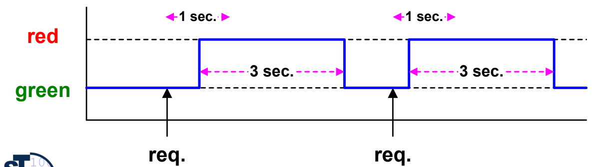
Contract = (assumption, promise)



Contract over continuous variable:

temp: [-10°,50°]

'after 5 sec. 25≤temp≤30'

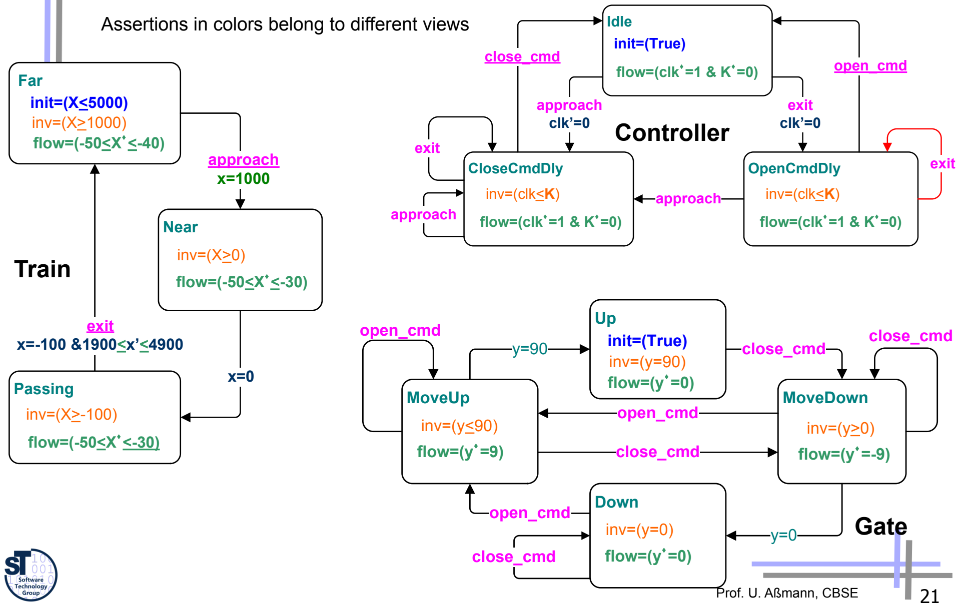


Contract over discrete variable:

lights :{red, green}, req: event

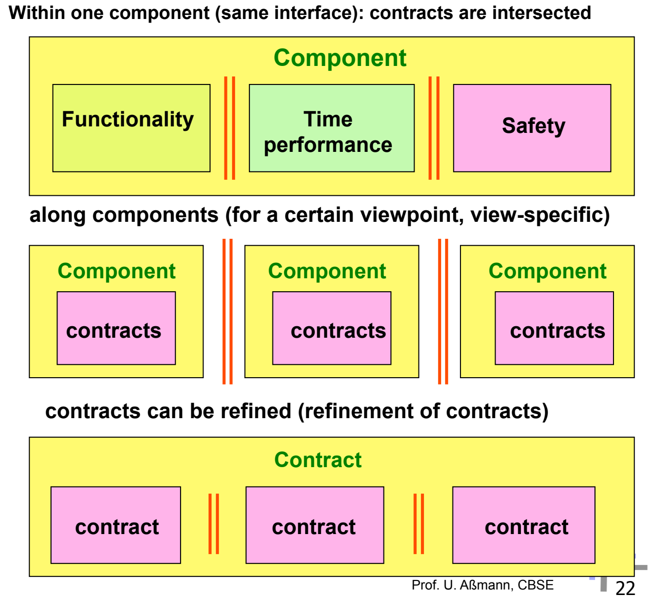
'lights initially green, and after each 'req', within 1sec, become red for 3 sec. then back green'

Hybrid Automata – Automata Representing Assertions



Contract Analysis

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

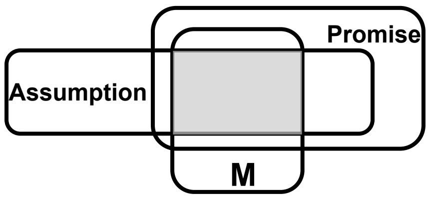


Basic Relations on Contracts: Satisfaction

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

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

(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':***

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

Basic Relations on Contracts: Dominance

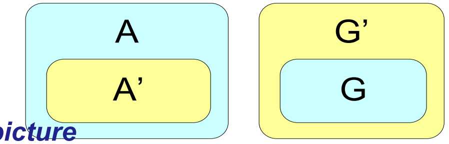
Dominance (contract conformance): Given contract: C=(A,G) C'=(A',G'), *implementation* M, *C dominates C'*:

$C<C' \Leftrightarrow_{def} A' \subseteq A$ 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***

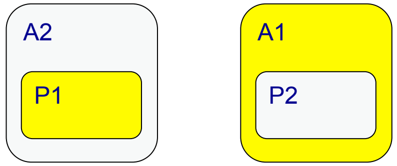
Claim: M|=C and C<C' ⇒ M|=C'

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

Compatibility of Contracts

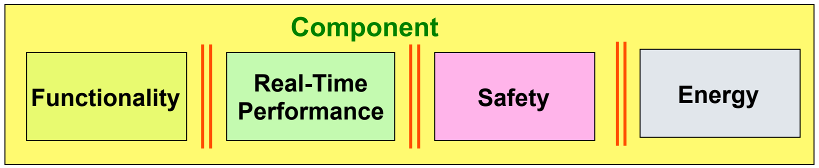
- **Compatibility** is a relation between two or more contracts *C1* .. *Cn*
- Two contracts *C1* and *C2* are **compatible** whenever the promises of one guarantee that the assumptions of the other are satisfied
  - When composing their implementations, the assumptions will not be violated
  - The corresponding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

  $C1 \leftrightarrow C2 \Leftrightarrow_{def} P1 \subseteq A2$ and $P2 \subseteq A1$
- **C1 is compatible to C2 if C1.P is weaker than C2.A, and C2.P weaker than C1.A**

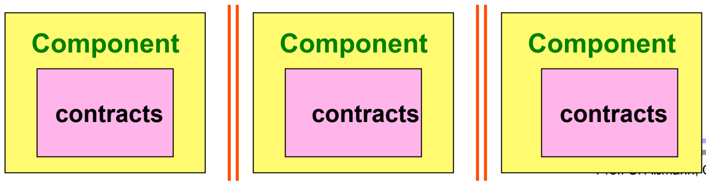


Composition of Contracts

- 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

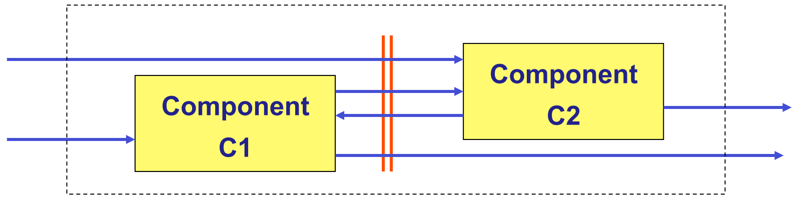


- along components – contracts of a certain viewpoint can be composed (with parallel composition)



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: $A = (A1 \cap A2) \cup \neg(G_1 \cap G_2)$, $G = G_1 \cap G_2$



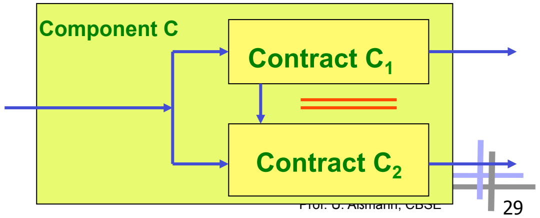
Composite Components

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)

$((Q \wedge \neg R \wedge O\neg R) \wedge \Diamond R) \rightarrow (\neg R)U(O(P \wedge \neg R)))$

"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*** }

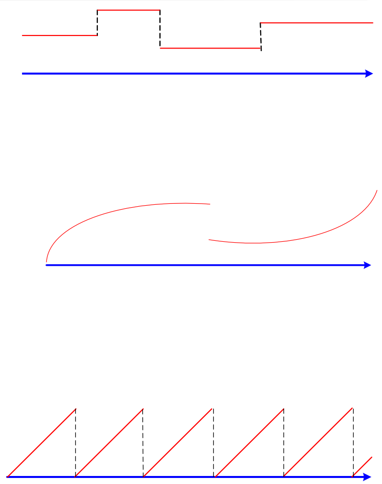
CSL Metamodel

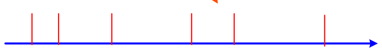
- [HRC-MM] is done in MOF and OCL
  - executable in MOF-IDE (Netbeans),
  - checked on well-formedness by OCL checkers
- Variables, assumptions
- More information about MOF-based metamodels and how to use them in tools -> Course Softwarewerkzeuge (WS)

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:

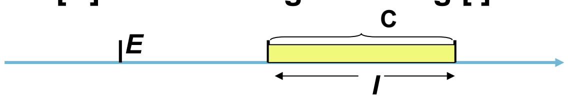
- Start with the informal requirement
  - Identify what has to be guaranteed by the component under consideration and what cannot be controlled and hence should be guaranteed by the environment:
  - Informal promise(s), Informal assumption(s)
- Identify the related interface: inputs / outputs
- Specify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

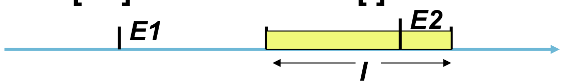
- **Informal Requirement:**
  "Whenever the request button is pressed a car should arrive at the station within 3 minutes."
- **Contract Pattern**:
  Whenever [E: event] occurs [E2: event] occurs within [I: interval]
- **Instantiated Contract**:
  Whenever *req-button-pressed* occurs *car-arrives-at-station*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

More Contract Patterns

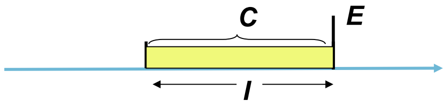
- **whenever [E] occurs [C] holds during following [I]**



- **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'= -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 two 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

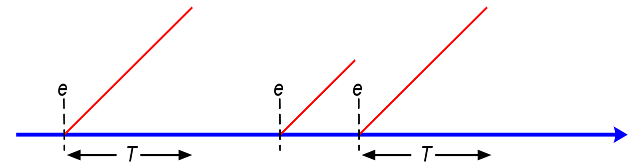
first e_2 after e_1

e_1 occurs, but not e_2

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

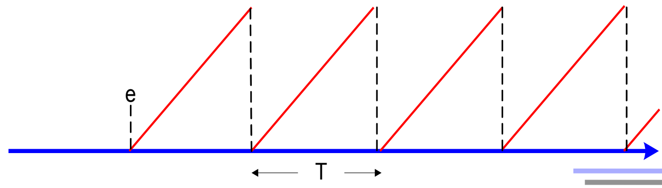
Timers

Timer(T) at e



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

PeriodicTimer(T) at e



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]

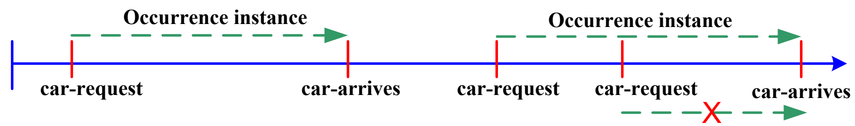
„Between the time an elevator is called at a floor and the time it stops at that floor the elevator can pass that floor at most twice."

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

Pattern Occurrence Types

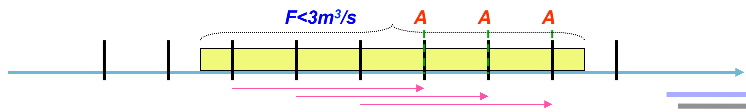
Iterative occurrences of events – non interleaving occurrence's instances

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



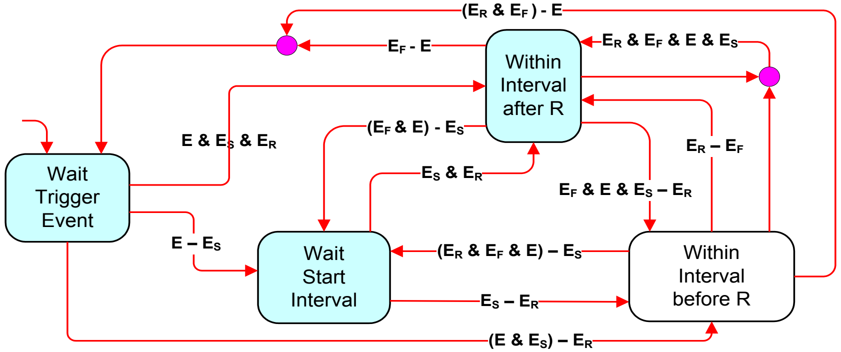
Flowing occurrences of events - interleaving occurrence's instances

[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]

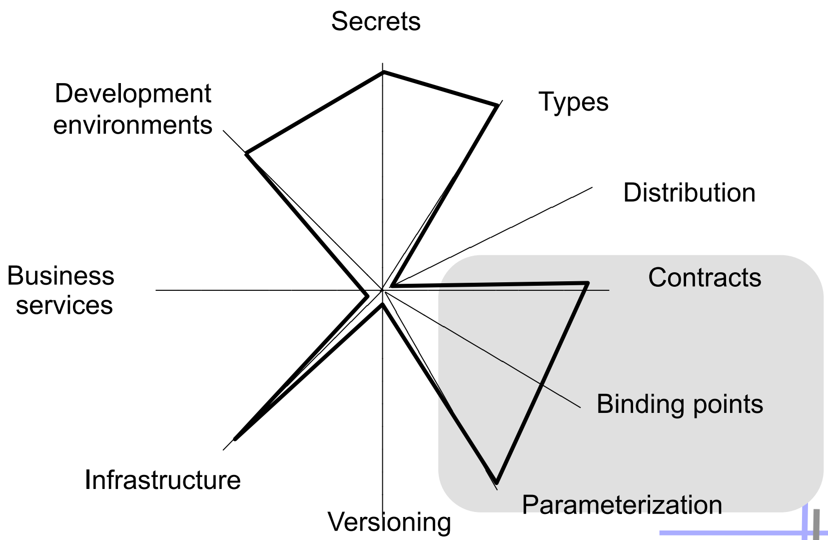
27.4. Self-Adaptive Systems

- 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

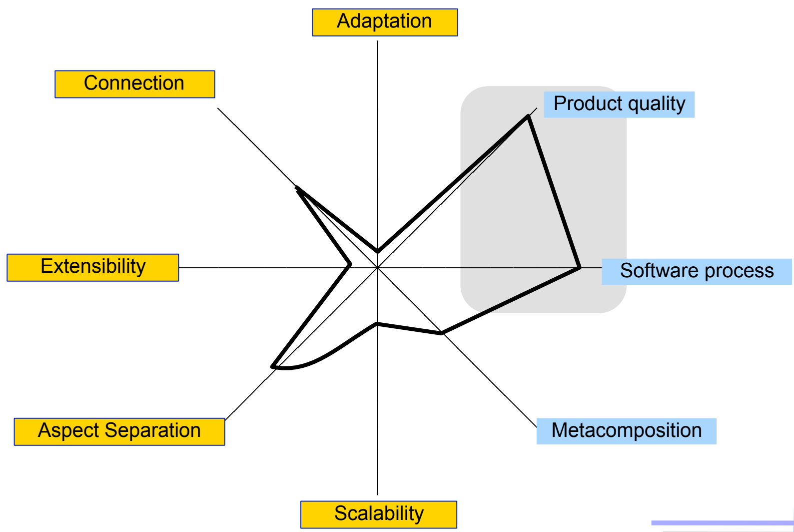
27.5 HRC as Composition System

- 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