Monitoring Violations & Threats of Security & Dependability: The SERENITY approach

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Lecture objectives

- To introduce the SERENITY approach to dynamic assembly and configuration of S&D solutions and the need for monitoring security and dependability properties at runtime
- To explain the SERENITY approach to monitoring and introduce the SERENITY runtime monitoring framework, called EVEREST
- To provide examples of using EVEREST for runtime monitoring of S&D properties
- To explain advanced features of EVEREST, namely the event diagnosis and the threat detection and reaction mechanisms

Outline

Part I: Overview of the SERENITY framework

- Overview of SERENITY
- S&D patterns
- An example
- Need for monitoring
- The SERENITY infrastructure

Part II: The SERENITY monitoring infrastructure

- The SERENITY monitoring approach
- Monitoring lifecycle
- Monitoring infrastructure

Part III: Specification of monitorable S&D properties

- Specification of monitoring rules
- Examples of monitoring rules

Part IV: Advanced Capabilities

- Monitoring process
- Diagnosis
- Threat detection

Part V: Reaction

- Reaction to monitoring results

Conclusions, Main resources and references

Part I:
Overview of the SERENITY framework

Overview of SERENITY

Aims:

Dynamic

- selection
- (re-) configuration
- integration, and
- deployment

of components that can realise Security and Dependability (S&D) solutions in applications, driven by S&D patterns

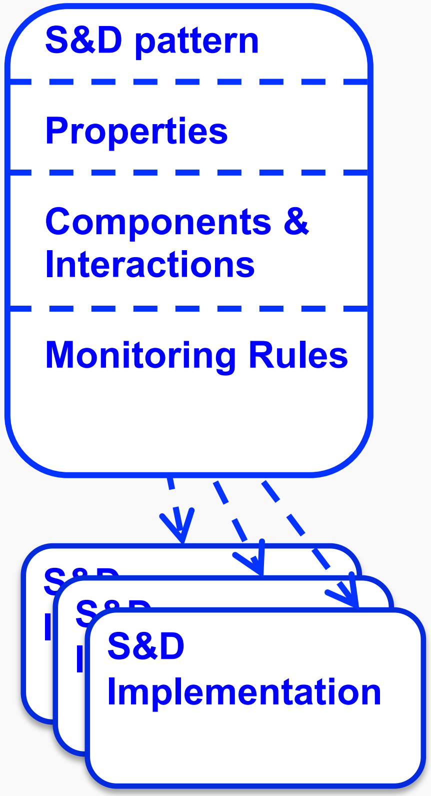
Motivation:

Applications

- Have continually changing S&D requirements
- Often need to operate in changing operational environments and contents
- Interact with dynamically assembled distributed components

S&D patterns

- Provide an abstract specification of solutions that can be deployed in a system to provide S&D properties and link this specification to alternative concrete implementations



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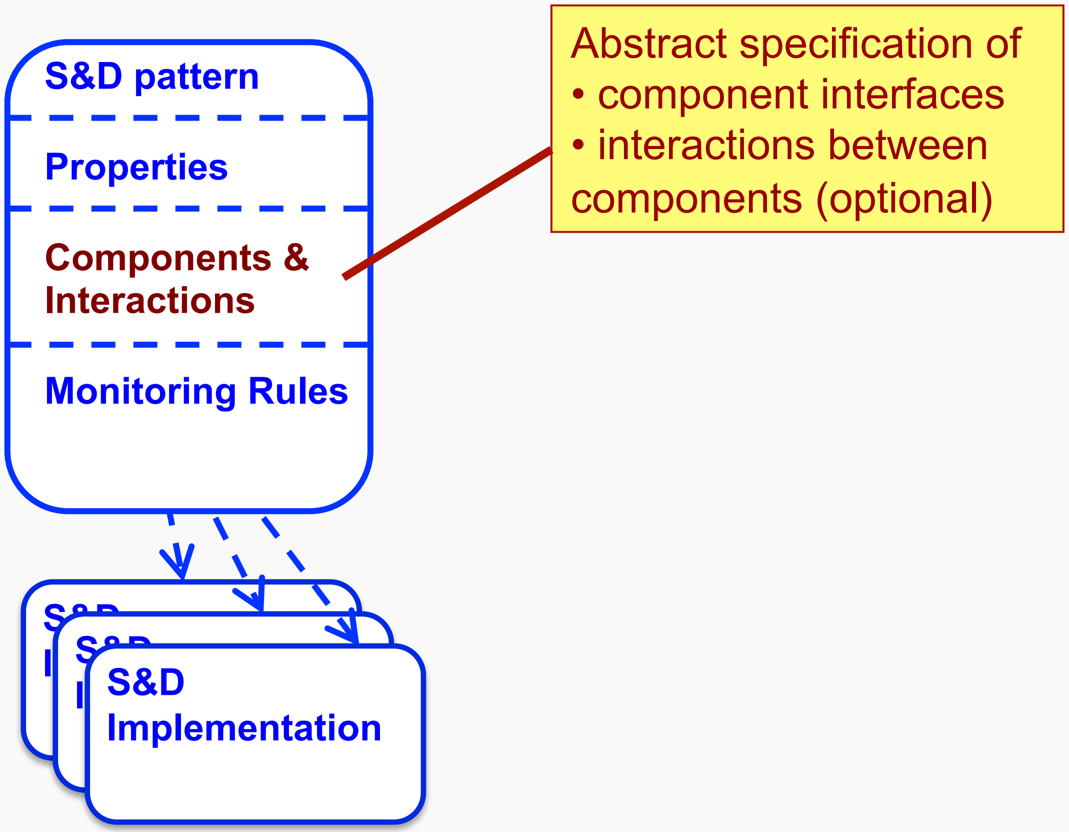

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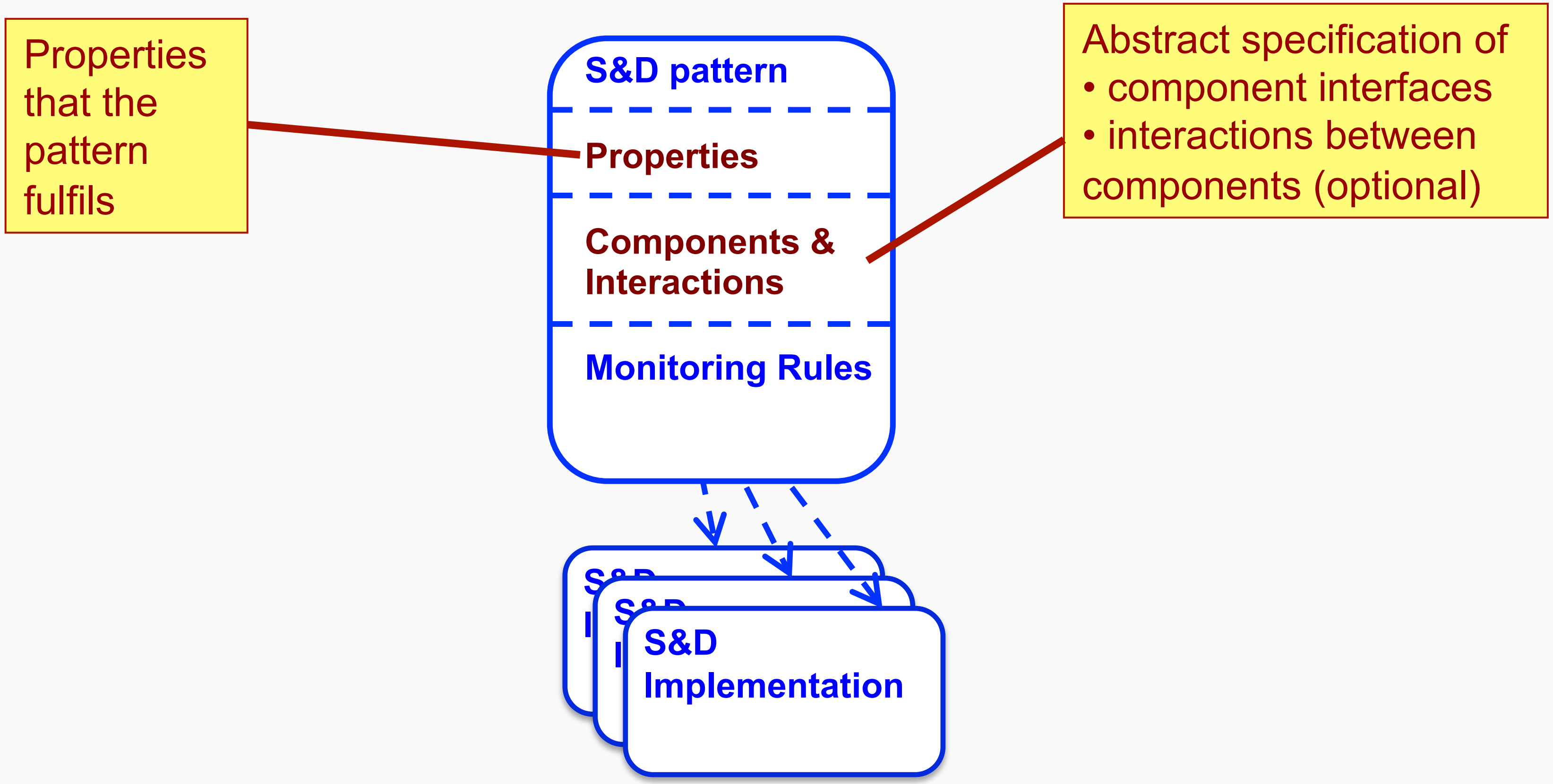

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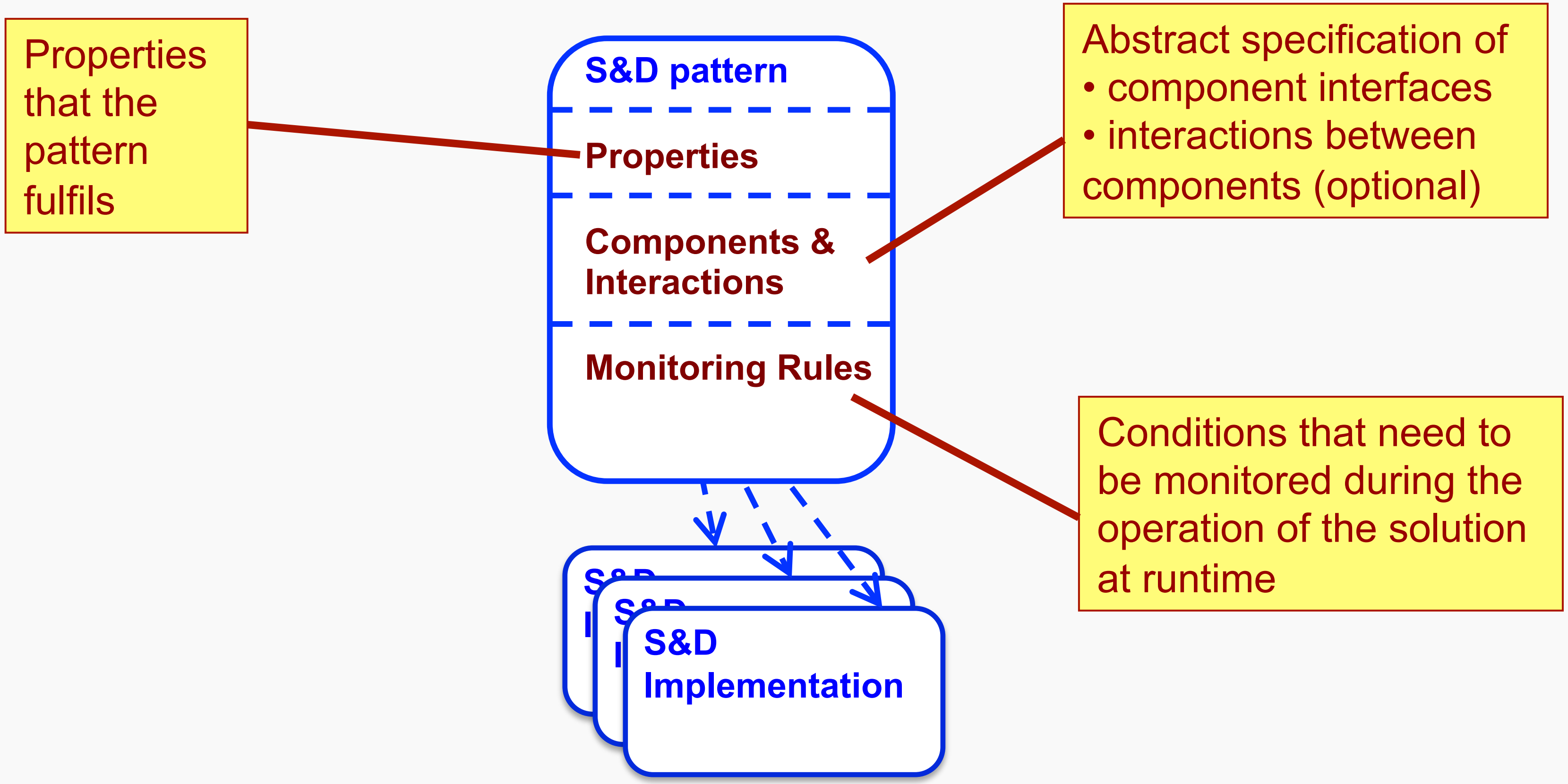

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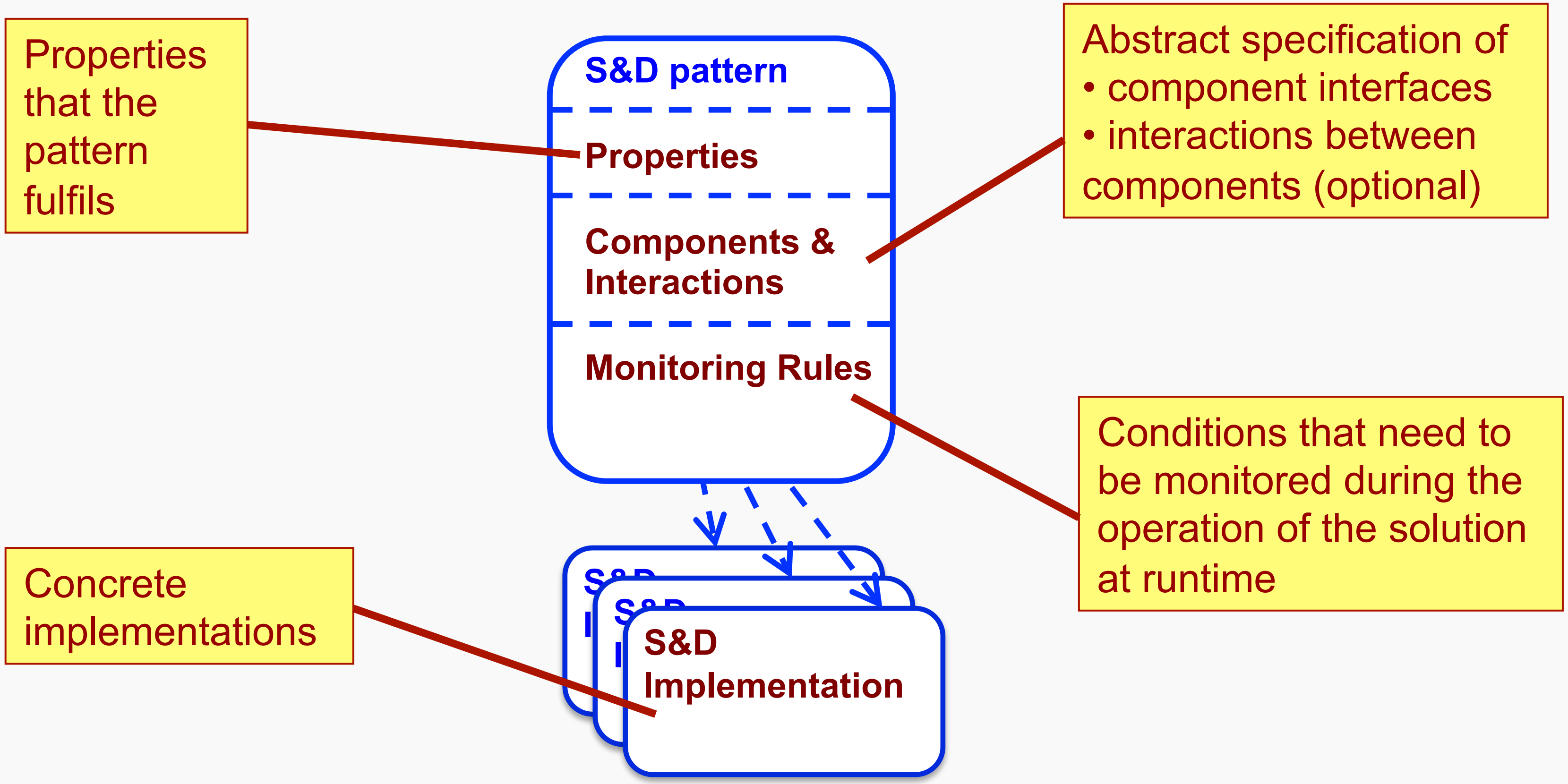

An example: Location based access control

- Access control system providing access to enterprise resources (e.g. printers, Internet access etc) from mobile user devices (PDAs, laptops) (based on [11])
- When a user requests access to a resource, the system may provide it depending on:
  - the credentials of the user,
  - the ability to authenticate the device from which access is requested, and
  - the location of the device

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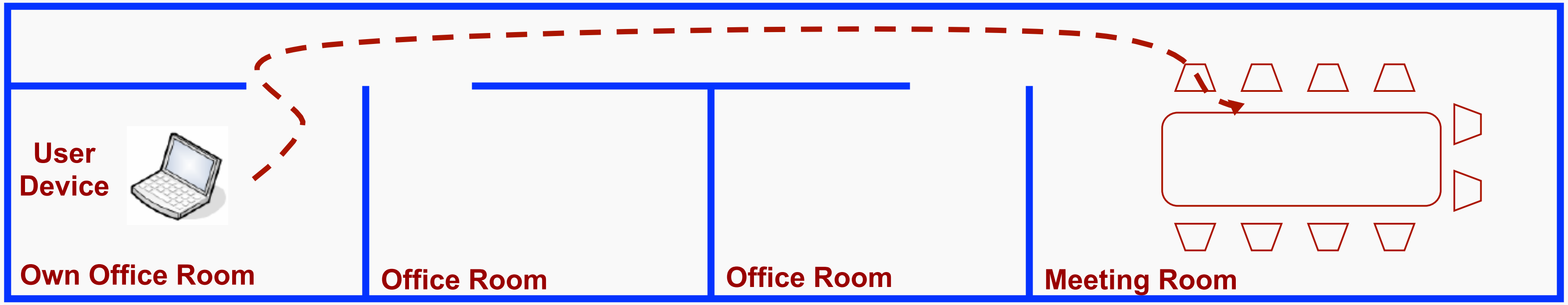


Access to
- Intranet, Internet
- Room's printer
- Printers in common areas

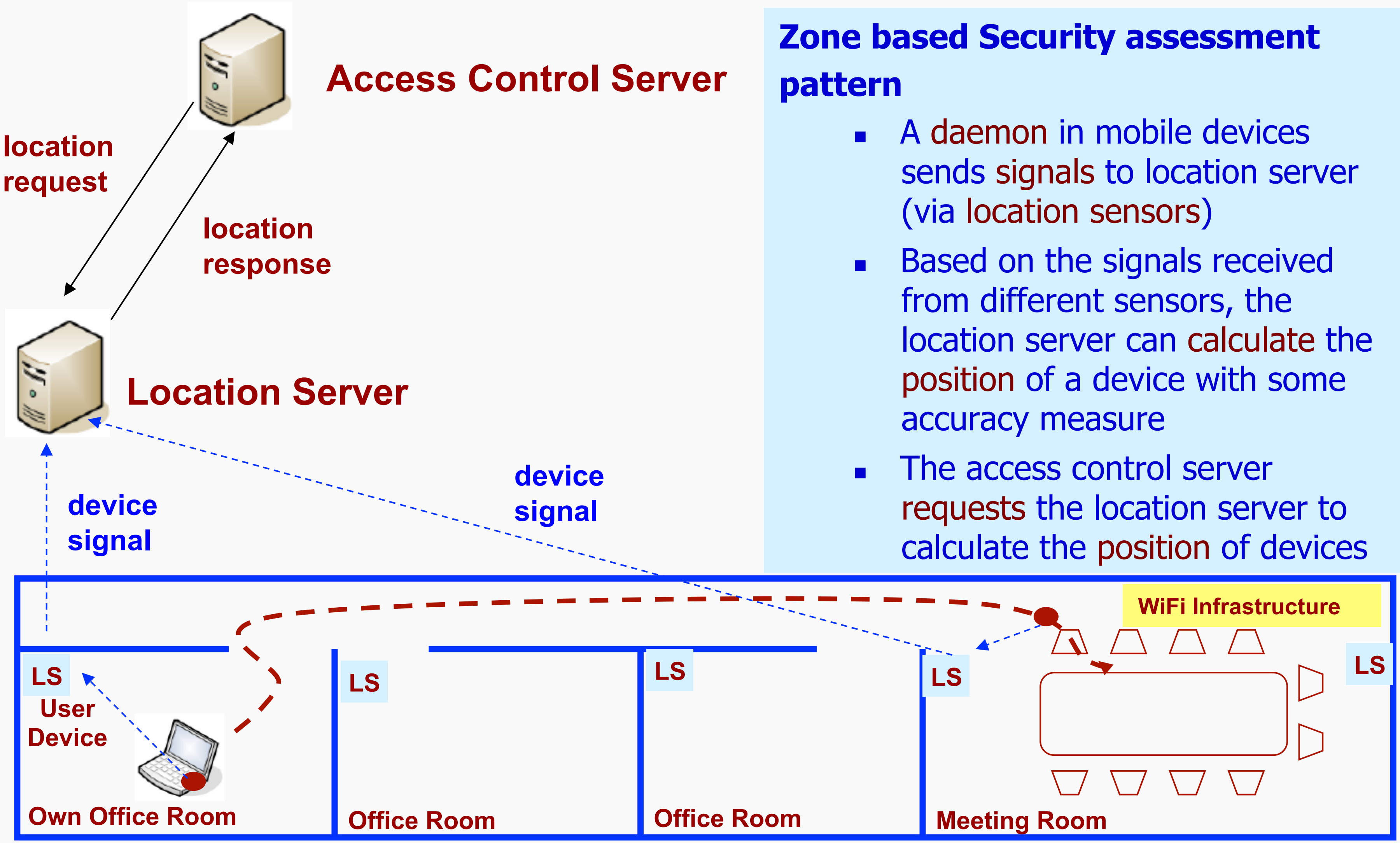
No access to
- printers in other rooms

Provided that both the mobile device and its user have been authenticated

Access to
- Room's printer
- Internet

No access to
- printers in other rooms
- Intranet

An example: device position calculation



Zone based Security assessment pattern

- A daemon in mobile devices sends signals to location server (via location sensors)
- Based on the signals received from different sensors, the location server can calculate the position of a device with some accuracy measure
- The access control server requests the location server to calculate the position of devices

An example: Device location pattern (DLP)

Device Location Pattern

Properties

Location Server: has TPM-based identity

Components

Location Server

locationRequest(devID:ID,loc: Location, acc: Float)

signal(devID: ID)

Monitoring Rules

Need for monitoring

Runtime monitoring of S&D solutions is required in order to

- Check preconditions and invariants required for the correct operation of the solutions
- Verify dynamically that an S&D solution operates according to its specification in all circumstances (static verification and testing cannot provide a full guarantee for this)
- Predict possible violations of conditions and take (if possible) pre-emptive actions

DLP: some monitoring conditions

- Availability of the location server:

  Whenever the access control server makes a request for the location of a device to the location server it must receive a response (or otherwise no access decisions can be made or access will be continually over-restricted)

- Liveness of signal daemons in mobile devices:

  Every device that is known to the control server should be sending signals to the location server periodically and the maximum period of not receiving a signal should not be less than *m* time units (or otherwise it won't be possible to calculate the position of the device)

- Accuracy of location information:

  The accuracy of the device location information that is provided by the location server must always (on average) exceed a certain accuracy threshold

Monitoring rules of DLP pattern

Device Location Pattern

Properties

Location Server: has TPM-based identity

Components

Location Server

locationRequest(devID:ID,loc: Location, acc: Float)

signal(devID: ID)

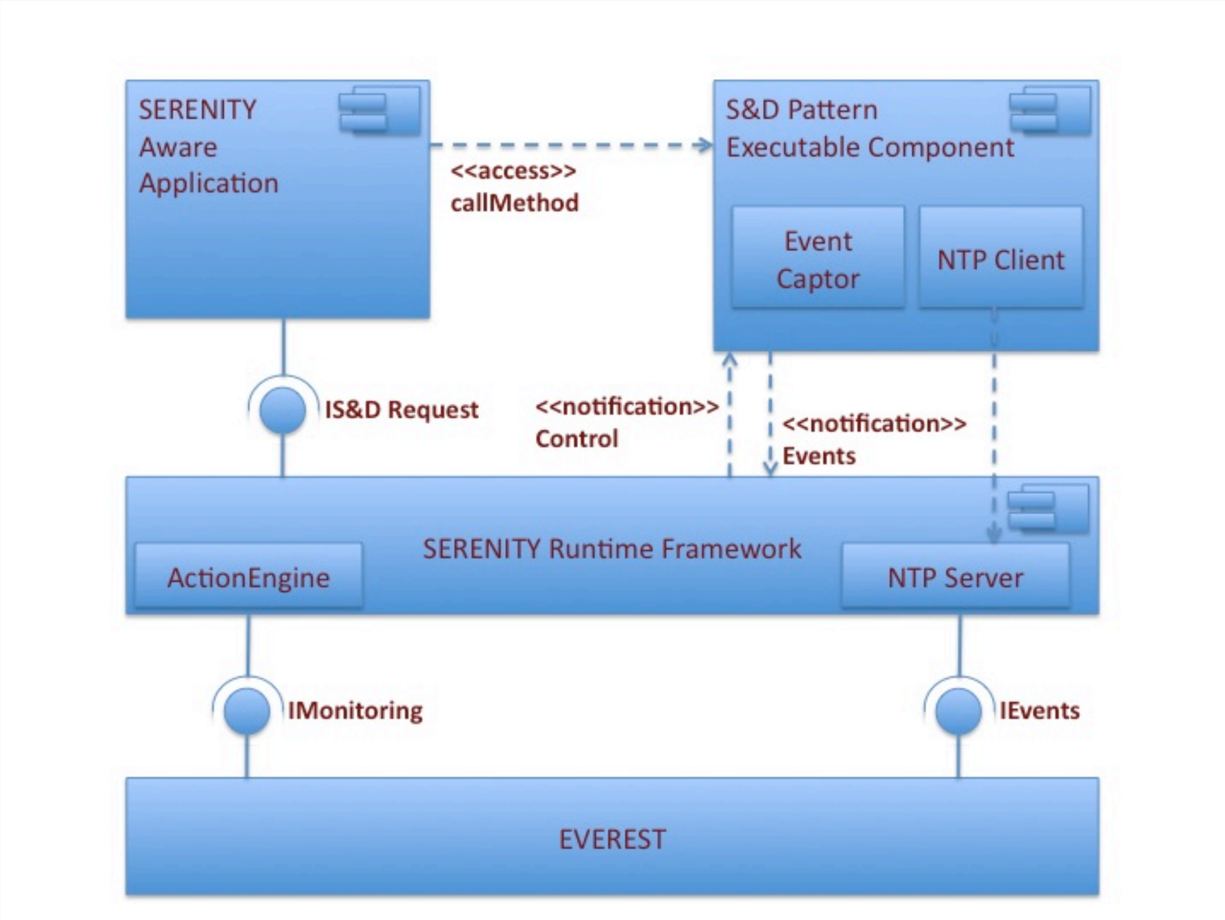
Monitoring Rules

<availability of location server>, notify SRF

<liveness of mobile device daemons>, notify application

<accuracy of location information>, notify SRF

SERENITY Infrastructure



SERENITY Runtime Framework

- Activates patterns and their executable implementations
- Sends monitoring rules to EVEREST
- Receives events from captors of pattern implementations and forwards them to EVEREST
- Polls EVEREST for results and executes actions according to them

EVEREST

- Is available as a service to the SERENITY runtime framework (SRF)
- Receives specifications of the rules to be monitored and runtime events from the SRF
- Performs the checking
- Can be polled for monitoring results

Part II:
The SERENITY monitoring infrastructure

Runtime monitoring

3 alternatives

- The application performs the checks itself
- The checks are performed by an external entity
- The checks are performed by both the application and an external entity

Runtime monitoring

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  Requires **extra programming** effort, **expensive** to change when the system is in operation and needs to deploy a new S&D solution, some checks need to be applied on the deployed S&D solution which the application has no control of

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  Requires **monitoring specifications**, **more flexible** when operational **environments change** and S&D **solutions change**, **can be applied** to **external collaborators,** **less efficient** than application based testing

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  Increased fault tolerance (two independent implementations of the same check), more **expensive** and **less flexible** option, **necessary** in certain circumstances

Runtime monitoring: The SERENITY approach

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Monitoring life cycle

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Development of S&D solutions

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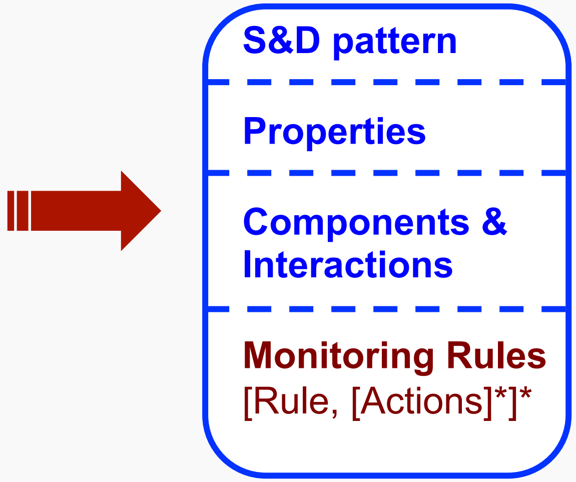
Development of S&D solutions

- Specify the conditions that need to be monitored at runtime and the actions that need to be taken when the conditions are violated within S&D patterns



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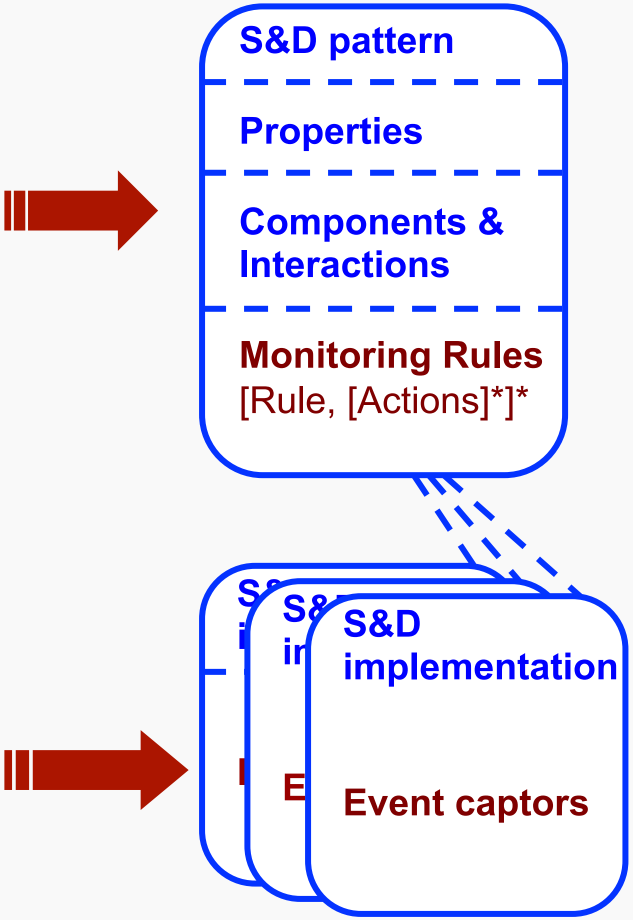

- Provide implementations of patterns (aka S&D solutions) incorporating captors that can provide the events required to monitor the conditions of the pattern

Monitoring life cycle

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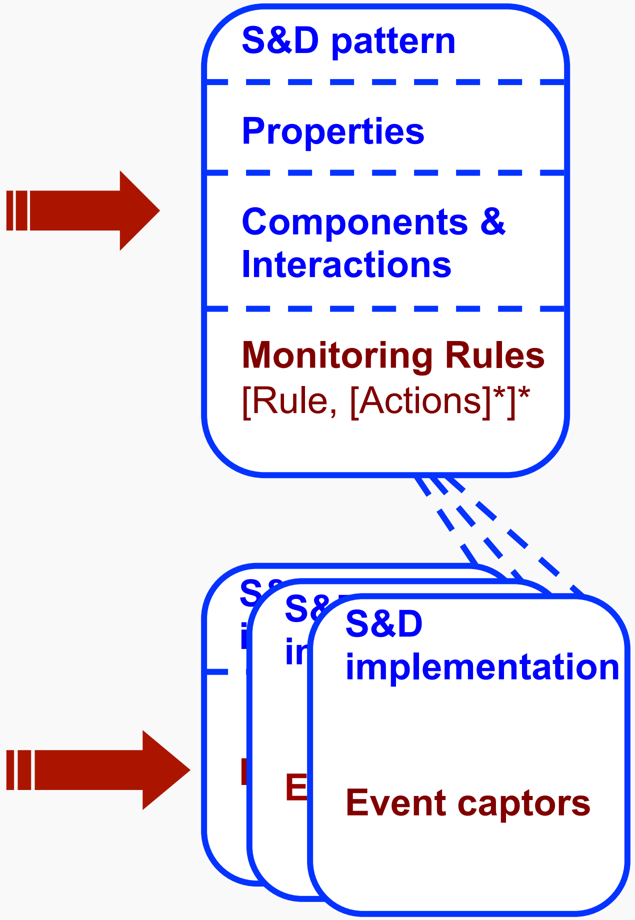

At runtime

When an S&D pattern is selected:

- Start the process of checking its monitoring rules
- Activate the relevant S&D implementation and its captors

Monitoring life cycle

Development of S&D solutions

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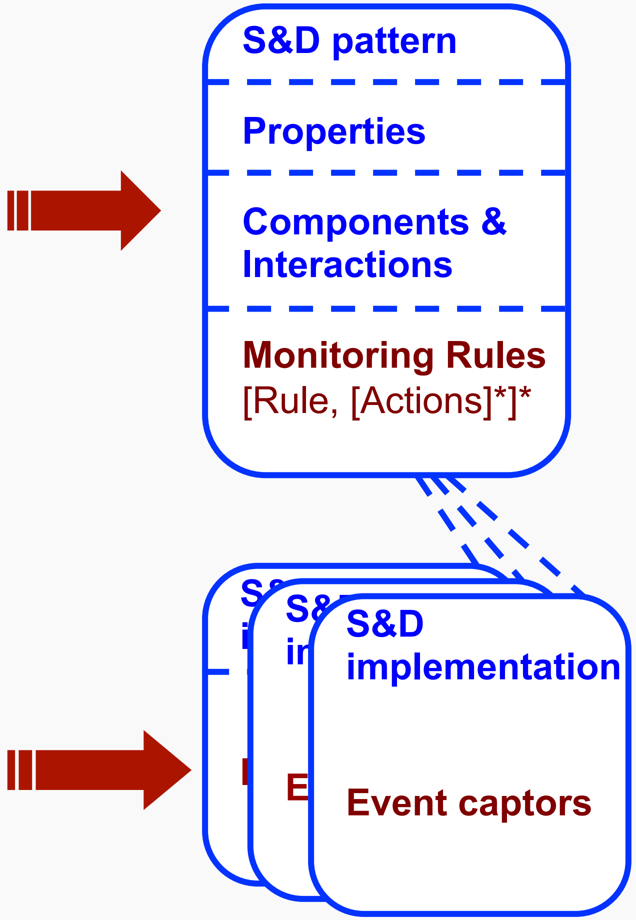


At runtime

When an S&D pattern is selected:

- Start the process of checking its monitoring rules
- Activate the relevant S&D implementation and its captors

When a monitoring rule is violated:

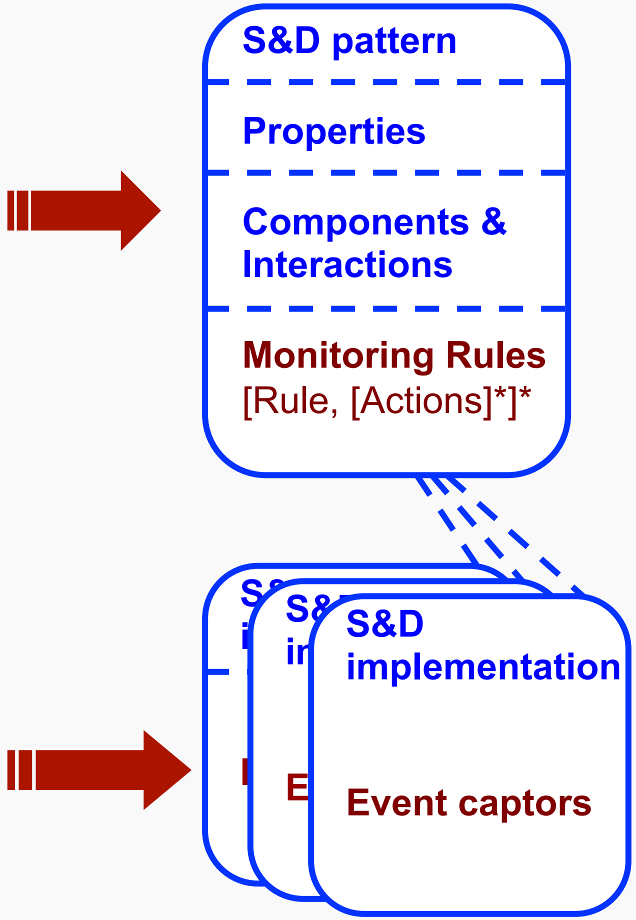
- Execute the action(s) specified for it (if any)

Monitoring life cycle

Development of S&D solutions

- Specify the conditions that need to be monitored at runtime and the actions that need to be taken when the conditions are violated within S&D patterns

- Provide implementations of patterns (aka S&D solutions) incorporating captors that can provide the events required to monitor the conditions of the pattern



At runtime

When an S&D pattern is selected:

- Start the process of checking its monitoring rules
- Activate the relevant S&D implementation and its captors

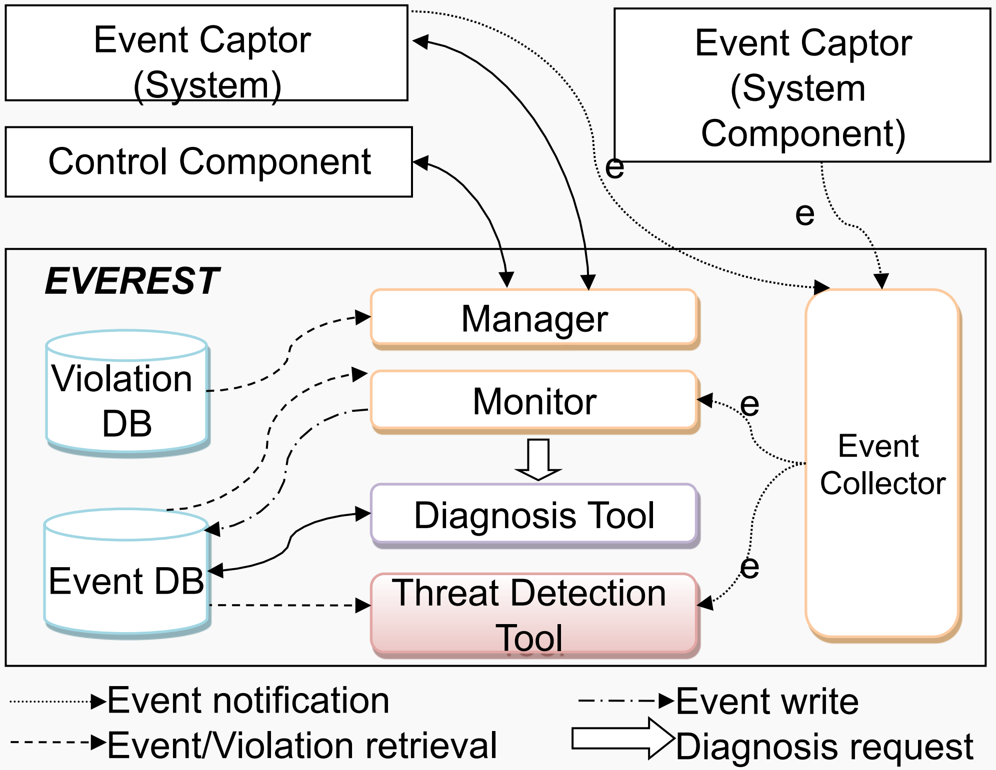
When a monitoring rule is violated:

- Execute the action(s) specified for it (if any)

When an S&D pattern is deactivated:

- Stop the process of checking its monitoring rules
- Deactivate the relevant S&D implementation and its captors

EVEnt REaSoning Toolkit (EVEREST)



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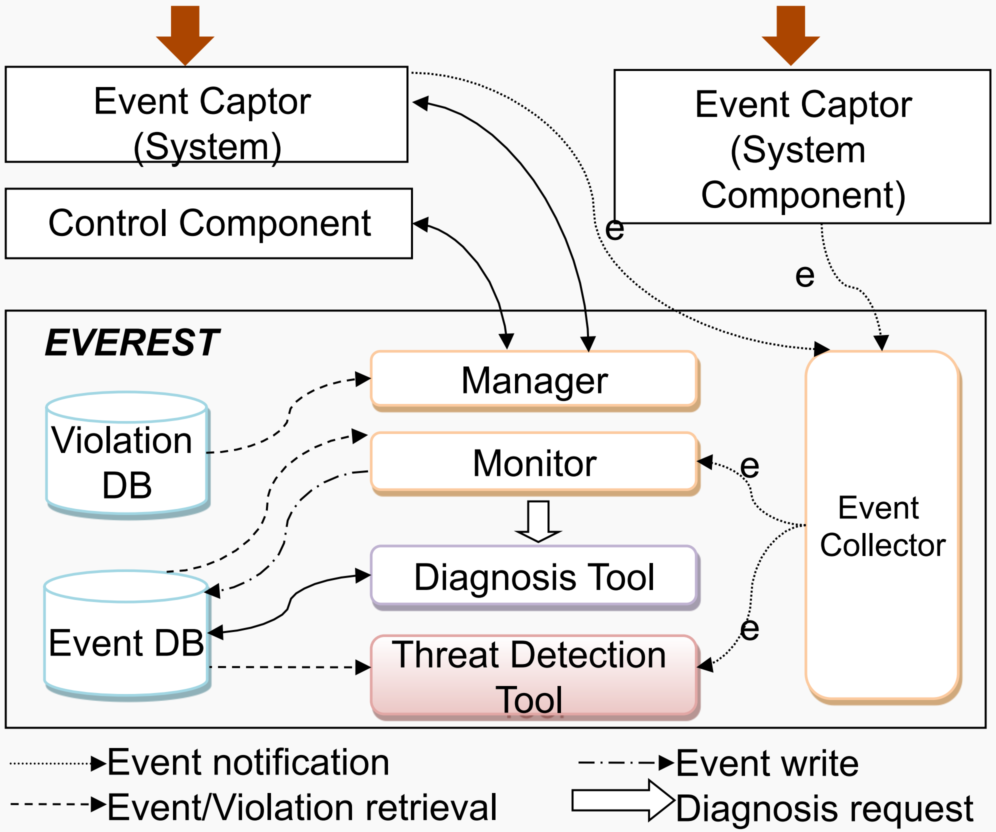

- Captures **events** through **event captors** associated with systems and their components

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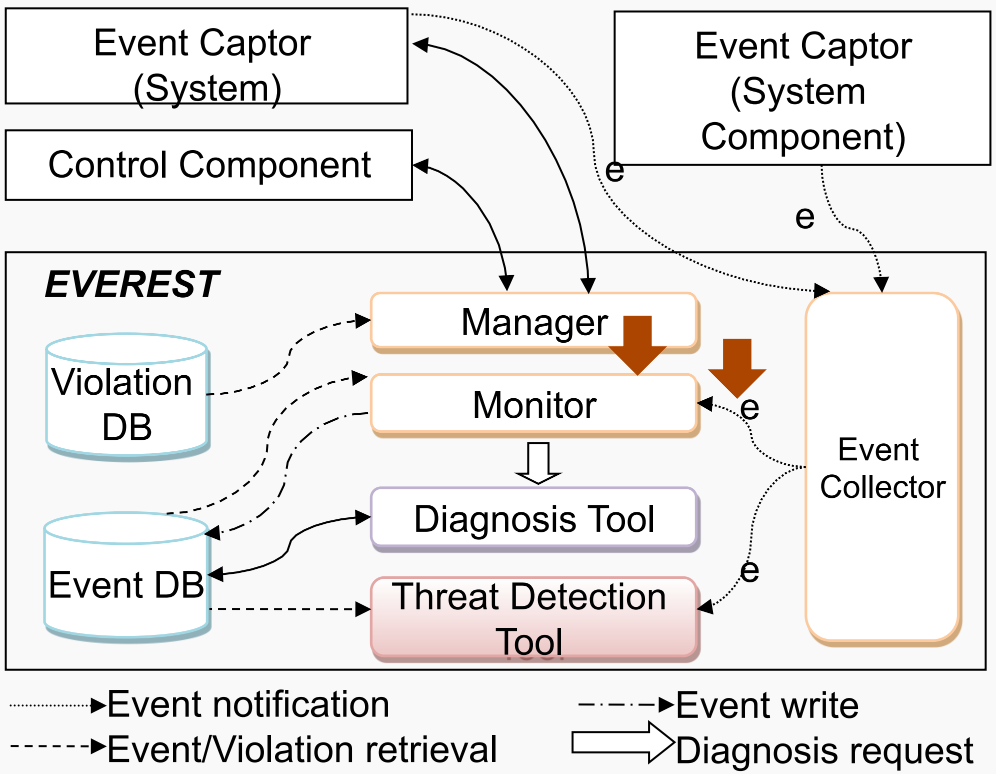

- Captures events through event captors associated with systems and their components
- Checks whether captured events (and events deduced from them) satisfy specific **S&D properties** expressed as **monitoring rules** (core **monitor**)

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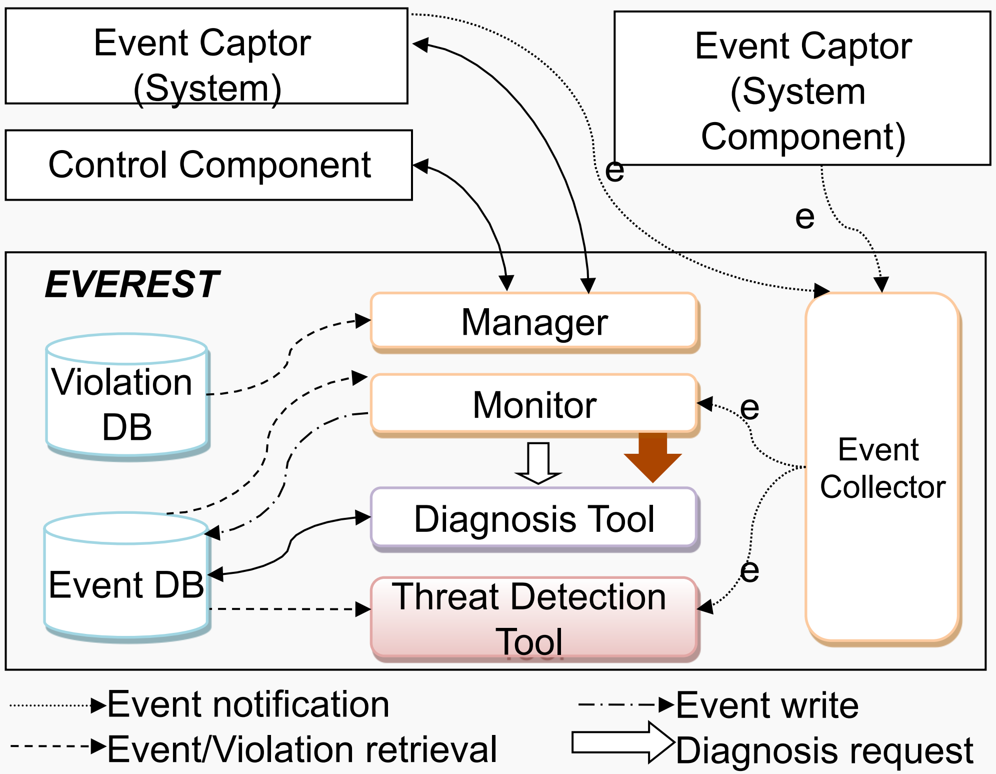

- Captures events through event captors associated with systems and their components
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- Assesses **event genuineness** by attempting to derive **explanations** of captured events (**diagnosis tool**)

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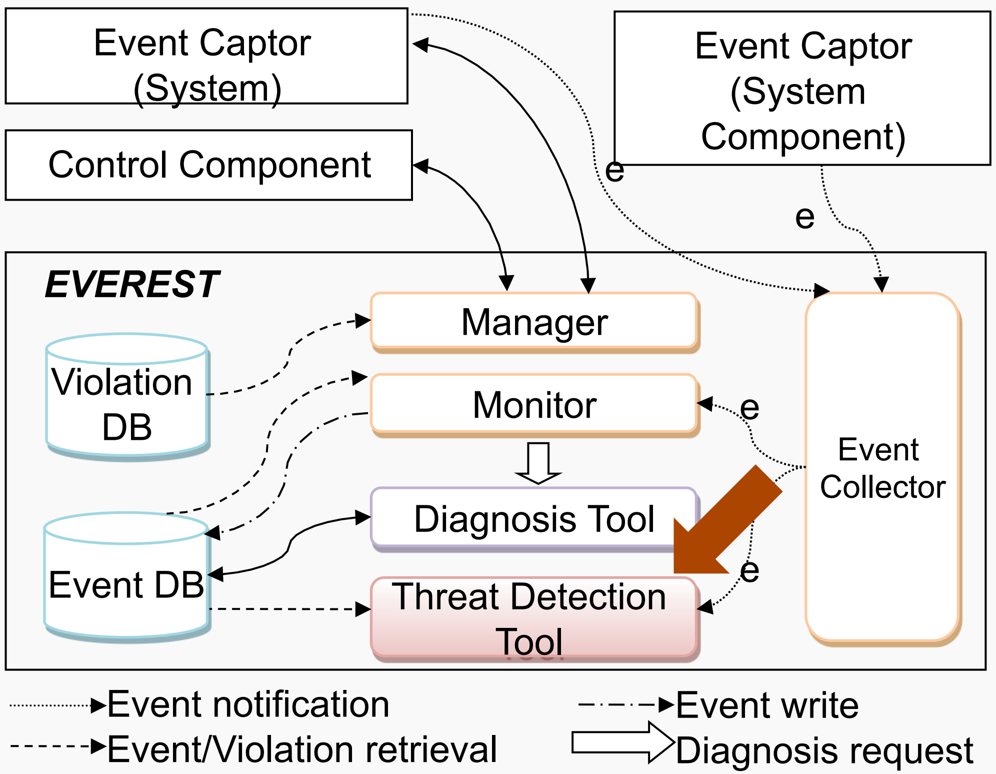

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- Checks whether captured events (and events deduced from them) satisfy specific S&D properties expressed as monitoring rules (core monitor)
- Assesses event genuineness by attempting to derive explanations of captured events (diagnosis tool)
- Predicts **potential violations** of monitoring rules based on historical data (**threat detection tool – TDT**)

Part III:

Specification of monitorable S&D properties

Specification of monitoring rules (1)

- Monitoring rules: express the properties/requirements that need to be monitored

- General form

$$B_{t1} \Rightarrow H_{t2} \text{ (if } B_{t1} \text{ is true then } H_{t2} \text{ must be true)}$$

- B_{t1}:
  - rule's body (a conjunction of conditions, e.g. occurrences of events, conditions regarding the state of the system)
  - It is typically expressed as a conjunction of Happens, HoldsAt, relational or time predicates
- H_{t2}:
  - rule's head (a number of consequences)
  - It is typically expressed as a conjunction of Happens, HoldsAt, relational or time predicates

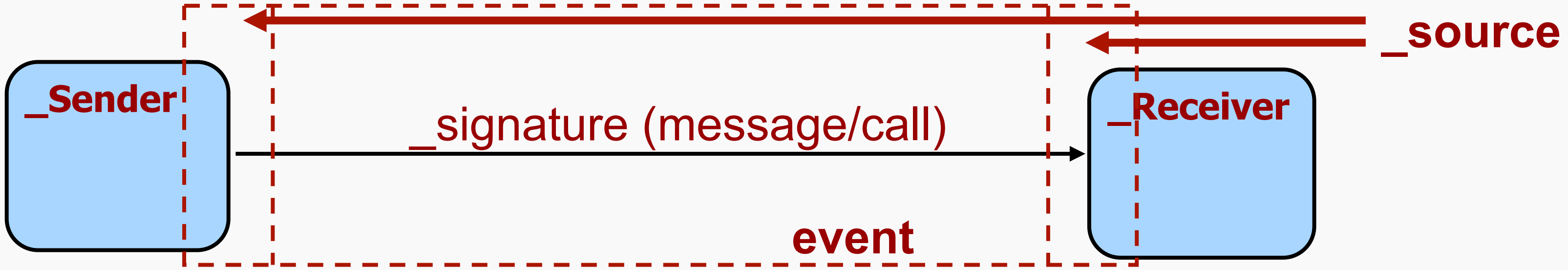
Specification of monitoring rules (2)

- Rules and assumptions are specified in Event Calculus – a first order temporal logic language – in terms of
  - **Events**: things that happen within a system of instantaneous duration (e.g. receipt of component messages, execution of internal or system operations)
  - **Fluents**: conditions about the state of a system

    relation(obj_1, …, obj_N)

- Predefined predicates:
  - Happens(e, t, $\Re$(t1,t2)) – occurrence of an event *e* of instantaneous duration at some time *t* within the time range $\Re$(t1,t2)
  - Initiates(e,f,t) – fluent *f* starts to hold after the event *e* at time *t*.
  - Terminates(e,f,t) – fluent *f* ceases to hold after the event *e* occurs at time *t*
  - HoldsAt(f,t) – fluent *f* holds at time t.
  - Relational predicates: x REL y (e.g. EqualTo, NotEqualTo, …)
  - Time predicates: t1 TREL t2 (e.g. TEqualTo, TLessThan …)

Specification of monitoring rules (3)



Events: General form

e(_id, _senderRole, _senderID, _receiverRole, _receiverID, _status, _signature _sourceRole, _sourceID))

- _signature: the type of a message sent by the component/system
- _status: indicates whether the message is incoming or outgoing
- _senderRole: the role of the component that sends the message
- _senderID: the id of the component that sends the message
- _receiverRole: the role of the component that receives the message
- _receiverID: the id of the component that receives the message
- _sourceRole: the role of the component at which the message is captured
- _sourceID: the id of the component at which the message is captured

Events typically correspond to operations defined in the interfaces of the components of the S&D pattern

Specification of monitoring rules (4)

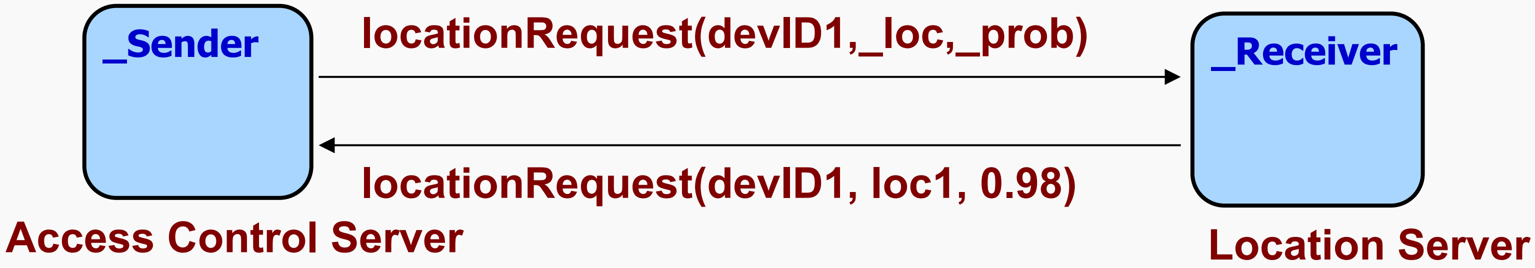
- Other features
  - Calls to built-in functions implementing complex computations (e.g. statistical functions)

Happens(e(…,REQ, o(),…), t_1, R(t_1, t_1)) ∧
Happens(e(…, RES, o(),…), t_2, R(t_1, t_2)) ∧
HoldsAt(o_response_times(RT[]), t_2) ⇒ m:append(RT[], $t_2 - t_1$), t_2)
HoldsAt(o_response_times(RT[]), t_1) ⇒ m:avg(RT[]) < k

Examples of monitoring rules:

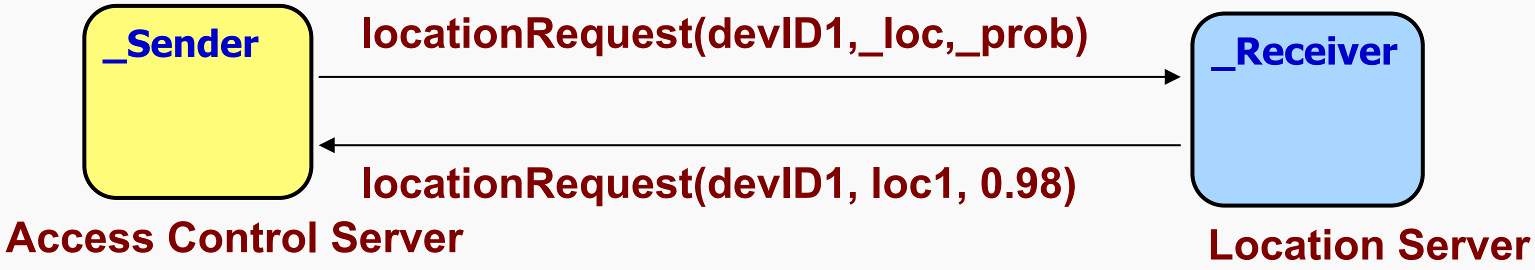
Part III

Rule for location server availability



Condition: when the access control server sends a location request to the location server it should receive a response from it within 3 seconds

Examples of monitoring rules:
Rule for location server availability



Condition: when the access control server sends a location request to the location server it should receive a response from it within 3 seconds

Rule 1

Happens(e(_eID1, _controlServerRole, _controlServerID, _locationServerRole, _locationServerID, REQ, locationRequest(_dev,_loc,_prob), _controlServerRole, _controlServerID), t1, R(t1, t1))

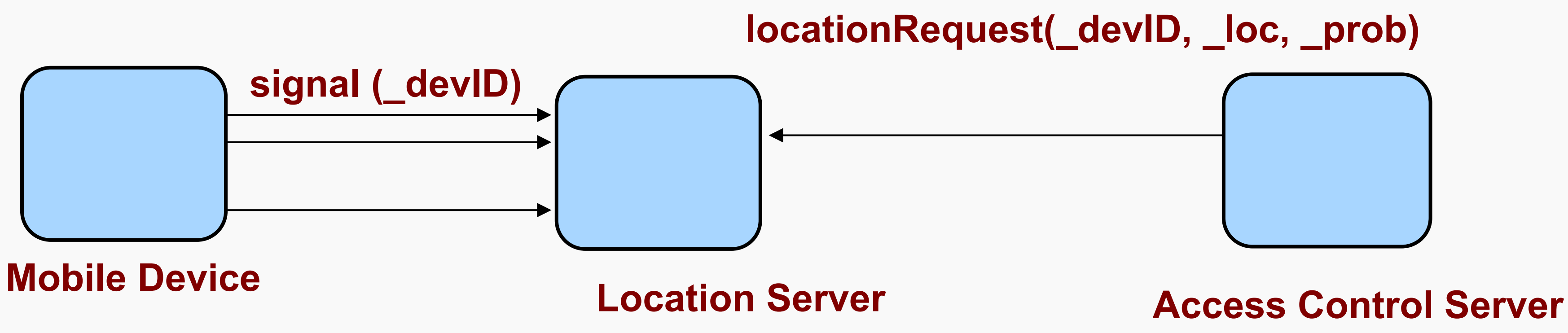
$\Rightarrow$

Happens(e(_eID2, _locationServerRole, _locationServerID, _controlServerRole, _controlServerID, RES, locationRequest(_dev, _loc, _prob), _controlServerRole, _controlServerID), t2, R(t1+1, t1+3000))

Examples of monitoring rules:

Part III

Rules for liveness of device daemons

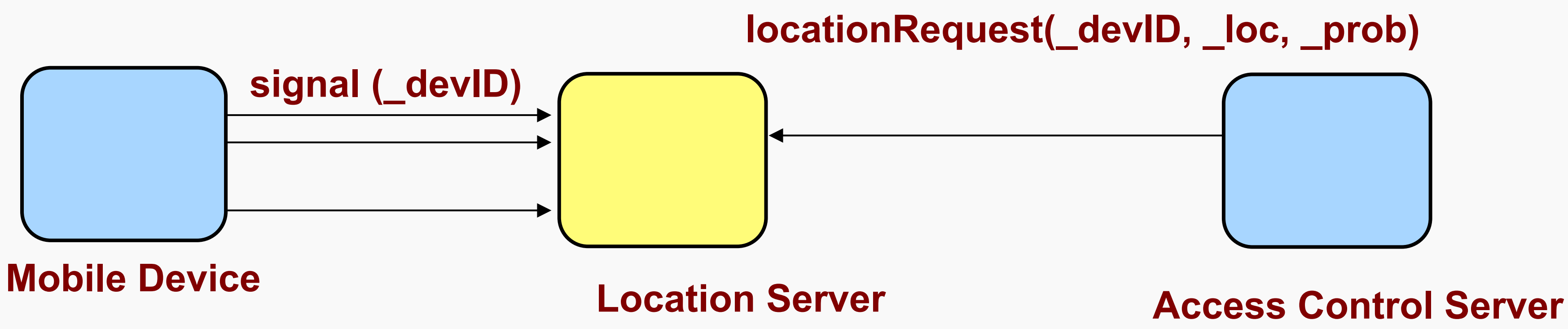


Condition: Every mobile device that is known to the control server should be sending signals to the location server periodically and the maximum period of not receiving a signal should not be less than *m* time units

Can be specified by 2 rules:

- A rule for checking when the first signal from a mobile device should be received
- A rule for checking the continuous receipt of signals

Examples of monitoring rules:
Rules for liveness of device daemons



Rule 2:

Happens(e(_eID1, _cServerRole, _cServerID, _lServerRole, _lServerID, REQ, locationRequest(_devID,_loc,_prob), _lServerRole, _lServerID), t1, R(t1,t1)) ∧

¬∃t2. **Happens**(e(_eID2, _cServerRole, _cServerID, _lServerRole, _lServerID, REQ, locationRequest(_devID,_loc1,_prob1), _lServerRole, _lServerID), t2, R(0,t1-1)) ⇒

∃t3. **Happens**(e(_eID3, _deviceRole, _devID, _lServerRole, _lServerID, RES, signal(_devID), _lServerRole, _lServerID), t3, R(t1-m,t1))

Rule 3:

Happens(e(_eID1, _deviceRole, _devID, _lServerRole, _lServerID, REQ, signal(_devID), _lServerRole, _lServerID), t1, R(t1,t1)) ⇒

Happens(e(_eID2, _deviceRole, _devID, _lServerRole, _lServerID, REQ, signal(_devID), _lServerRole, _lServerID), t1, R(t1,t1+m)) ∧ _eID1 ≠ _eID2

Examples of monitoring rules:

Rule for accuracy of location information

Condition: The accuracy of the device location information that is provided by the location server must always exceed a certain accuracy threshold

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Rule for accuracy of location information

Condition: The accuracy of the device location information that is provided by the location server must always exceed a certain accuracy threshold

Rule 4

Happens(e(_eID1, _locationServerRole, _locationServerID, _controlServerRole, _controlServerID, RES, locationRequest(_dev,_loc,_prob), _controlServerRole, _controlServerID), t1, R(t1, t1))

$\Rightarrow$ _prob $\geq$ AT

Assumptions

- Used to deduce information about the state of the system and/or the occurrence of events
- Two types:
  - Monitoring assumptions: express how the state of a "system" that is being monitored is affected by events
  - Diagnostic assumptions: express expected patterns of correlated events (e.g. sequences of operation calls)
- Have the same general form with rules:

$$B_{t1} \Rightarrow H_{t2}$$

- B_{t1}: assumption's body (a conjunction of Happens, HoldsAt, relational or time predicates
- H_{t2}: assumption's head
  - In monitoring assumptions: a conjunction of fluent initiation and/or termination predicates (Initiates, Terminates predicates)
  - In diagnostic assumptions: a conjunction of Happens predicates

Assumptions: example

Condition: A device requesting access to a resource must have been authenticated

Assumptions: example

Condition: A device requesting access to a resource must have been authenticated

Rule 5

Happens(e((_eID1,,_sndRole,_sndID,
_recRole, _recID, REQ, **requestAccess(_devID, _resID)**, _recRole,_recID), t_1,
$R(t_1, t_1)) \Rightarrow$
HoldsAt(AUTHENTICATED(_devID), t_1, $R(t_1, t_1)$)

Assumption A1 (monitoring assumption)

Happens(e(_eID2,_recRole,_recID,
_senRole, _senID, RES, **connect(_devID, _res)**
_recRole,_recID), t_1, $R(t_1, t_1)) \wedge$ _res = True $\Rightarrow$
Initiates(e(_eID2, …), AUTHENTICATED(_devID), t_1, $R(t_1, t_1)$)

Monitoring Process

- It is based on a generic event calculus reasoning engine (see [1,6,7,8])
- Rule checking using
  - Runtime events
  - Fluents established by assumptions (deductive reasoning)
- Checks cover both past and bounded future EC formulas
  - Past formulas:

    $Happens(\ e_1,\ t_1,\ R(t_1,\ t_1)) \Rightarrow Happens(\ e_2,\ t_2,\ R(0,\ t_1))$
  - Bounded Future formulas:

    $Happens(\ e_1,\ t_1,\ R(t_1,\ t_1)) \Rightarrow Happens(\ e_2,\ t_2,\ R(t_1,\ t_1+K))$
- Ability to analyse
  - events captured from distributed sources with different clocks
  - events arriving at the monitor not in the same order as the order of their capture

Part IV:
Advanced Capabilities (Diagnosis and Prediction)

Monitoring process: diagnostic capabilities

- Given a violation of an S&D monitoring rule

  $$R: E_1, E_2, E_3, \ldots, E_n \Rightarrow E_{n+1}$$

  Calculate beliefs in the genuineness of the events $E_1, E_2, \ldots, \neg E_{n+1}$ which are involved in the violation since events might be the result of an attack or fault
- Overall Approach (see [5] and [7])
  - The genuineness of an event depends on the ability to find a valid explanation for it
    - An event explanation is a logical combination of other events and states of the system which would have the event as a consequence
    - An event explanation is considered to be valid if it has as consequences other events which have also been observed and are genuine
  - Possible event explanations are generated by abductive reasoning using the monitoring specifications of the active patterns of the system that is being monitored
  - Event genuineness is assessed by beliefs computed according the Dempster-Shafer theory of evidence

Diagnosis: Assessing Event Genuineness

Belief in event genuineness:

Assumption:

An event is genuine if there is at least one valid explanation for it, i.e., an explanation whose further consequences (if any) are genuine

Process:

- Generate explanations using abductive reasoning and a system behaviour model (expressed as assumptions in EC-Assertion)
- Check explanation validity by checking if the expected consequences of an explanation are genuine events themselves
- Limit analysis to a period "around" the event (diagnosis window)

Belief functions:

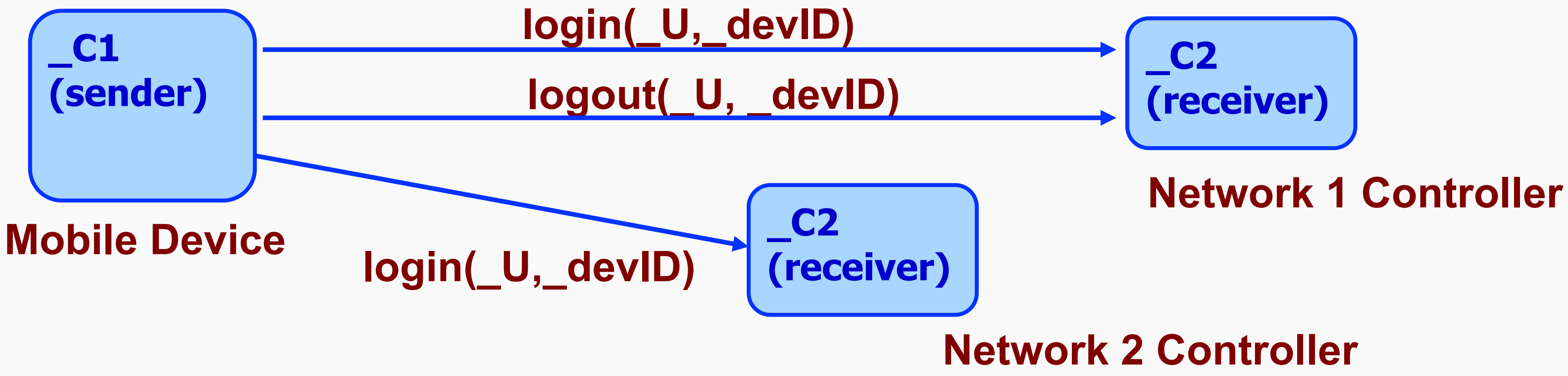
$m(E_i) = m^o(E_i) \times \{\Sigma_{J \subseteq EXP(Ei) and\ J \neq \emptyset}(-1)^{|J|+1}\{\Pi_{x \in J}\ mv\,(x,E_i)\}$ *If* $EXP(E_i) \neq \emptyset$

$= m^o(E_i) \times \beta_1$ *Otherwise*

$mv(x,E_i) = \Sigma_{S \subseteq Cons(x/Ei)\ and\ S \neq \emptyset}(-1)^{|S|+1}\{\Pi_{e \in S}\ m(e,E_i)\}$ *If* $Cons(x/E_i) \neq \emptyset$

$= \beta_2$ *Otherwise*

Diagnosis: Example



- Condition: no user should be allowed to login onto different parts of the WiFi network simultaneously (to reduce scope for masquerading attacks):

Rule-5:

∀ _U: User; _C1: Client; _C2, _C3: NetworkController; t1, t2:Time

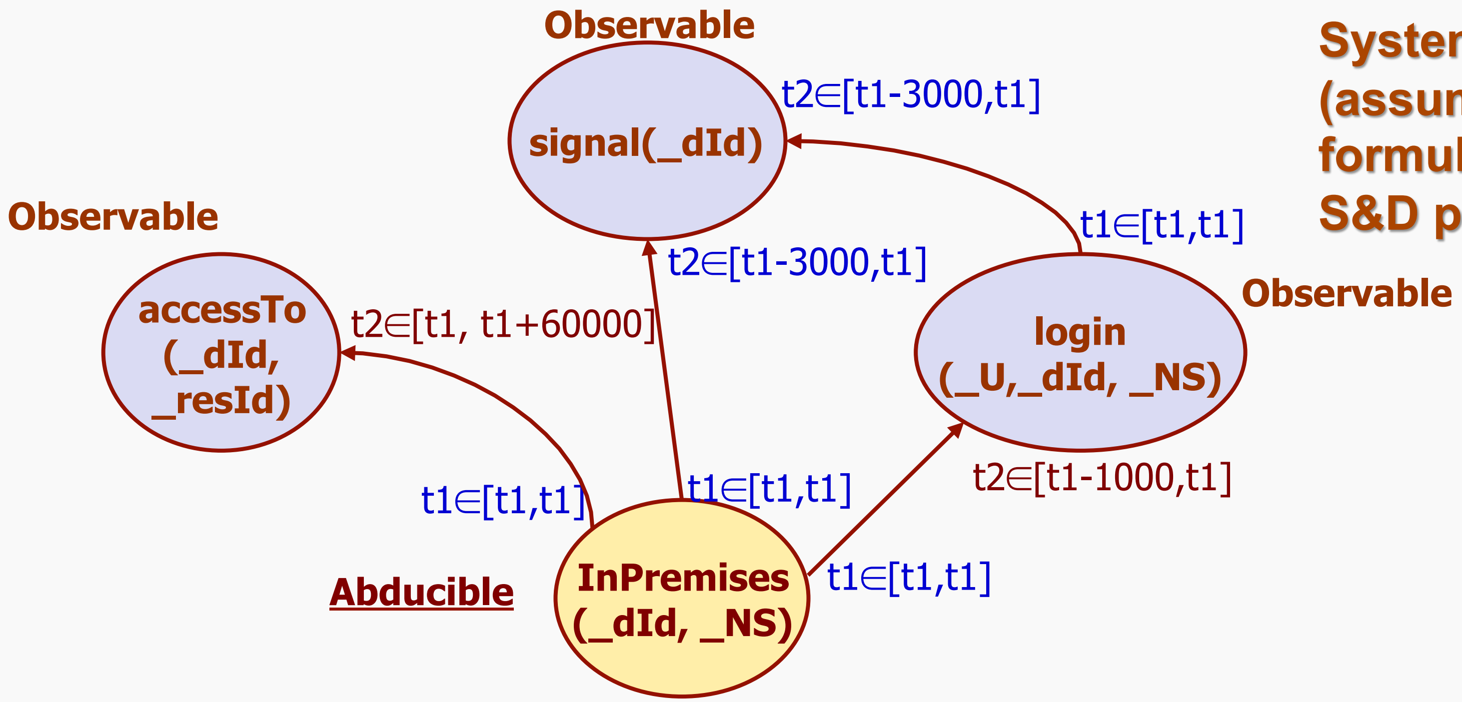
Happens(e(_E1, _C1Role, _C1, _C2Role, _C2,REQ, login(_U,_C1), _C2Role, _C2), t1,ℜ(t1,t1)) ∧

Happens(e(_E2, _C1Role , _C1, _C3Role, _C3,REQ, login(_U,_C1),_C3Role,_C3), t2,ℜ(t1,t2)) ∧ _C2 ≠ _C3

⇒

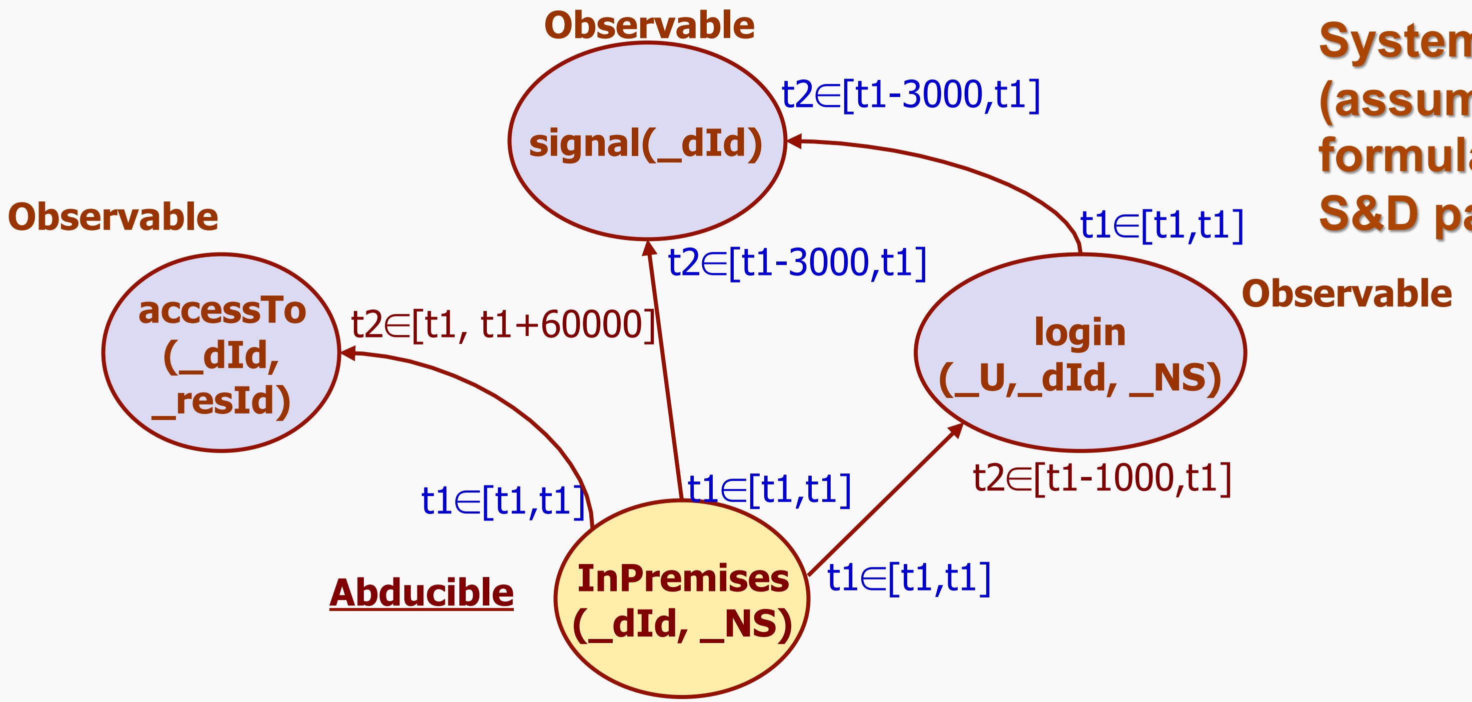
∃ t3: Time **Happens**(e(_E3,_C1,_C2,REQ, logout(_U,_C1), _C2),t3,ℜ(t1+1,t2-1))

Diagnosis: Example



System model (assumption formulas in the S&D pattern)

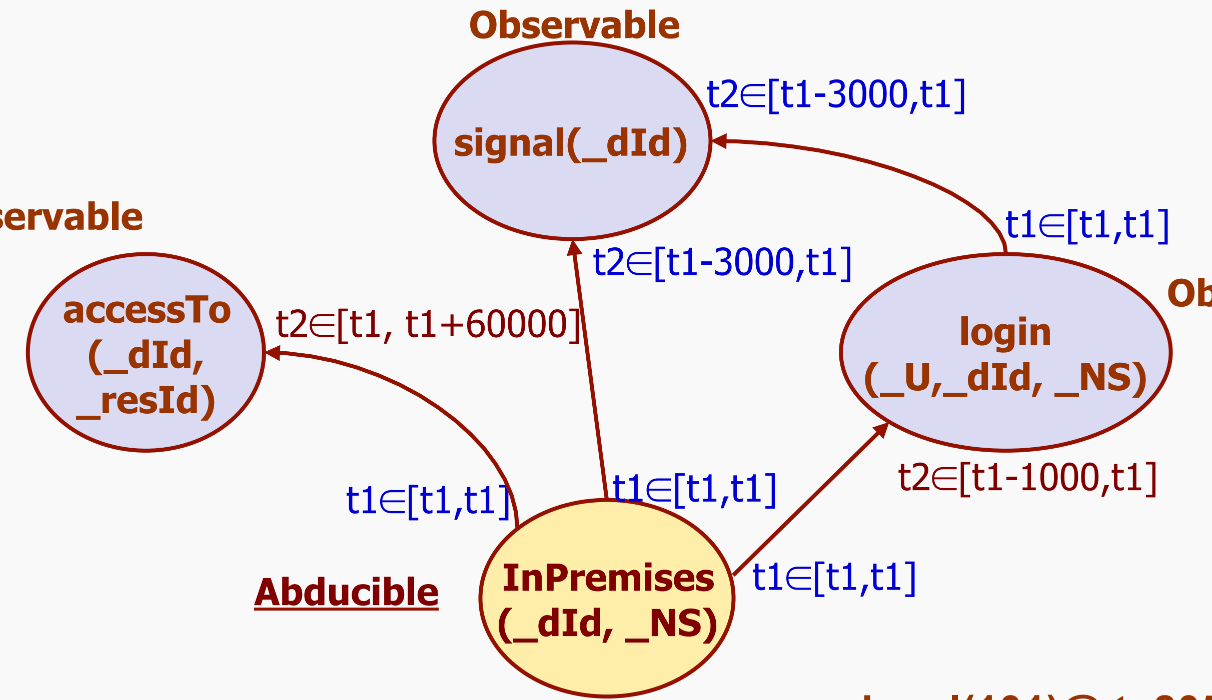
Diagnosis: Example



System model (assumption formulas in the S&D pattern)

- login(_, 101, n1) @ t=10050 $\Rightarrow_A$ InPremises (101,n1) @ t∈[9050,10050)
- InPremises(101,n1) @ t∈[9050,10050) ⇒ **signal(101) @ t∈[6050,10050)**
- InPremises(101,n1) @ t∈[9050,10050) ⇒ **accessTo(101, _) @ t∈[9050,69050)**

Diagnosis: Example



System model (assumption formulas in the S&D pattern)

- login(_, 101, n1) @ t=10050 $\Rightarrow_A$ InPremises (101,n1) @ t∈[9050,10050)
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- InPremises(101,n1) @ t∈[9050,10050) ⇒ **accessTo(101, _) @ t∈[9050,69050)**

- **signal(101)@ t=8050**
  m(login(...)) = β_1 = 0.2
- **signal(101)@ t=8050**
  accessTo(101, _) @ t = 9801
  m(login(…)) = $\beta_1 + \beta_1 - \beta_1 \times \beta_1$ = 0.36
- **Explanation with no consequences**
  m(login(…)) = β_2 = 0.1

Monitoring process: threat detection capabilities

Detection of potential violations of S&D monitoring rules

$$R: E_1, E_2, E_3, \ldots, E_n \Rightarrow E_{n+1}$$

Calculate belief that R will be violated given the observation of a subset of $E_1, E_2, \ldots, E_{n+1}$

- Events might
  - Not be observed in the order they are expected by R
  - Be the result of an attack or fault (and therefore a belief in their genuineness needs to be estimated; see diagnosis)
- Approach (see [1])
  - Use DS beliefs to measure the likelihood of events genuineness and the likelihood of conditional event occurrence
  - Negate the rule to get the exact pattern of events that violates it
  - Construct a belief network indicating how beliefs in the violation of the rule can be updated as partial evidence about events in the pattern emerges

Threat detection: Belief graphs

- Negate the rule

  <u>Rule-5 attack signature</u>:

  ∀ _U: User; _C1: Client; _C2, _C3: NetworkController; t1, t2:Time

  Happens(e(_E1,_C1Role,_C1,_C2Role,_C2,REQ, login(_U,_C1,_C2),_C2Role, _C2),t1,$\Re$(t1,t1)) ∧

  Happens(e(_E2,_C1Role,_C1,_C3Role,_C3,REQ, login(_U,_C1,_C3),_C3Role, _C3),t2,$\Re$(t1,t2)) ∧ _C2 ≠_C3

  ⇒ ∀t3:Time ¬**Happens**(e(_E3,_C1Role,_C1,_C2Role, _C2,REQ, logout(_U,_C1,_C2), _C2Role, _C2),t3,$\Re$(t1+1,t2-1))

- Belief graph
  - Nodes represent events in rule attack signatures
  - "Start node": starting point for evidence collection
  - Edges: temporal constraints over events + belief functions

Threat detection: Belief graphs

- Negate the rule

  Rule-5 attack signature:

  ∀ _U: User; _C1: Client; _C2, _C3: NetworkController; t1, t2:Time

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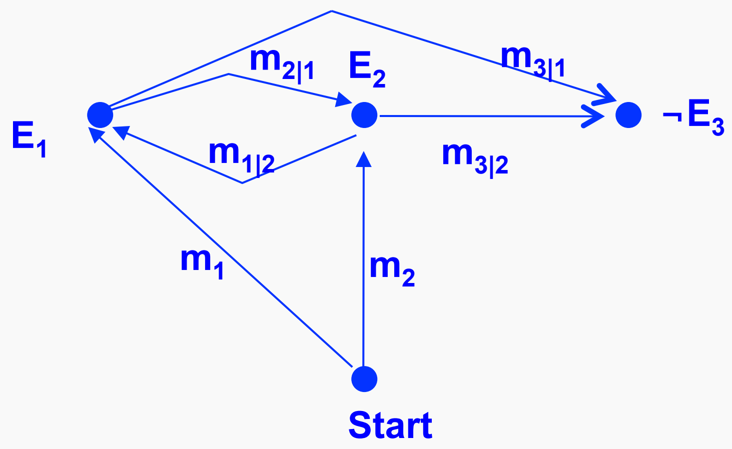
  Happens(e(_E2,_C1Role,_C1,_C3Role,_C3,REQ, login(_U,_C1,_C3),_C3Role, _C3),t2,ℜ(t1,t2)) ∧ _C2 ≠ _C3

  ⇒ ∀t3:Time ¬**Happens**(e(_E3,_C1Role,_C1,_C2Role, _C2,REQ, logout(_U,_C1,_C2), _C2Role, _C2),t3,ℜ(t1+1,t2-1))

- Belief graph
  - Nodes represent events in rule attack signatures
  - "Start node": starting point for evidence collection
  - Edges: temporal constraints over events + belief functions



Threat Detection: Belief functions

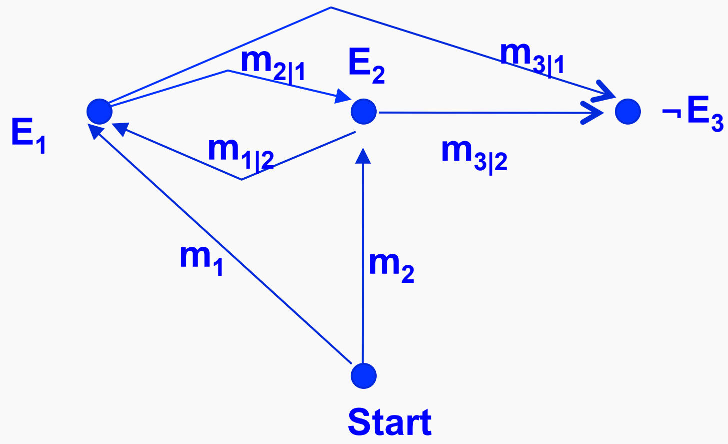
Conditional belief in event occurrences:

$$m_{i|j}(e_i) = \frac{\Sigma_{e \in Elog(Ej)}\, m(e) \times \{\Sigma_{J \subseteq Elog(Ei|e) and\ J \neq \emptyset} (-1)^{|J|+1} \{\Pi_{x \in J}\, m(x)\}}{\Sigma_{e \in Elog(Ej)}\, m(e)}$$

$$m_{i|j}(\neg e_i) = \frac{\Sigma_{ej \in Elog(Ej)}\, m(e) \times \{\Sigma_{ei \in Elog(Ei|ej)}\, m(\neg e_i)\}}{\Sigma_{ej \in Elog(Ej)}\, m(e)}$$

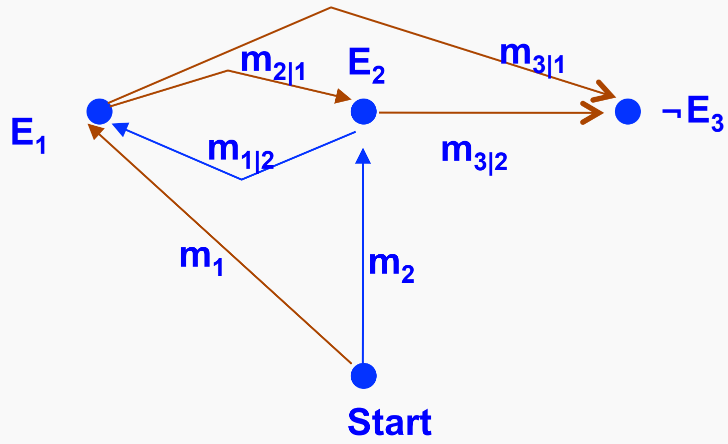
- Elog(E_j): Sample of N (sample size) randomly selected E_j events within the given sampling period
- Elog(E_i|e): set of the events of type E_i in the event log that have occurred within the time period determined by *e* and up to the time point when $m_{i/j}$ is calculated
- m(e)/m(x): basic belief in genuineness of e/x

Threat Detection: Example



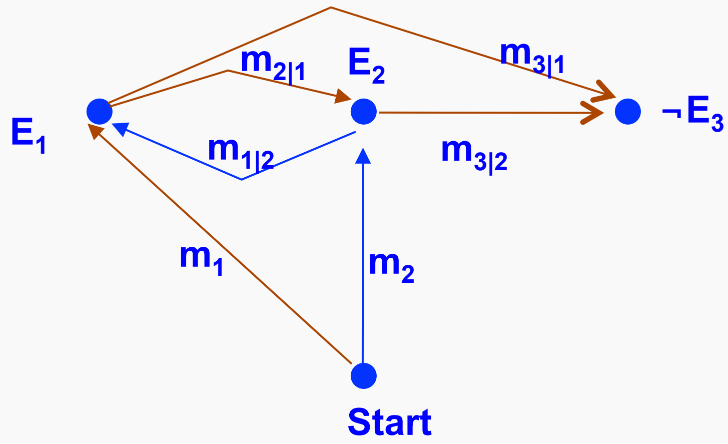
Threat Detection: Example

- login(u1, 101, n1) @ t=10050 occurs



Threat Detection: Example

- login(u1, 101, n1) @ t=10050 occurs



$m_1(E1) = k_1 = 0.8$

$m_1(\neg E1) = k_1' = 0.1$

$m_{2|1}(E2|E1) = k_{21} = 0.6$

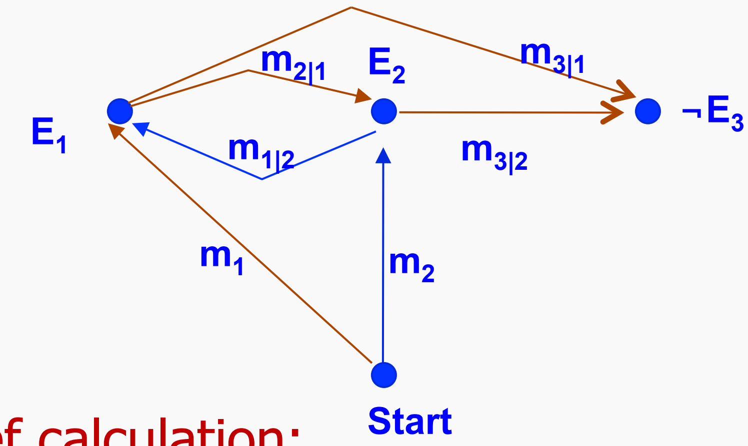
$m_{2|1}(\neg E2|E1) = k_{21}' = 0.4$

$m_{3|1}(E3|E1) = k_{31} = 0.2$

$m_{3|1}(\neg E3|E1) = k_{31}' = 0.6$

Threat Detection: Example

- login(u1, 101, n1) @ t=10050 occurs



$m_1(E1) = k_1 = 0.8$

$m_1(\neg E1) = k_1' = 0.1$

$m_{2|1}\ (E2|E1) = k_{21} = 0.6$

$m_{2|1}\ (\neg\ E2|E1) = k_{21}' = 0.4$

$m_{3|1}\ (E3|E1) = k_{31} = 0.2$

$m_{3|1}\ (\neg\ E3|E1) = k_{31}' = 0.6$

Threat belief calculation:

$$(m_1 \oplus m_{2|1} \oplus m_{3|1}(E_1 \wedge E_2 \wedge \neg E_3)) =$$

$$\frac{k_{31}^{\copyright}k_{21}k_1 + k_{31}^{\copyright}k_1(1-k_{21}-k_{21}^{\copyright}) + k_{31}^{\copyright}k_{21}(1-k_1-k_1^{\copyright})}{1-(k_{31}^{\copyright}k_{21}^{\copyright}(1-k_1^{\copyright})+k_{31}^{\copyright}k_{21}^{\copyright}(1-k_1^{\copyright})} =$$

$$\frac{0.6*0.6*0.8+0.6*0.8*0+0.6*0.6*1}{1*(0.2*0.4*0.9+0.6*0.4*0.9)} = 0.45$$

Threat Detection: Evaluation

Evaluated properties

- Threat reaction time: TRT = $T_{mon} - T_{TDT}$
- Precision: $PR = TTS_{BR} / (TTS_{BR} + FTS_{BR})$
  - TTS_{BR} : number of threat signals with a belief in a given range (BR) that ended up to eventual violations of the relevant rule detected by the EVEREST monitor (true signals)
  - FTS_{BR}: number of the threat signals with belief in a given range (BR) that did not correspond to an eventual violation of the relevant rule
- Analysis of effect of
  - Diagnosis window (DW)
  - Sample size (SS)

Set up

  - Simulation of workflow of LBACS system
  - 8 sets of 2,000 events (different variances in inter-event arrival times)

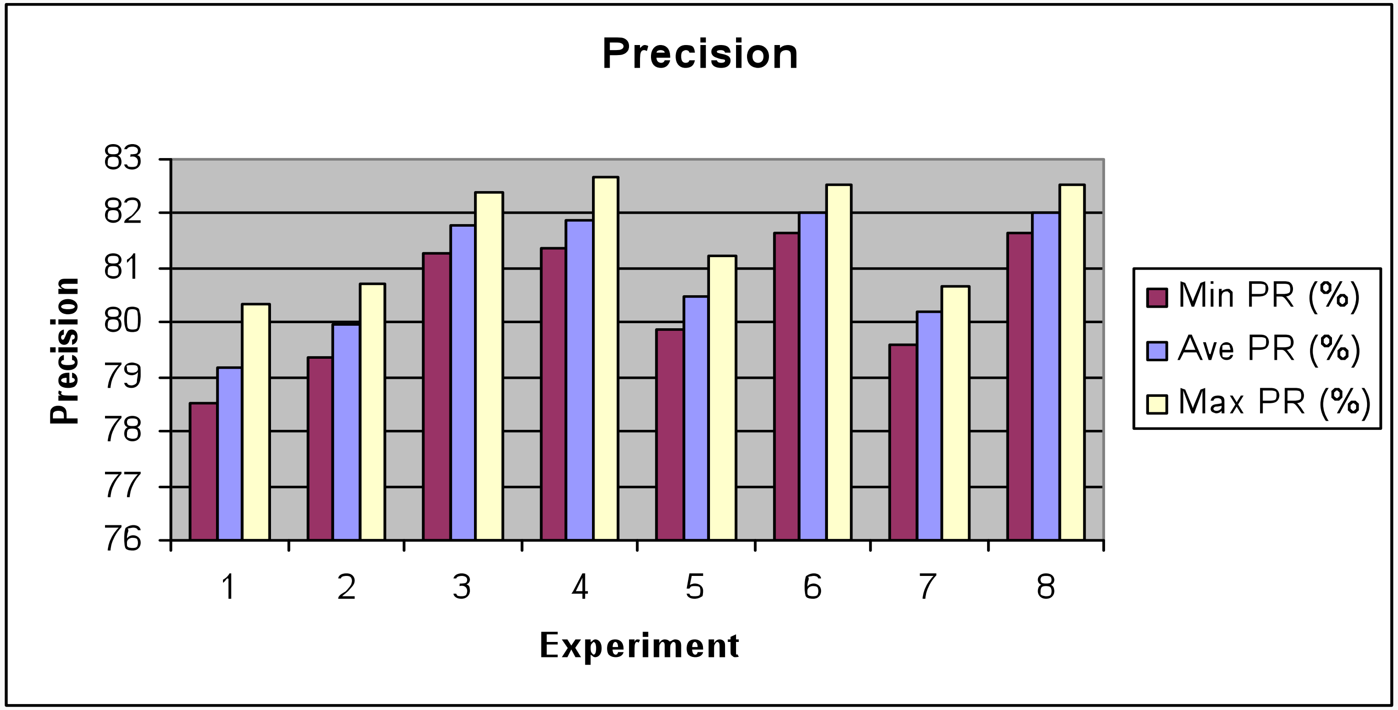
Threat Detection: TRT

EXP	VV	DW	SS	pos %	neg %	ave TRT	max TRT	min TRT
1	0.3	15000	10	77.54	21.51	9.3	852.5	-4.2
2	0.3	20000	15	73.21	26.53	10.4	753.9	-4.5
3	0.5	15000	10	80.18	19.02	12.5	1137	-1.9
4	0.5	20000	15	72.08	27.39	13.2	1111	-3
5	0.6	15000	10	79.45	20.03	12.3	1077	-2.3
6	0.6	20000	15	74.87	24.74	14	1077	-29
7	0.9	15000	10	80.24	18.85	13.6	1077	-3
8	0.9	20000	15	74.87	24.74	14.1	1077	-29

TRT (secs)

- Average threat reaction time: 9.3 to 14.1 seconds
- Sufficient time for taking some types of pre-emptive action (e.g. deactivation of system components)

Threat detection: precision



- Varied from 78% to 83%
- Diagnosis window (DW) and sample size (SS) increments caused marginal increase in it (≤ 1.8 %) – see Exp1/Exp2, Exp3/Exp4, Exp5/Exp6, Exp7/Exp8 (caused maximum increase)

Part V:
Reaction

Reaction to monitoring results

- In some cases, following the detection of a problem whilst monitoring an S&D solution it might be possible to take some action that
  - Rectifies the problem, and/or
  - Prevents further harm
- Examples: In LBACS:
  - If the location server becomes unavailable, it might be necessary to deactivate the operation of the system unless the problem is repaired (action 1)
  - If more than X location sensors become unavailable the system may switch to WiFi only access control solution and access to certain resources may be deactivated (action 2)
- Some actions are possible to automate …

Our approach in SERENITY

- Reactions are realised by actions taken at runtime by the SERENITY Runtime Framework following the receipt of monitoring results from EVEREST

- Specification of actions:

  Rule specification = EC formula + [($action_1$, cnd_1), …, ($action_N$, cnd_N)]

- Semantics:
  - Each of the actions ($action_i$) is executed only if the condition associated with it is also satisfied (cnd_i)
  - The actions are executed in the exact order that they appear in the rule specification

- The SRF supports only predefined types of actions
- Complex conditions may be associated with actions

Predefined action types

- Action types
  - `DeactivatePattern()`
  - `RestartPattern()`
  - `NotifySRF(String external_SRF_ID, String Message)`
  - `NotifyApplication(String message)`
  - `StopMonitoringRules(String ruleID1, String ruleID2,… String ruleIDn)`
  - `StartMonitoringRules(String ruleID1, String ruleID2,… String ruleIDn)`
  - `Log()`

Monitoring results

- **Basic monitoring**

  Rule: $E_1, E_2, E_3, \ldots, E_n \Rightarrow E_{n+1}$

  - detect whether $E_1, E_2, E_3, \ldots, E_n, \neg E_{n+1}$ has happened
  - **RESULTS:** Instances of the events $E_1, E_2, E_3, \ldots, E_n, \neg E_{n+1}$ that have caused the violation are returned by EVEREST

- **Monitoring with enabled diagnosis**

  Rule: $E_1, E_2, E_3, \ldots, E_n \Rightarrow E_{n+1}$

  - detect whether $E_1, E_2, E_3, \ldots, E_n, \neg E_{n+1}$ are genuine
  - **RESULTS:** As in core monitoring + a belief range $[Bel(E_i), 1\text{-}Bel(\neg E_i)]$ indicating the belief in the genuineness of each of the events E_i

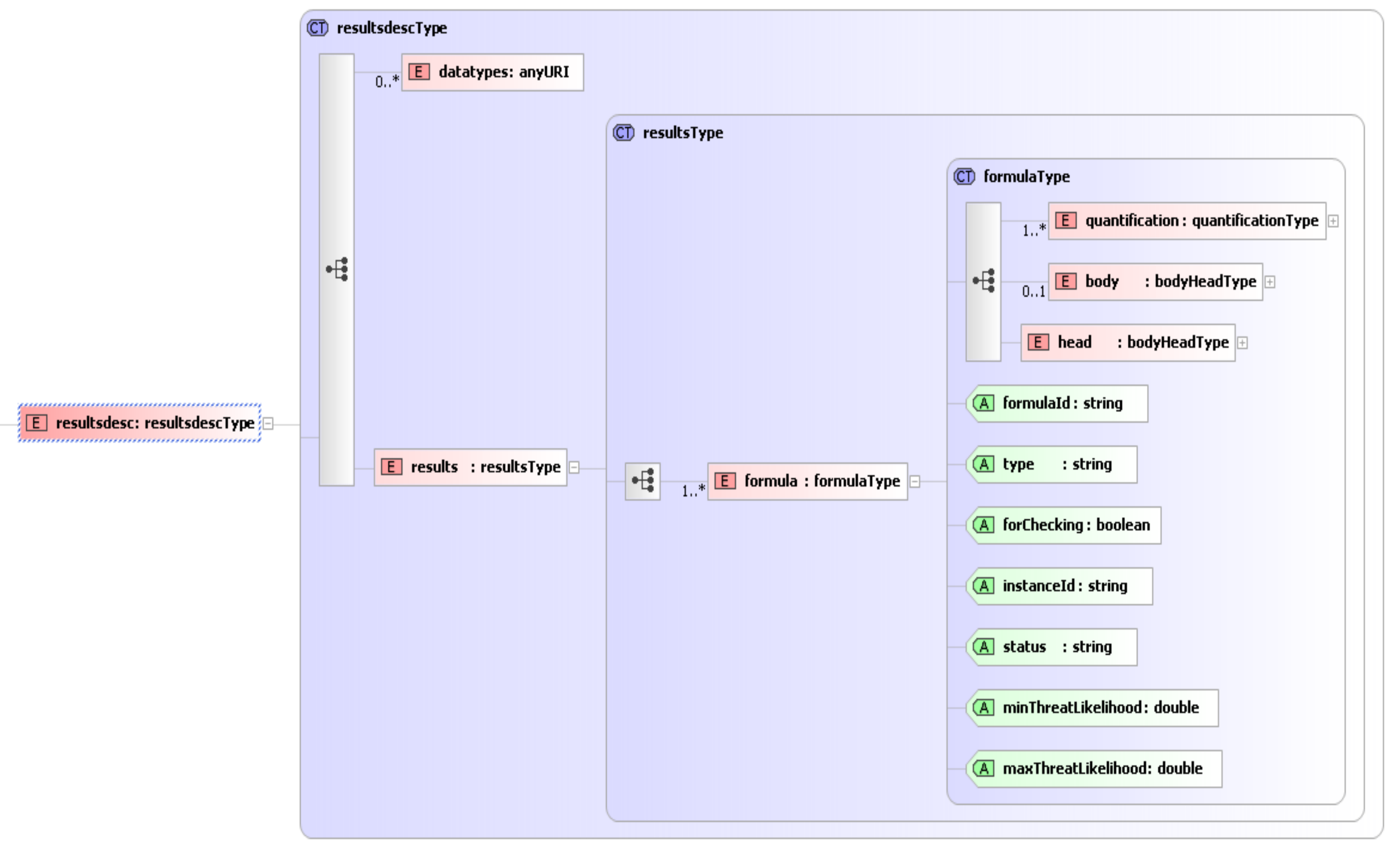
- **Treat detection**

  Rule: $E_1, E_2, E_3, \ldots, E_n \Rightarrow E_{n+1}$

  - Given a subset of seen events $OE \subset \{E_1, E_2, E_3, \ldots, E_n\}$ calculate the probability that $\{E_1, E_2, E_3, \ldots, E_n\} - OE \cup \{\neg E_{n+1}\}$ will occur
  - **RESULTS:** instances of the seen set of events OE, belief ranges for their genuineness + a belief range for a potential violation of the rule

Monitoring results

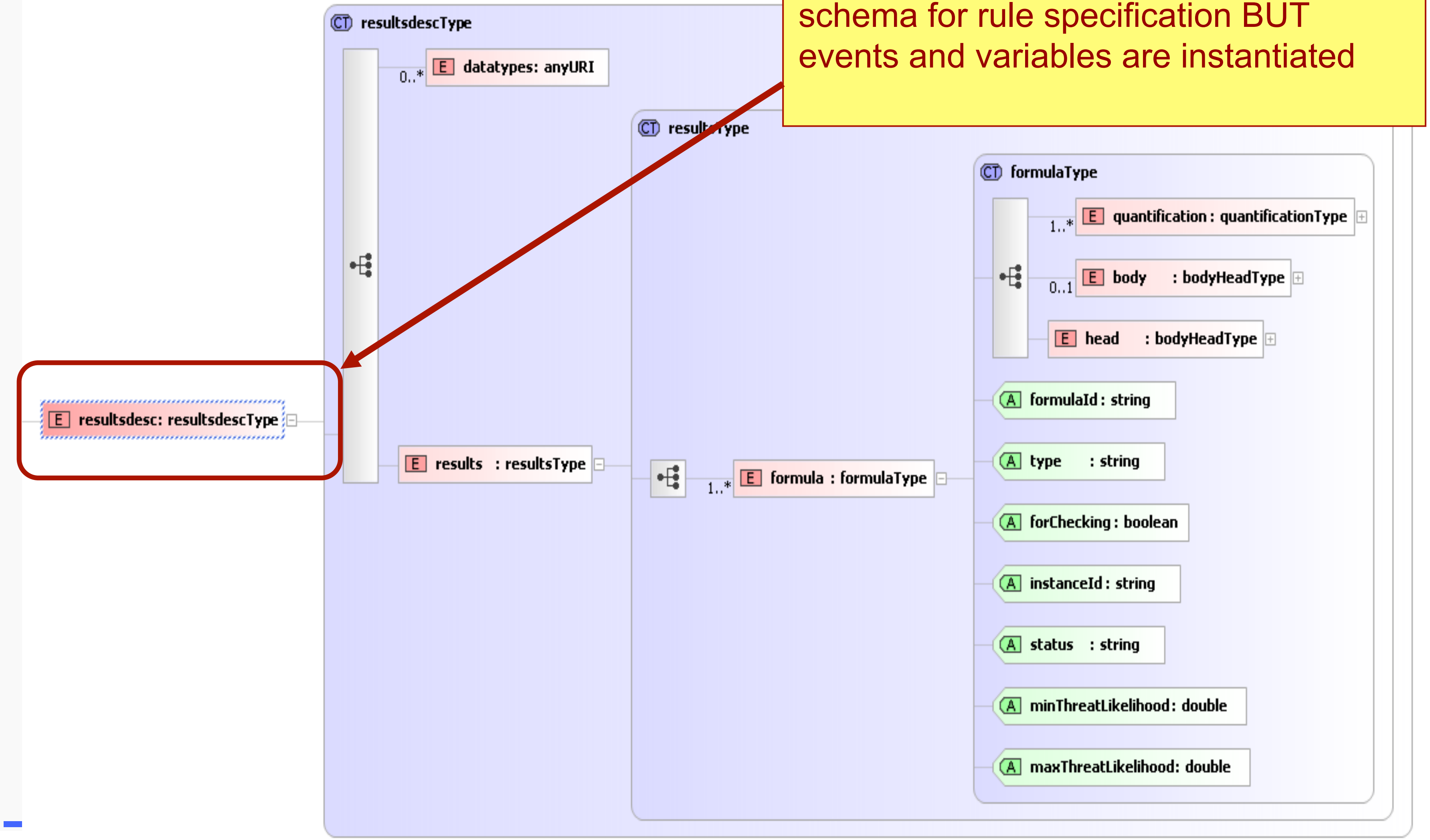
- Reported to SRF in XML



Monitoring results

- Reported to SRF in XML

The basic schema is the same as the schema for rule specification BUT events and variables are instantiated



Monitoring results

- Reported to SRF in XML

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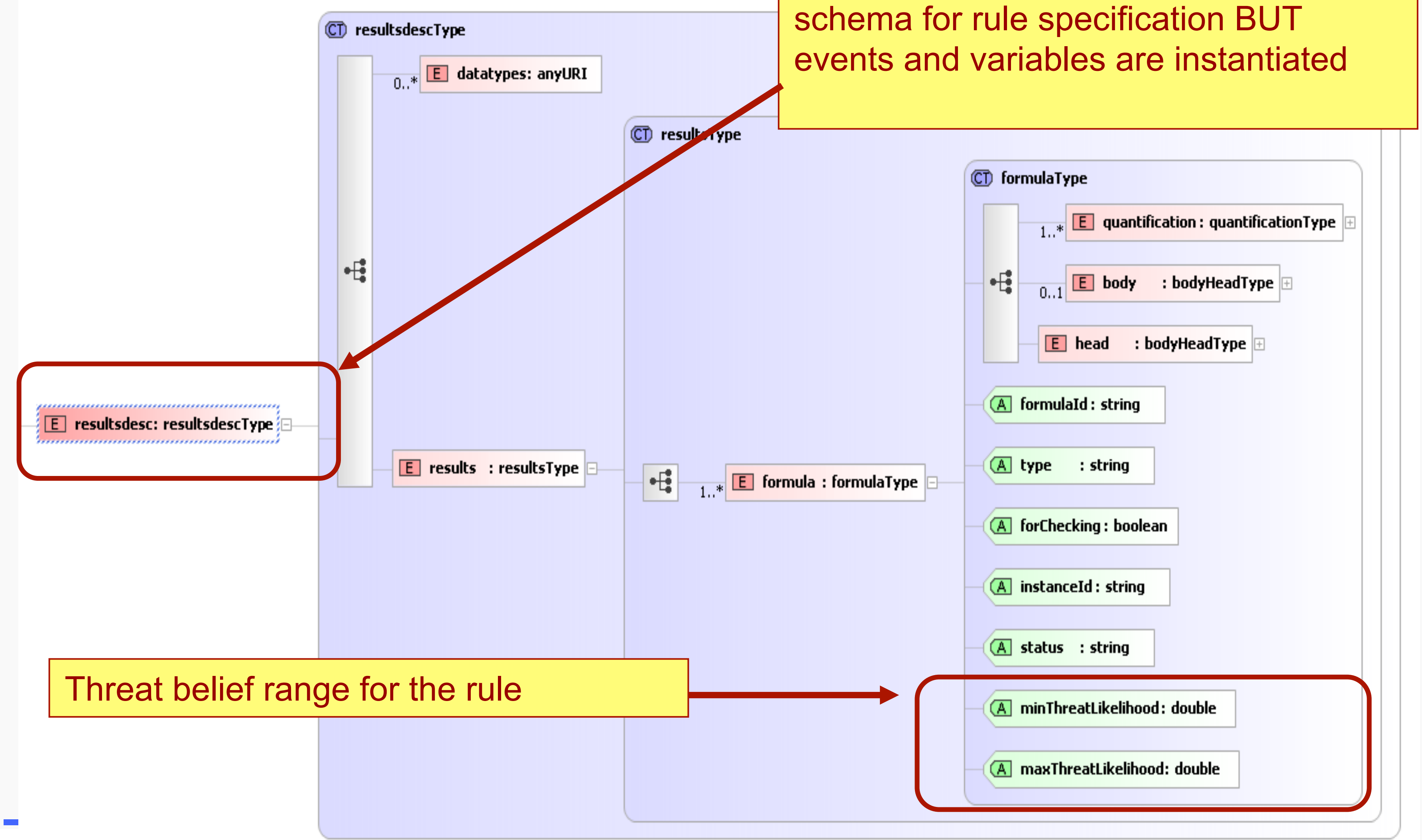
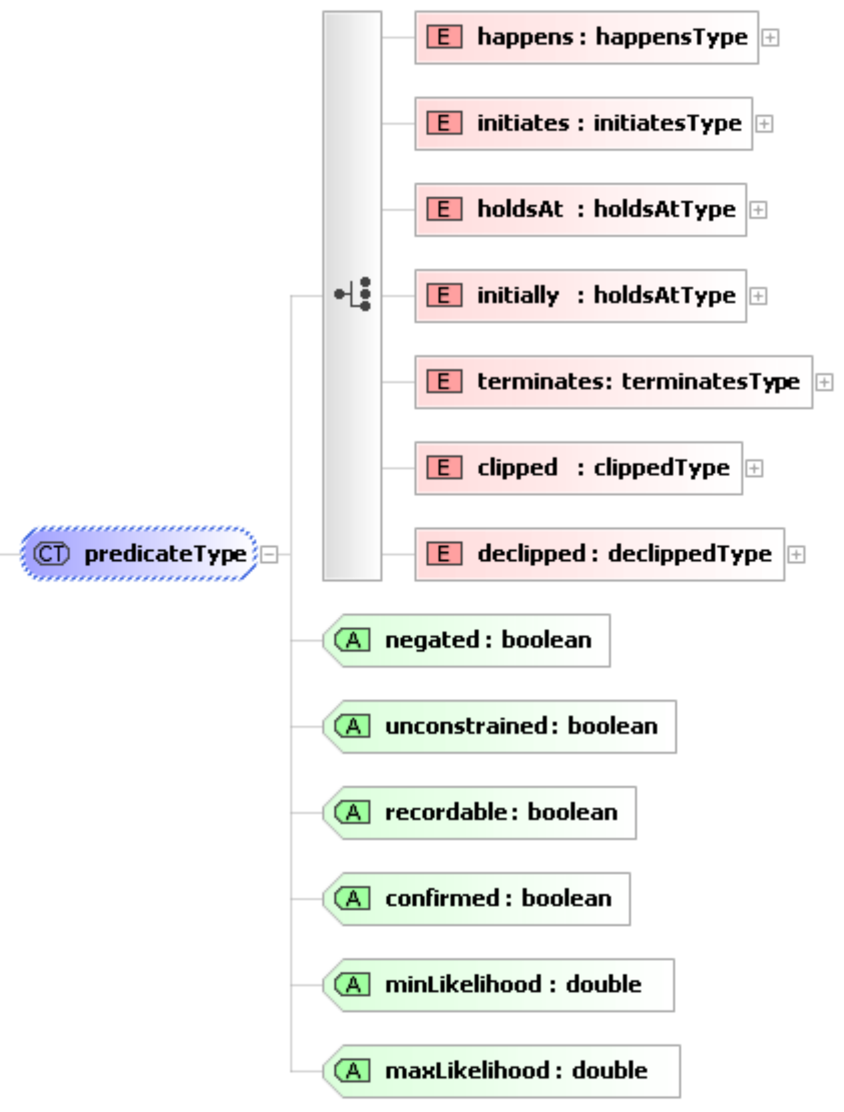


Threat belief range for the rule

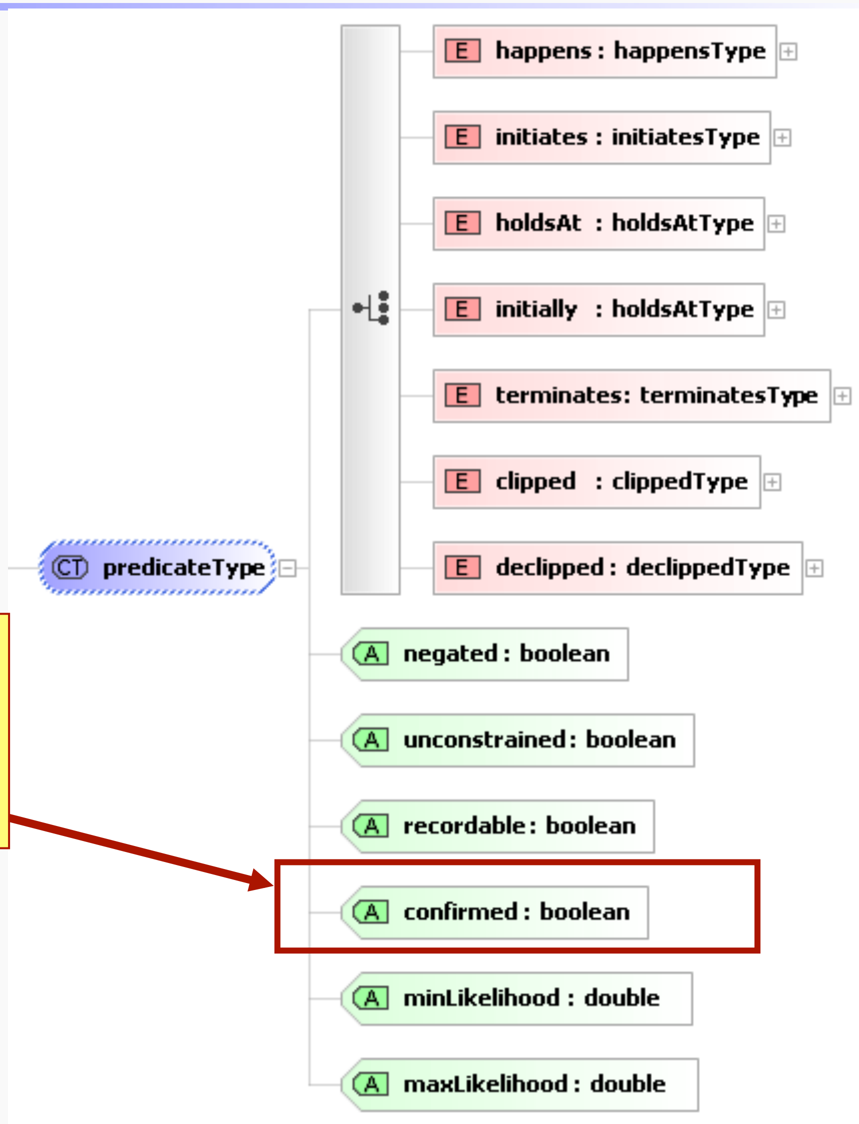
Monitoring results

- **At the level of individual conditions**



Monitoring results

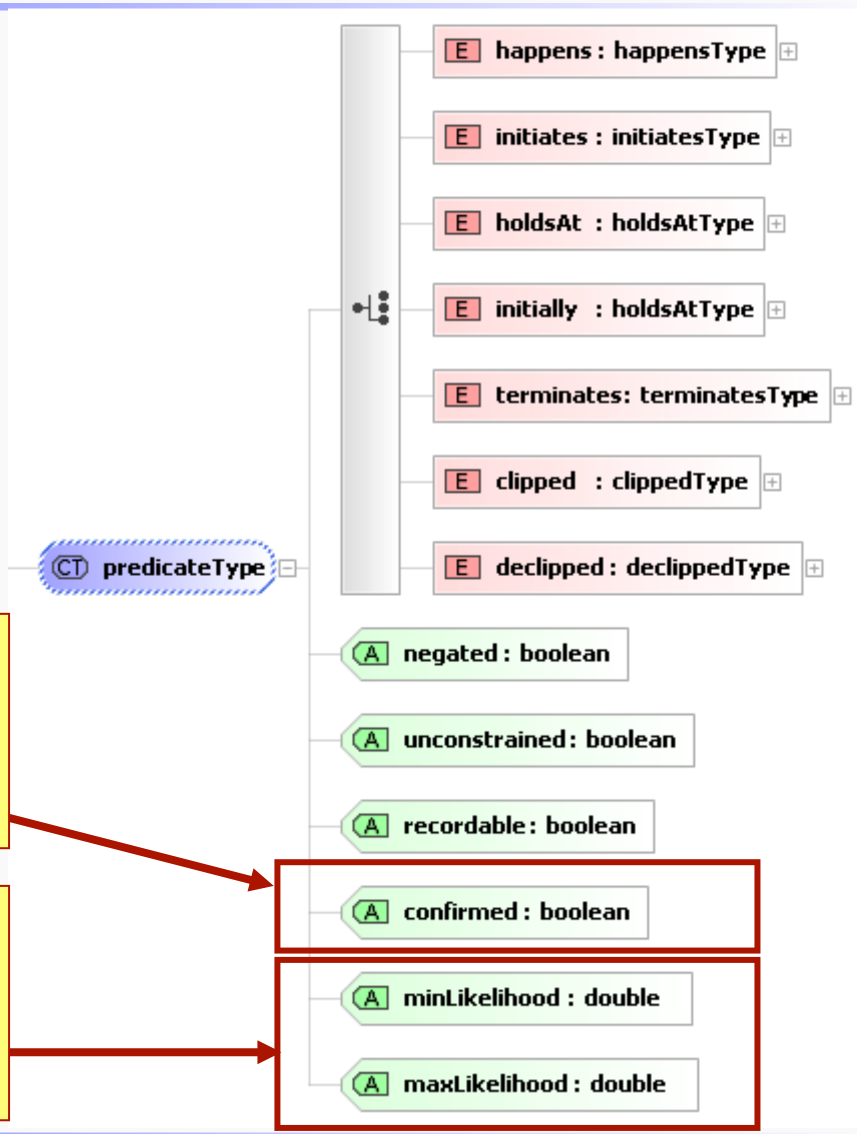
- **At the level of individual conditions**



Attribute indicating whether the event unified with the predicate is genuine; used only in diagnosis results

Monitoring results

- **At the level of individual conditions**

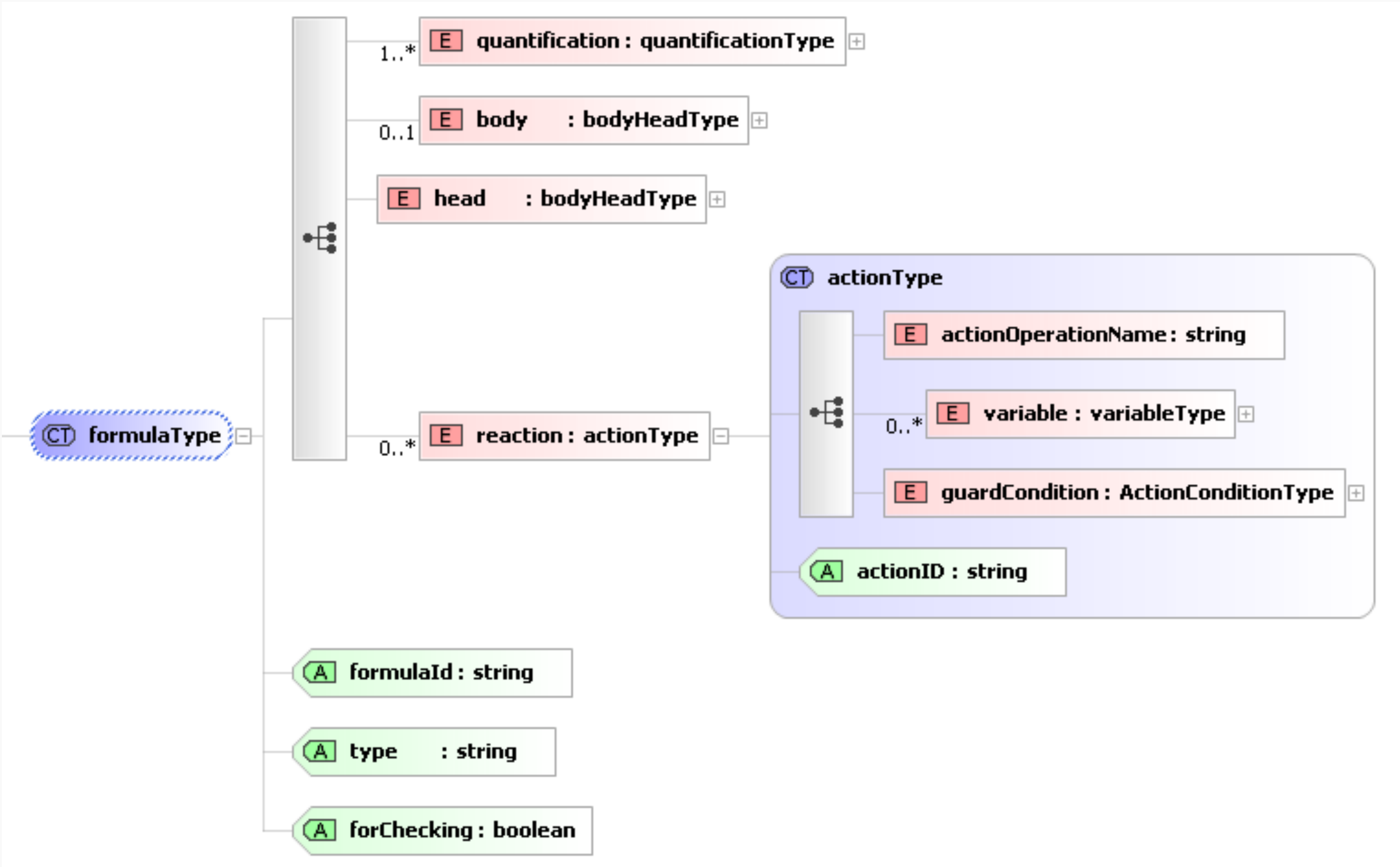


Attribute indicating whether the event unified with the predicate is genuine; used only in diagnosis results

Attributes representing the predicate belief range; used both for diagnosis and threat detection results

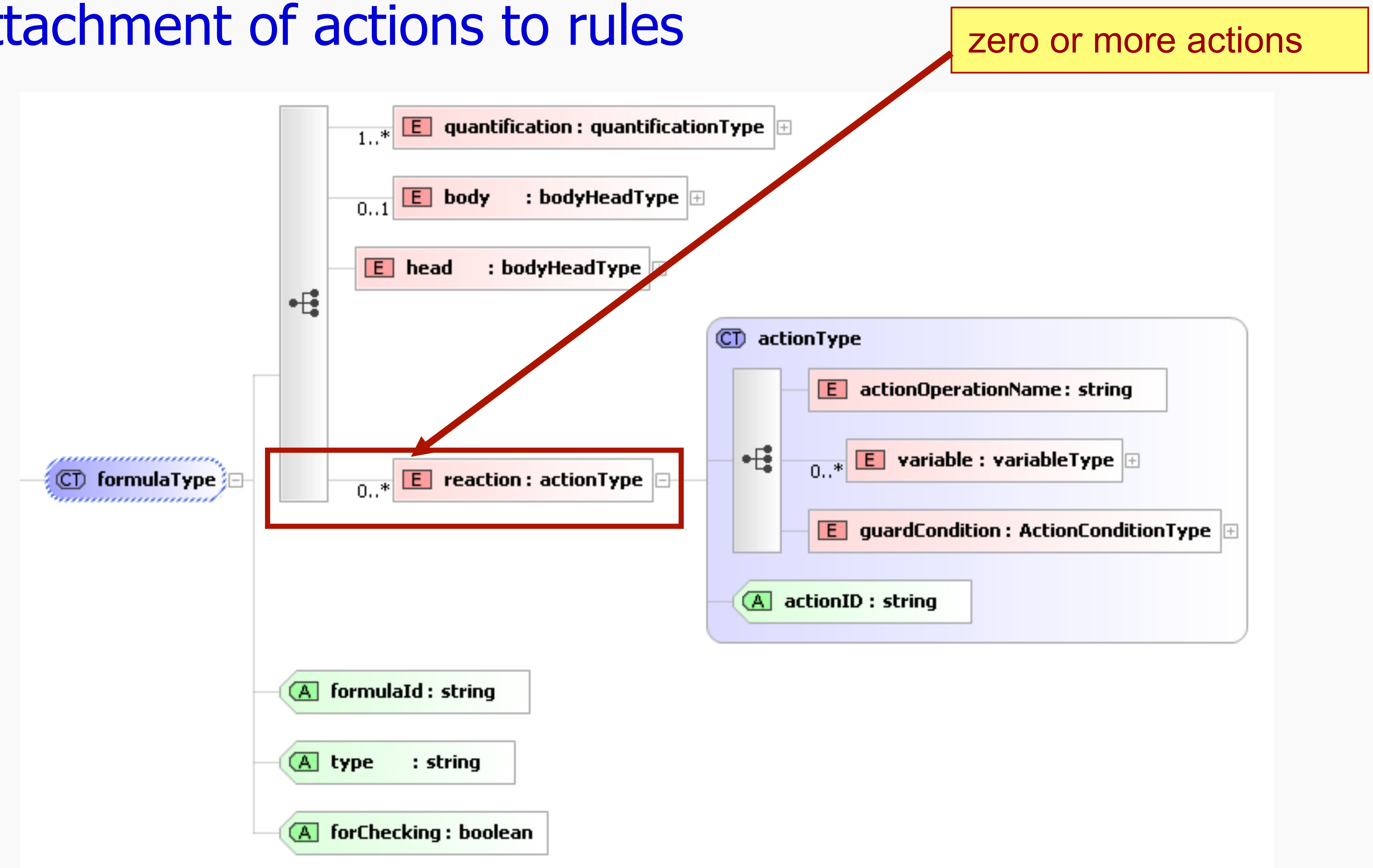
Action specification schema

- Attachment of actions to rules



Action specification schema

- Attachment of actions to rules

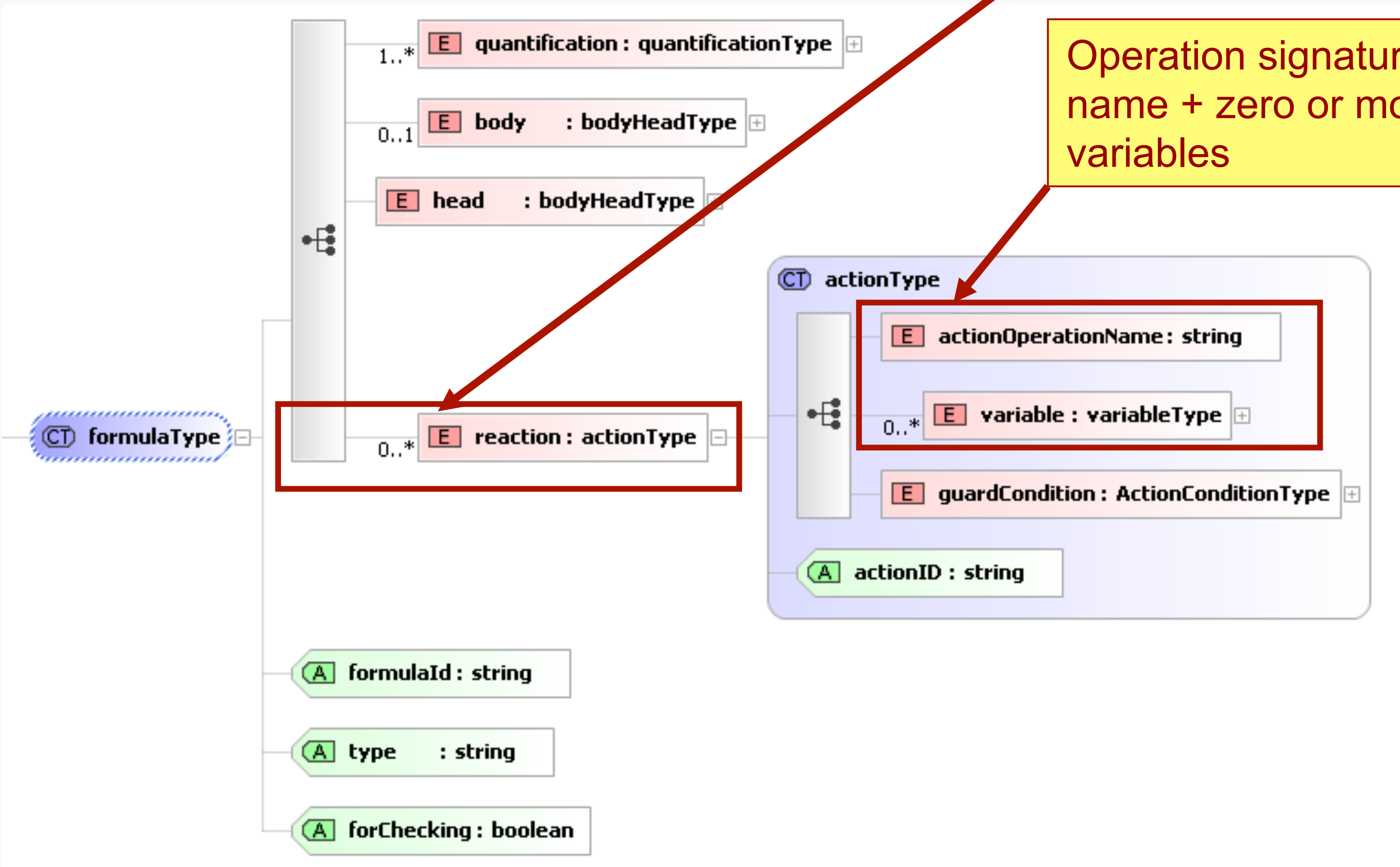


Action specification schema

- Attachment of actions to rules

zero or more actions

Operation signature: name + zero or more variables



Action specification schema

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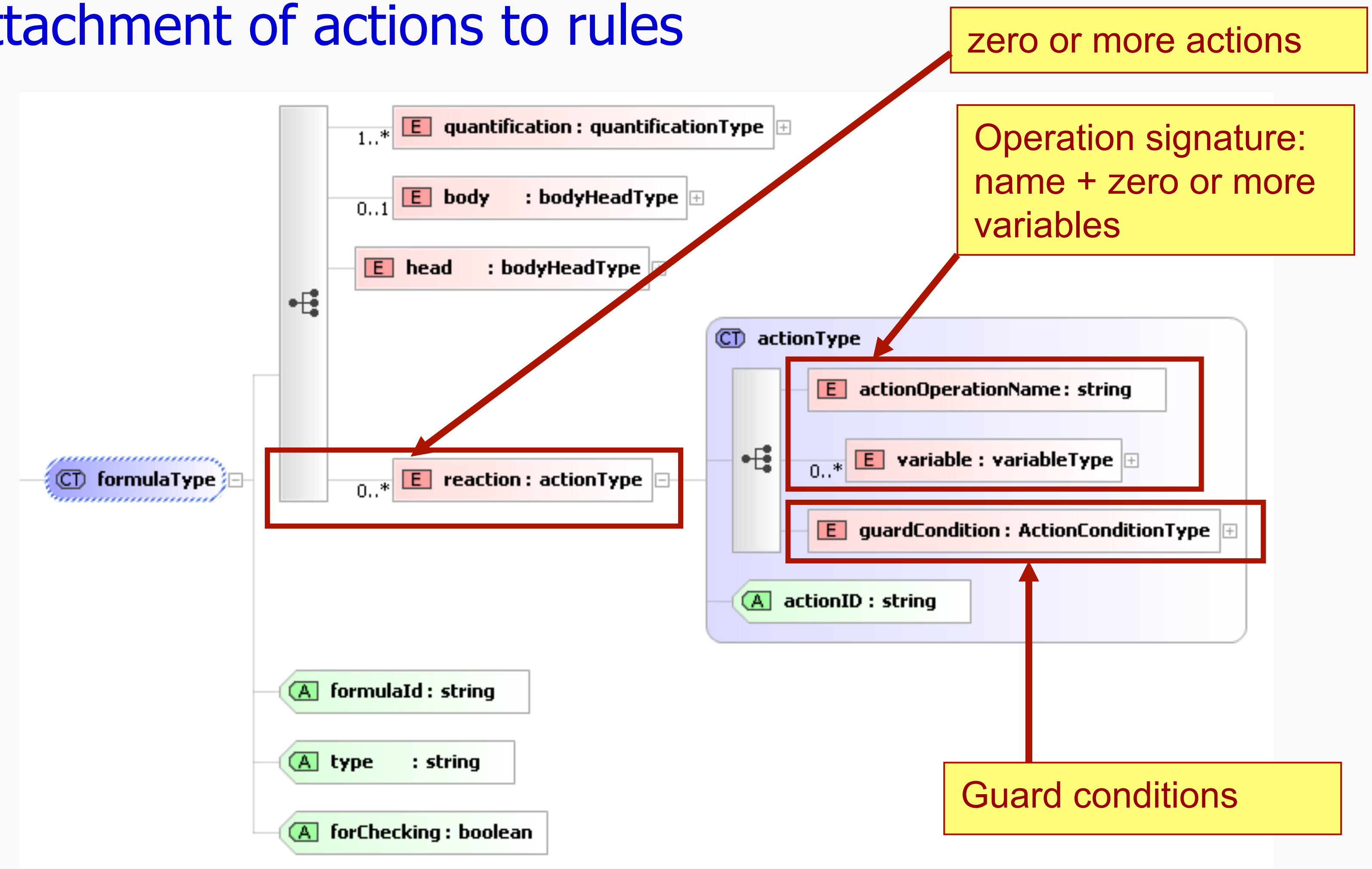
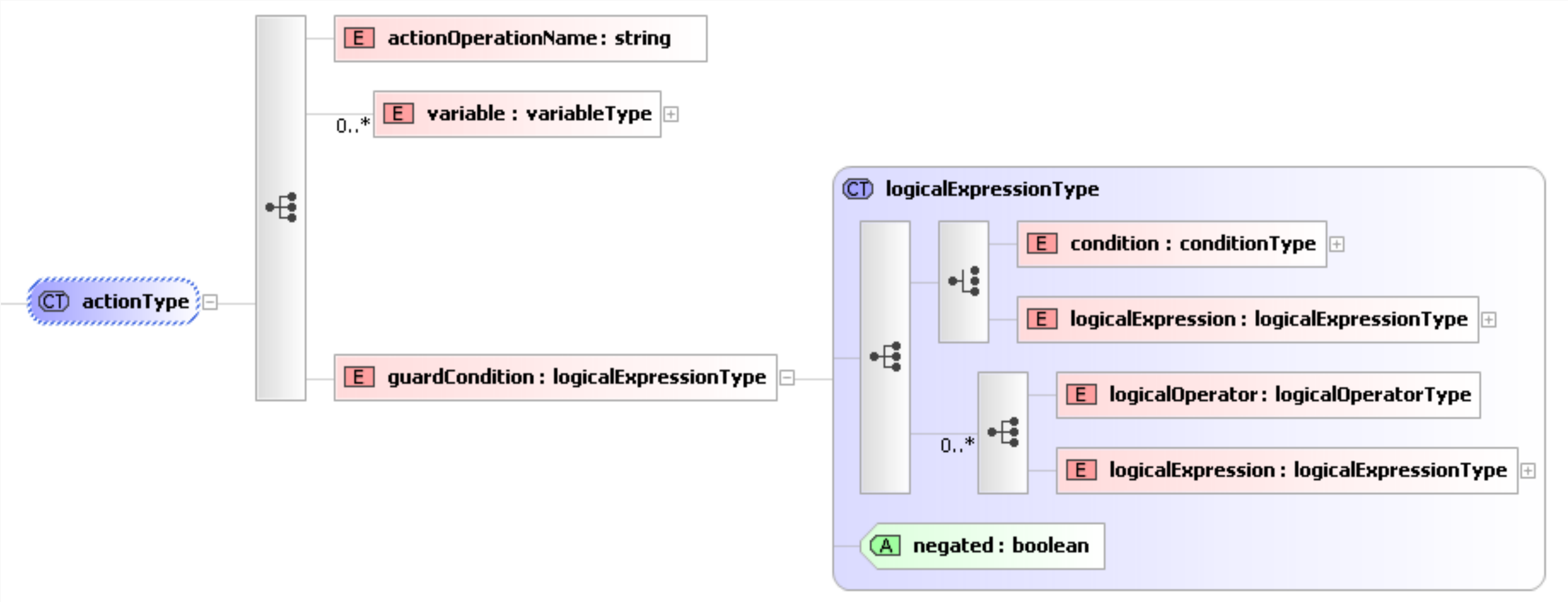


Action specification schema

- Specification of guard conditions for actions



Action specification schema

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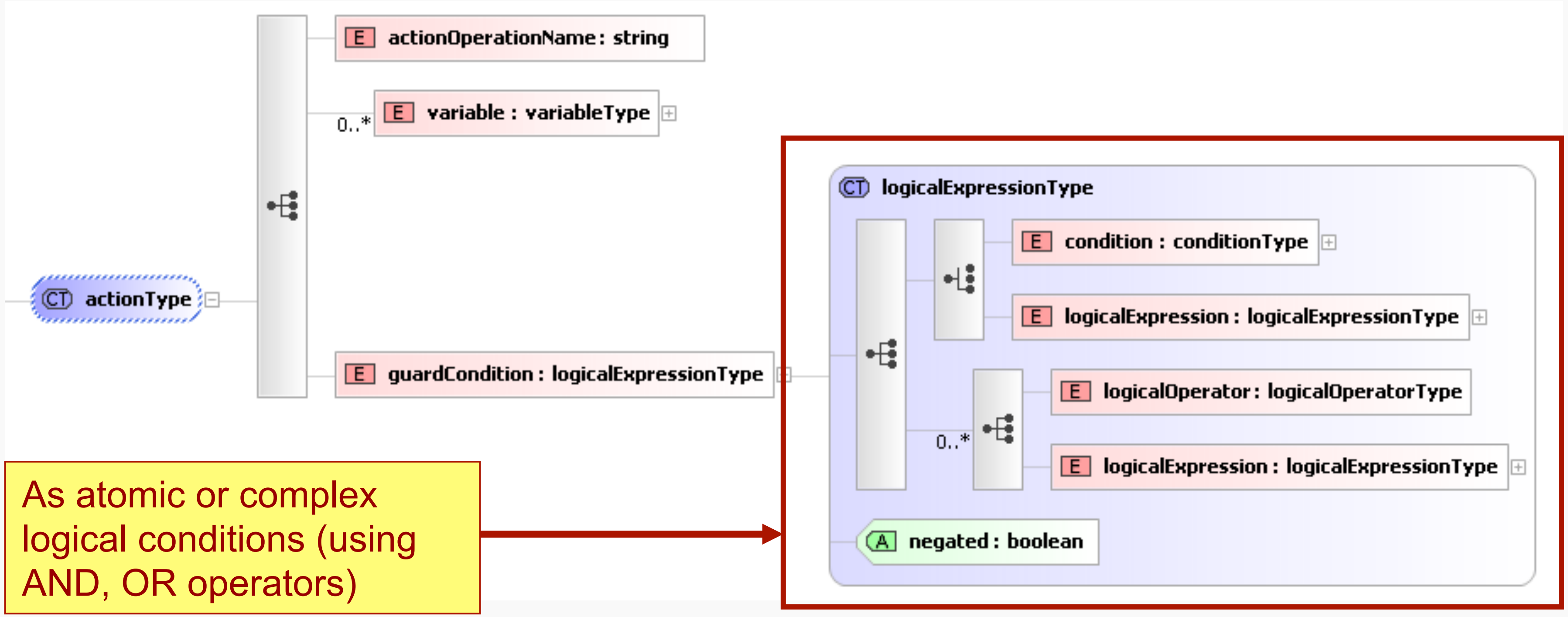
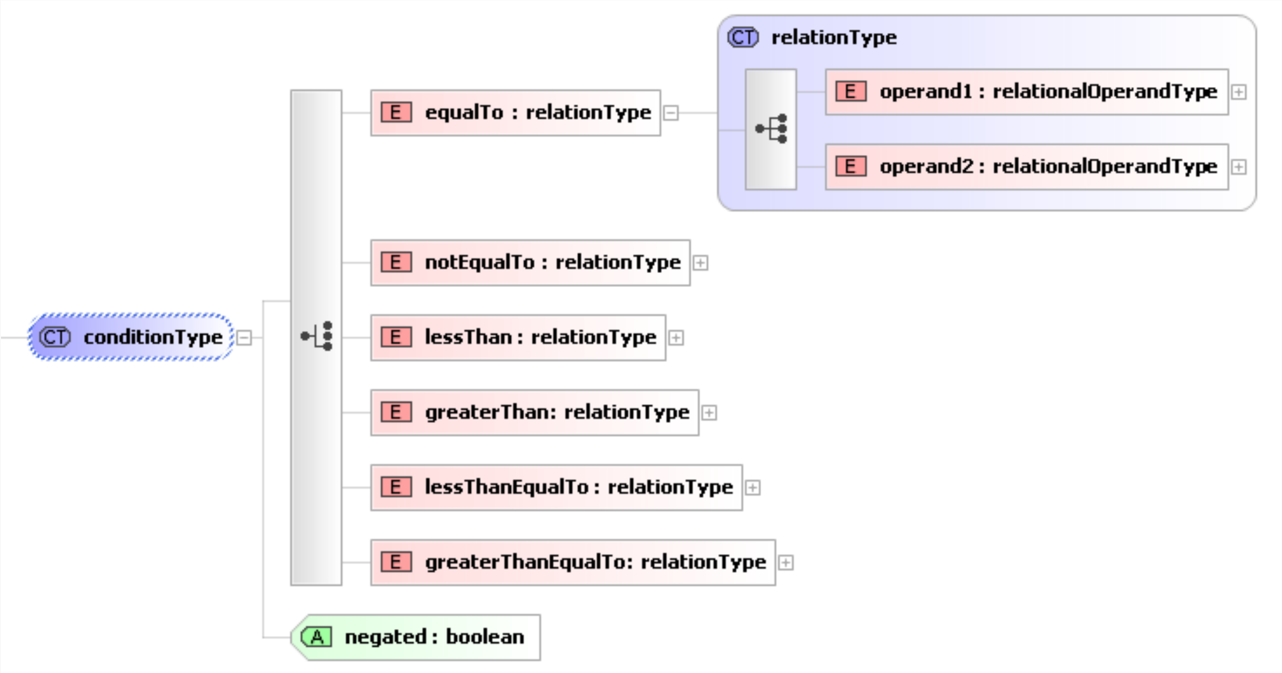


As atomic or complex logical conditions (using AND, OR operators)

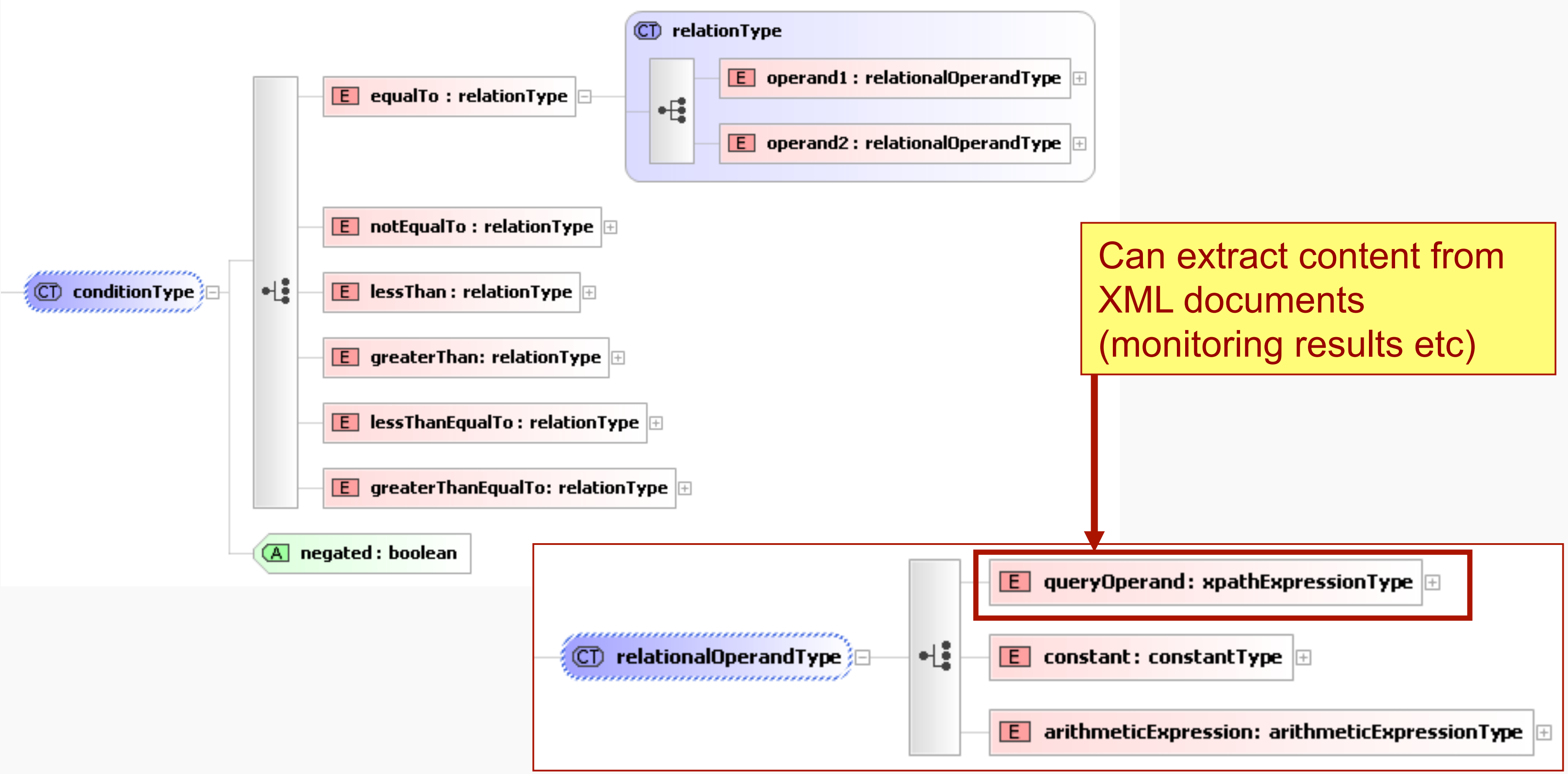
Action specification schema

- Specification of guard conditions for actions



Action specification schema

- Specification of guard conditions for actions



Actions: example 1

Rule-5: $\forall$ _U: User; _C1: Client; _C2, _C3: NetworkController; t1, t2:Time
Happens(e(_E1, _C1R, _C1, _C2R, _C2,REQ, login(_U,_C1), _C2R, _C2), t1,$\Re$(t1,t1)) $\wedge$
Happens(e(_E2, _C1R , _C1, _C3R, _C3,REQ, login(_U,_C1),_C3R, _C3), t2,$\Re$(t1,t2)) $\wedge$ _C2 $\neq$_C3
$\Rightarrow$ $\exists$ t3: Time **Happens**(e(_E3,_C1,_C2,REQ, logout(_U,_C1), _C2),t3,$\Re$(t1+1,t2−1))

Actions: example 1

Rule-5: $\forall$ _U: User; _C1: Client; _C2, _C3: NetworkController; t1, t2:Time
Happens(e(_E1, _C1R, _C1, _C2R, _C2,REQ, login(_U,_C1), _C2R, _C2), t1,$\Re$(t1,t1)) $\wedge$
Happens(e(_E2, _C1R , _C1, _C3R, _C3,REQ, login(_U,_C1),_C3R, _C3), t2,$\Re$(t1,t2)) $\wedge$ _C2 $\neq$ _C3
$\Rightarrow$ $\exists$ t3: Time **Happens**(e(_E3,_C1,_C2,REQ, logout(_U,_C1), _C2),t3,$\Re$(t1+1,t2−1))

```
<action>
   <actionOperationName>NotifyApplication</actionOperationName>
   <variable persistent="0" forMatching="false“>
            <varName>userId</varName><varType>string</varType>
            <value>/resultsdesc/results/formula/body/predicate[0]/happens/ic_term/variable[0]
            /varName[text()=“_U"]/value</value>
   </variable>
  <guardCondition negated="false">
  <condition negated="false">
     <equalTo>
            <operand1><queryOperand>
            <document><name>R5_Result</name><type>MonitoringResults</type></document>
            <xpath>/resultsdesc/results/formula[@status] </xpath>
            </queryOperand></operand1>
            <operand2><constant><type>STRING</type>
                        <value>Inconsistency_WRT_Recorded_Behaviour</value></constant>
            </operand2>
     </equalTo>
  </condition>
 </guardCondition>
</action>
```

Action taken if *Rule-5* is violated

Actions: example 2

Rule-5: ∀ _U: User; _C1: Client; _C2, _C3: NetworkController; t1, t2:Time
Happens(e(_E1, _C1R, _C1, _C2R, _C2,REQ, login(_U,_C1), _C2R, _C2), t1,$\Re$(t1,t1)) ∧
Happens(e(_E2, _C1R , _C1, _C3R, _C3,REQ, login(_U,_C1),_C3R, _C3), t2,$\Re$(t1,t2)) ∧ _C2 ≠ _C3
⇒ ∃ t3: Time **Happens**(e(_E3,_C1,_C2,REQ, logout(_U,_C1), _C2),t3,$\Re$(t1+1,t2−1))

Actions: example 2

Rule-5: ∀ _U: User; _C1: Client; _C2, _C3: NetworkController; t1, t2:Time
Happens(e(_E1, _C1R, _C1, _C2R, _C2,REQ, login(_U,_C1), _C2R, _C2), t1,ℜ(t1,t1)) ∧
Happens(e(_E2, _C1R , _C1, _C3R, _C3,REQ, login(_U,_C1),_C3R, _C3), t2,ℜ(t1,t2)) ∧ _C2 ≠_C3
⇒ ∃ t3: Time **Happens**(e(_E3,_C1,_C2,REQ, logout(_U,_C1), _C2),t3,ℜ(t1+1,t2−1))

```
<action>
   <actionOperationName>NotifySRF</actionOperationName>
   <variable persistent="0" forMatching="false“>
         <varName>instanceId</varName><varType>string</varType>
         <value>/resultsdesc/results/formula [@instanceId]</value>
   </variable>
  <guardCondition negated="false">
  <condition negated="false">
     <greaterThan>
         <operand1><queryOperand>
         <document><name>R5_Result</name><type>MonitoringResults</type></document>
         <xpath>/resultsdesc/results/formula[@minThreatLikelihood]</xpath>
         </queryOperand></operand1>
         <operand2><constant><type>DOUBLE</type> <value>0.6</value></constant>
         </operand2>
     </greaterThan>
  </condition>
 </guardCondition>
</action>
```

Action taken if the overall threat likelihood of *Rule-5* exceeds 0.6

Actions: example 3

Rule-5: $\forall$ _U: User; _C1: Client; _C2, _C3: NetworkController; t1, t2:Time
Happens(e(_E1, _C1R, _C1, _C2R, _C2,REQ, login(_U,_C1), _C2R, _C2), t1,$\Re$(t1,t1)) $\wedge$
Happens(e(_E2, _C1R , _C1, _C3R, _C3,REQ, login(_U,_C1),_C3R, _C3), t2,$\Re$(t1,t2)) $\wedge$ _C2 $\neq$_C3
$\Rightarrow$ $\exists$ t3: Time **Happens**(e(_E3,_C1,_C2,REQ, logout(_U,_C1), _C2),t3,$\Re$(t1+1,t2−1))

Actions: example 3

Rule-5: $\forall$ _U: User; _C1: Client; _C2, _C3: NetworkController; t1, t2:Time
Happens(e(_E1, _C1R, _C1, _C2R, _C2,REQ, login(_U,_C1), _C2R, _C2), t1,$\Re$(t1,t1)) $\wedge$
Happens(e(_E2, _C1R , _C1, _C3R, _C3,REQ, login(_U,_C1),_C3R, _C3), t2,$\Re$(t1,t2)) $\wedge$ _C2 $\neq$ _C3
$\Rightarrow$ $\exists$ t3: Time **Happens**(e(_E3,_C1,_C2,REQ, logout(_U,_C1), _C2),t3,$\Re$(t1+1,t2−1))

```
<action>
   <actionOperationName>NotifyApplication</actionOperationName>
   <variable persistent="0" forMatching="false“>
               <varName>networkControllerId</varName><varType>string</varType>
               <value>/resultsdesc/results/formula/body/predicate[1]/happens/ic_term/
                        variable[2]/varName[text()=“_C1"]/value</value>
   </variable>
  <guardCondition negated="false">
  <condition negated="false">
     <greaterThan>
               <operand1><queryOperand>
               <document><name>R5_Result</name><type>MonitoringResults</type></document>
               <xpath>/resultsdesc/results/formula/body/predicate[2][@minLikelihood]</xpath>
               </queryOperand></operand1>
               <operand2><constant><type>DOUBLE</type> <value>0.6</value></constant>
               </operand2>
     </greaterThan>
  </condition>
 </guardCondition>
</action>
```

Action taken if the belief in the genuineness of second login is less than 0.4

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Conclusions

- SERENITY provides an infrastructure for selecting and deploying S&D solutions at runtime based on S&D patterns
- It also provides a monitoring framework for runtime checks of conditions related to the correct operation of S&D patterns
- These conditions are specified as monitoring rules in Event Calculus
- Monitoring rules are specified as part of S&D patterns and need to be accompanied by the actions that should be taken when they are violated
- The monitoring infrastructure provides
  - basic monitoring and diagnosis capabilities
  - threat detection capabilities (i.e., detection of potential violations of monitoring rules)

Ongoing work

- Extension of predictive capabilities of EVEREST to support forecasting of violations of aggregate properties (e.g., MTTF, MTTR)
- Extension of EVEREST to support protocols for reliable messaging (WS-ReliableMessaging) and message authentication (WS-Security)
- Support for evolution of S&D solutions both at the pattern and the implementation level

Main resources

- SERENITY Book

  Spanoudakis G., Mana A., Kokolakis S.: Security and dependability for Ambient Intelligence, Advances in Information Security Book Series, Springer, ISBN-978-0-387-88775-3, 2009

- SERENITY Forum

  www.serenity-forum.org

  Includes technical reports, papers, examples of S&D patterns, tutorials e.t.c

Thank you

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