Software Verification and Validation (VIMMD052)

Verification of the Architecture Design

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Overview

- Motivation
  - Architecture design and languages
  - What is determined by the architecture?
  - What kind of verification methods can be used?
- Requirements based architecture analysis
  - ATAM: Architecture Trade-off Analysis
- Systematic analysis methods
  - Interface analysis
  - Fault effects analysis
- Model based quantitative evaluation
  - Performance evaluation
  - Dependability evaluation

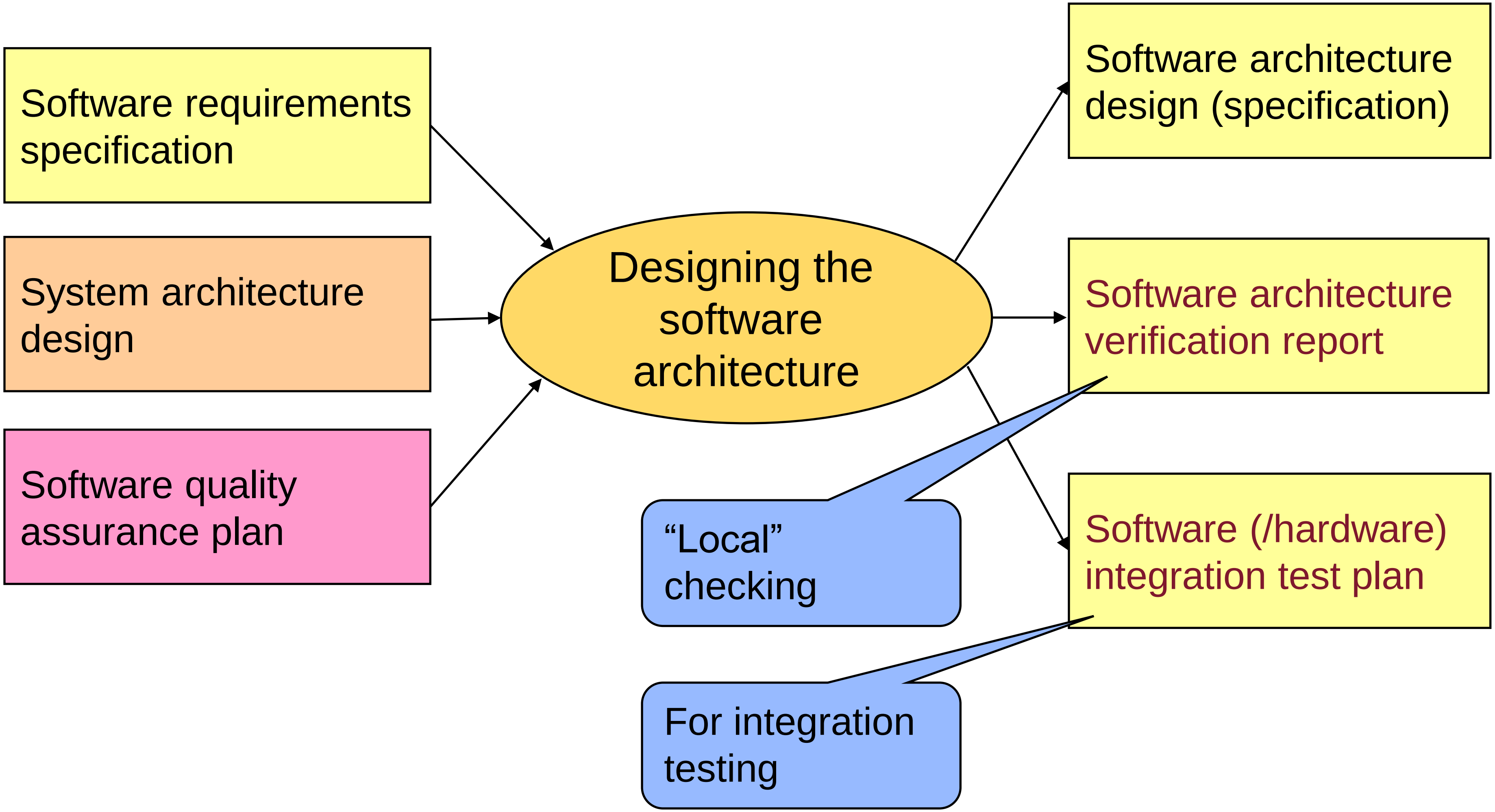
Motivation

Architecture design and languages

What is determined by the architecture?

What kind of verification methods can be used?

Inputs and outputs of the phase



Software requirements specification

System architecture design

Software quality assurance plan

Designing the software architecture

Software architecture design (specification)

Software architecture verification report

Software (/hardware) integration test plan

“Local” checking

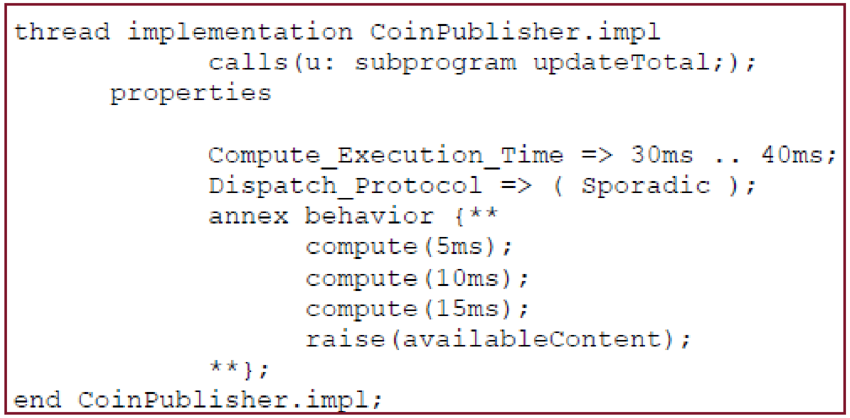
For integration testing

Architecture design

- What is the architecture?
  - Components (with properties)
  - Relations among them (use of service, deployment, …)
- Design decisions
  - Selecting components and specifying their relations
    - Implementing system functions by interactions of components
    - Hardware-software separation and interactions
  - Specifying properties of components
    - Performance, redundancy, safety, ...
  - Using architecture design patterns
    - E.g., MVC, N-tier, …
  - Re-use off-the-shelf (OTS) and existing components

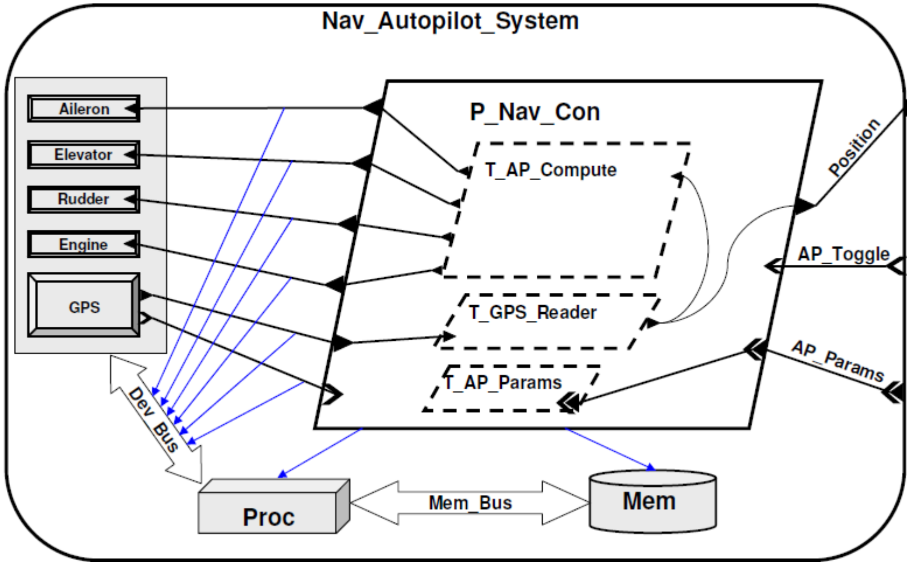
Typical languages for architecture design

- UML
- SysML (e.g., Block diagram)
- AADL: Architecture Analysis and Design Language
  - Components
  - Relations: Data/event interchange on ports
  - Mapping to hardware
  - Properties for analysis

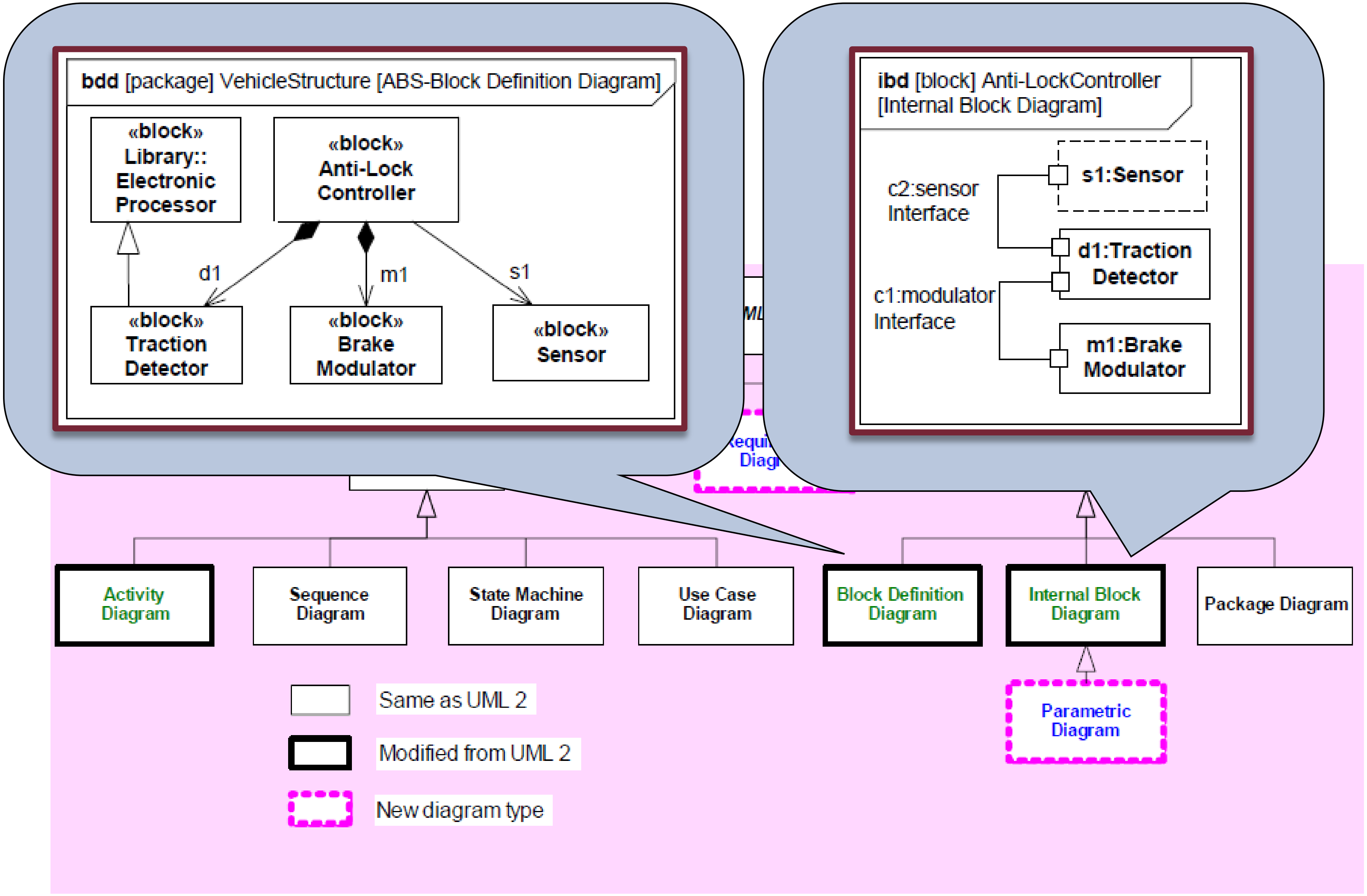


```
thread implementation CoinPublisher.impl
            calls(u: subprogram updateTotal;);
       properties

            Compute_Execution_Time => 30ms .. 40ms;
            Dispatch_Protocol => ( Sporadic );
            annex behavior {**
                  compute(5ms);
                  compute(10ms);
                  compute(15ms);
                  raise(availableContent);
            **};
end CoinPublisher.impl;
```



Typical languages for architecture design: SysML

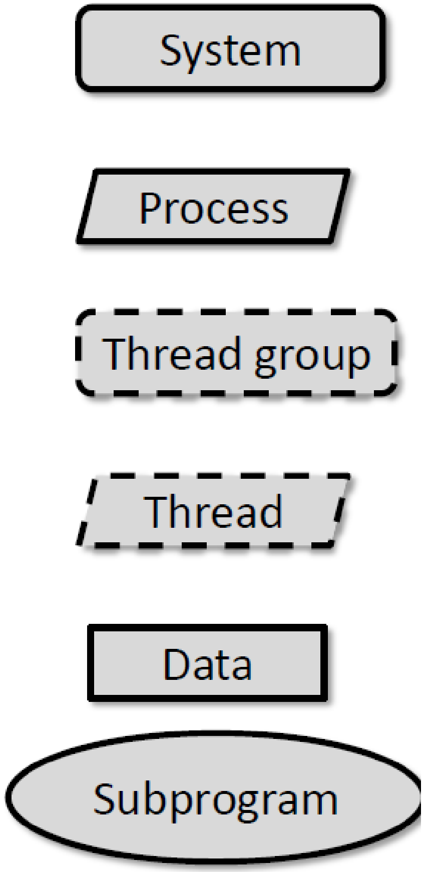


Typical languages for architecture design: AADL

AADL: Architecture Analysis and Design Language (v2: 2009)

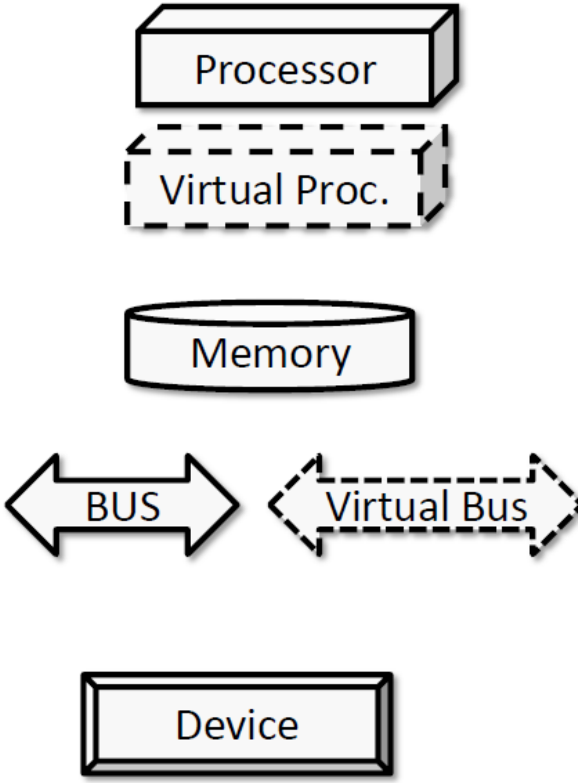
- For embedded systems (SAE)

- Software components
  - System: Hierarchic structure of components
  - Process: Protected address range
  - Thread group: Logic group of threads
  - Thread: Concurrently schedulable execution unit
  - Data: Sharable data
  - Subprogram: Sequential, callable code unit



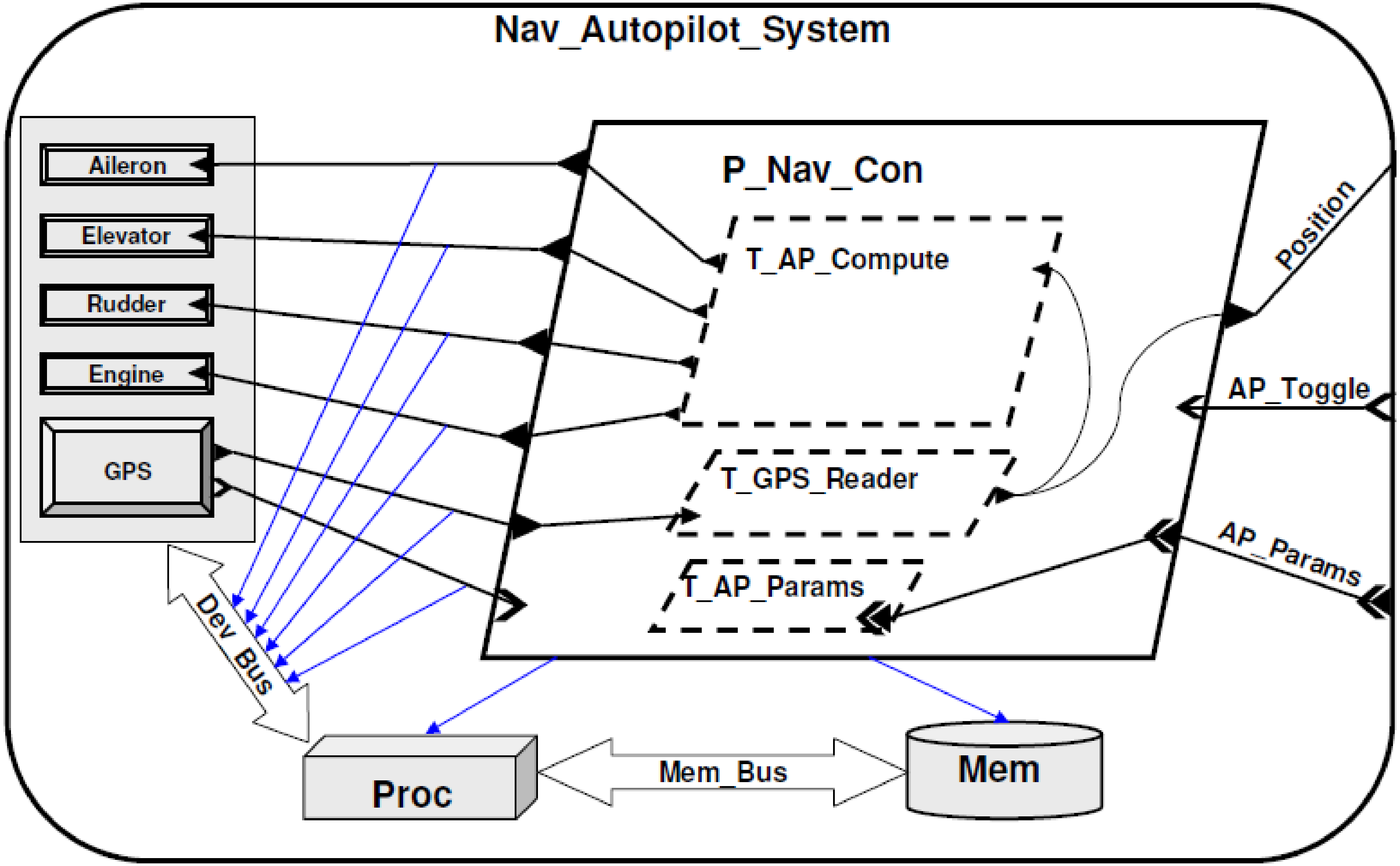
Typical languages for architecture design: AADL

- Hardware components
  - Processor, Virtual Processor: Platform for scheduling of threads/processes
  - Memory: Storage for data and executable code
  - Bus, Virtual Bus: Physical or logical unit of connection
  - Device: Interface to/from external environment
- Mapping
  - Between software and hardware
  - Between logical (virtual) and physical components



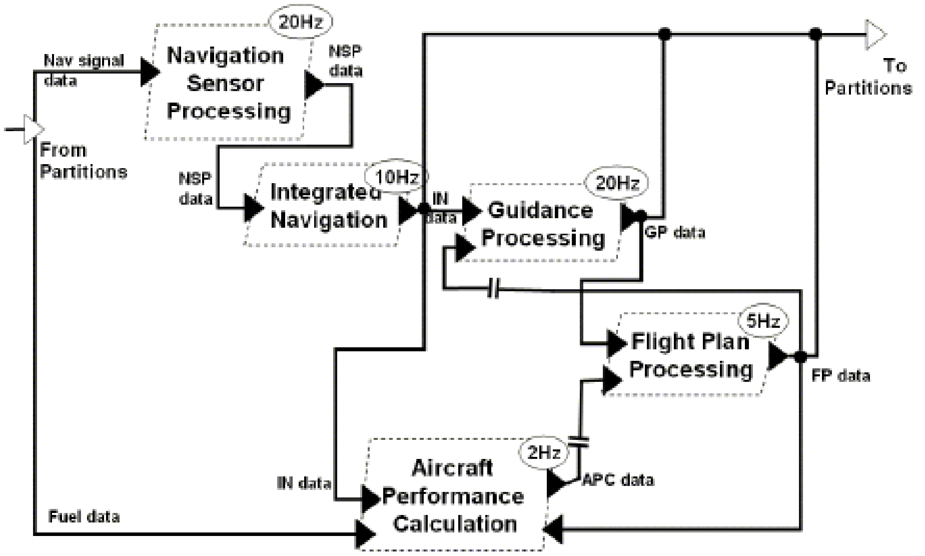
Typical languages for architecture design: AADL

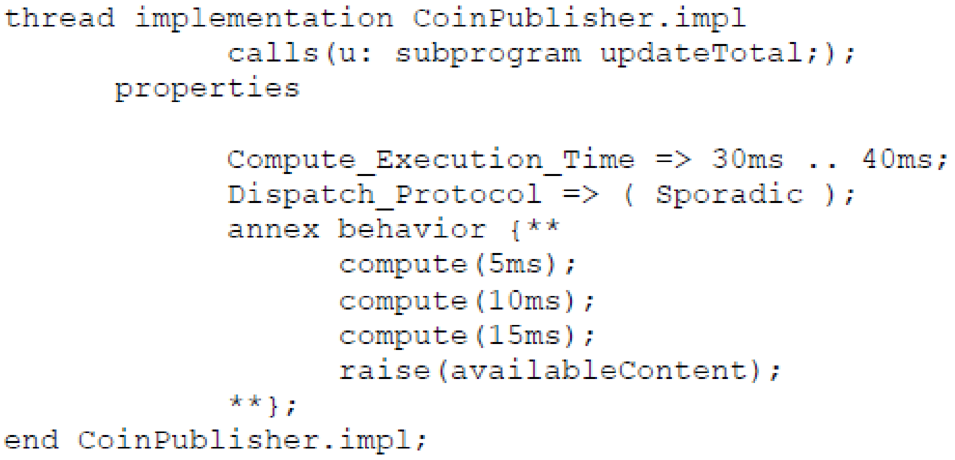
- Example: Mapping between components



Typical languages for architecture design: AADL

- Relations
  - Data and event flow on ports
- Property specification for analysis
  - Timing
  - Scheduling
  - Error propagation (using an extension of AADL)
- Models in graphical, textual, XML formats





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end CoinPublisher.impl;
```

What is influenced by the architecture? 1/2

- **Performance**
  - Resource assignment: Parallel processing, queuing policy, deployment of critical services
  - Resource management: Scheduling of resources, dynamic resource assignment, load balancing
- **Dependability**
  - Error detection: Push/pull monitoring, exception handling
  - Fault tolerance: Static redundancy, dynamic redundancy, forward/backward recovery
  - Fault handling: Reconfiguration, graceful degradation
- **Security**
  - Protection of sensitive data: Components for authentication, authorization, data hiding
  - Detection of intrusion: Confinement of illegal access
  - Recovery after intrusion: Maintenance of data integrity

What is influenced by the architecture? 2/2

- **Maintainability**
  - Encapsulation: Semantic coherence
  - Avoiding domino effect of changes: Information hiding, confinement, usage of proxies
  - Late binding: Runtime registration, configuration descriptors, polymorphism
- **Testability**
  - Assuring controllability and observability
  - Separation of interfaces and implementation
  - Recording and replaying interactions
- **Usability**
  - Separation of user interface
  - Maintenance of user model, task model, system model in runtime

Example: Architecture for software safety (EN 50128)

- Highly recommended techniques for SIL 3 and SIL 4
  - Defensive programming
  - Fault detection and diagnostics
  - Failure assertion programming
  - Diverse programming
  - Storing executed cases
  - Software fault effect analysis

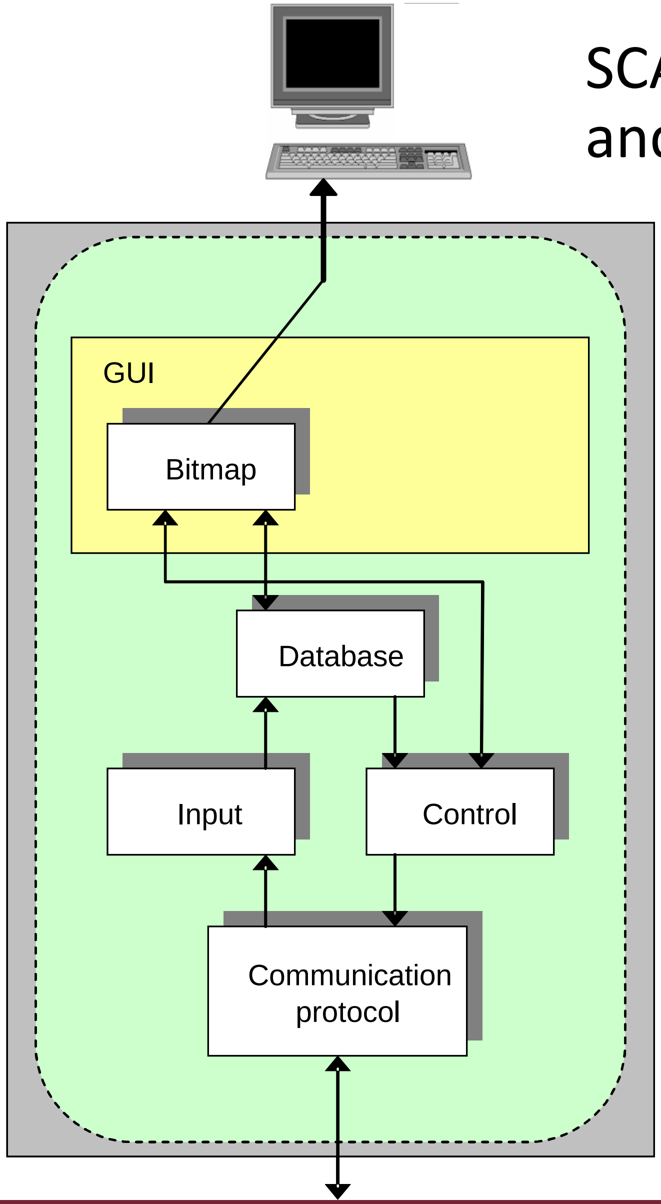
  –> Software, information and time redundancy

Combination of techniques is allowed

Reference for error detection

- Not recommended techniques
  - Forward and backward recovery
  - Artificial intelligence based fault handling
  - Dynamic software reconfiguration

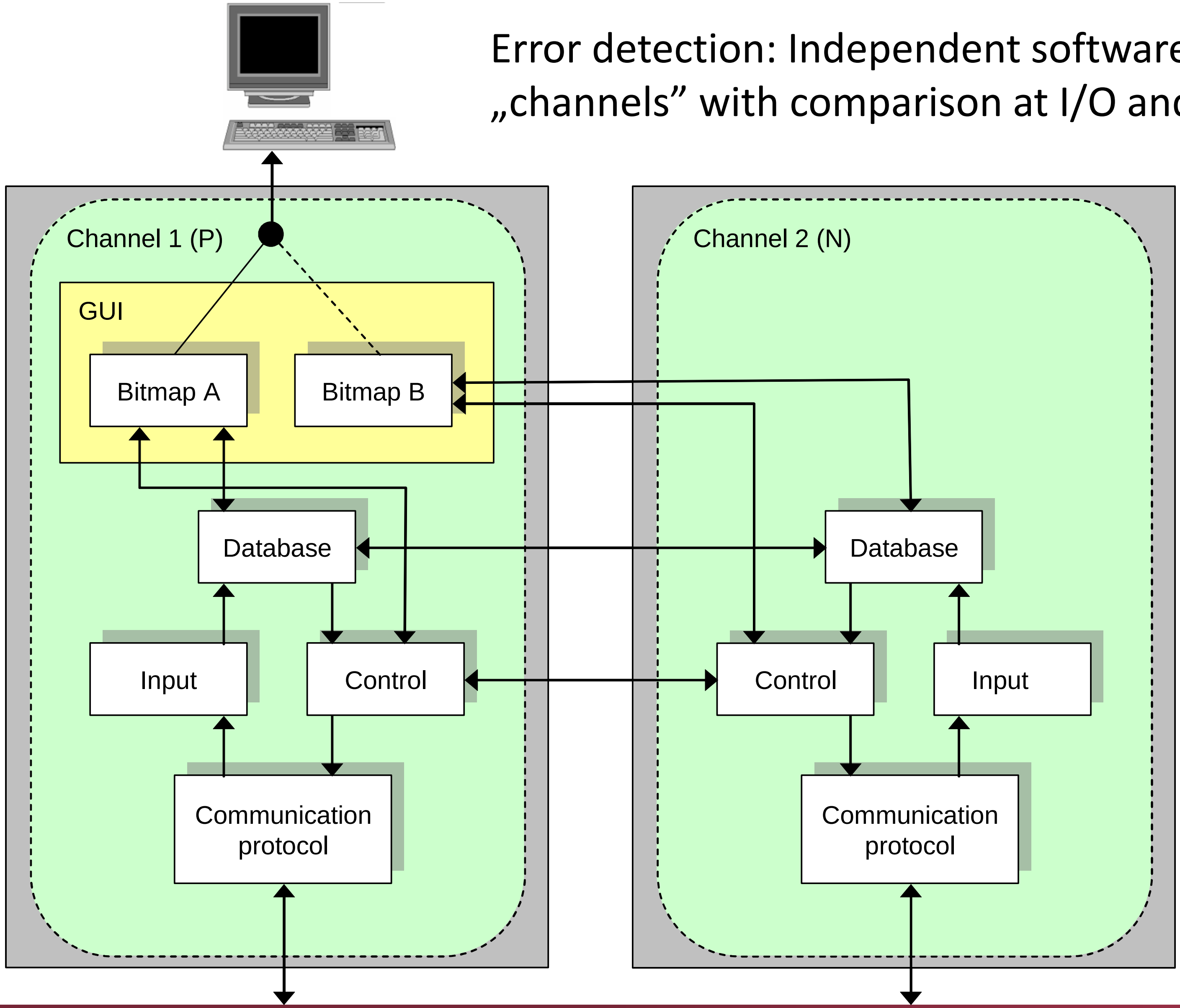
Example: Safety architecture 1/2



SCADA system: Supervisory Control and Data Acquisition

Example: Safety architecture 2/2

Error detection: Independent software „channels” with comparison at I/O and HMI



Summary: System properties and the design space

System property	Related design decisions (examples)
Performance	Resource assignment, resource management
Dependability	Error detection, fault tolerance, fault handling
Security	Protection against illegal access, detection of intrusion, maintenance
Maintainability	Encapsulation, avoiding domino effect, late binding
Testability	Controllability, observability, separation of interfaces
Usability	Separation and maintenance of user, task and system models

Overview: What are the verification techniques?

- Review: Analysis of requirements and architecture related decisions
  - Architecture trade-off analysis (ATAM)
- Static analysis: Systematic architecture analysis
  - Interface analysis
    - Conformance of required and offered interfaces
  - Fault effect analysis by combinational techniques
    - Component level faults ↔ System level effects
- Quantitative analysis: Model based evaluation
  - Evaluation of extra-functional properties by constructing and solving an analysis model
    - Computing system level properties on the basis of the local properties of components and relations

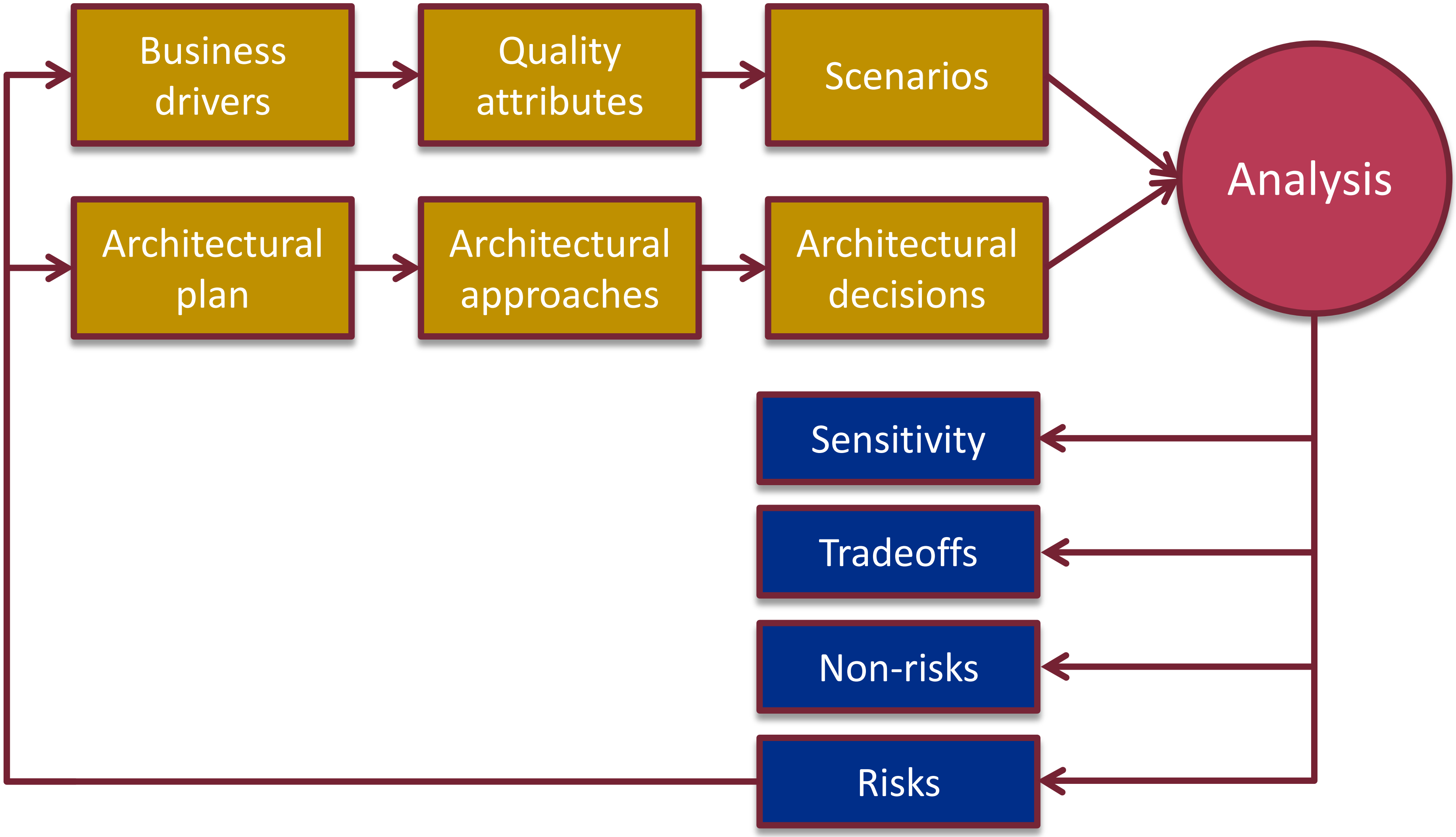
Analysis of requirements and architecture related decisions

ATAM: Architecture Trade-off Analysis

Requirements based architecture analysis

- Architecture Tradeoff Analysis Method (ATAM) goals
  - What are the quality objectives and their attributes?
    - What are the relations and priorities of the quality objectives?
  - How does the architecture satisfy the quality objectives?
    - Do the architecture level design decisions support the quality objectives and their priorities? What are the related risks?
- Basic ideas
  - Systematic collection of quality objectives and attributes: Utility tree with priorities
  - Capturing and understanding the objectives: Scenarios (that exemplify the role of the quality attribute)
  - Architecture evaluation: What was the design decision, what are the related sensitivity points, tradeoffs, risks?

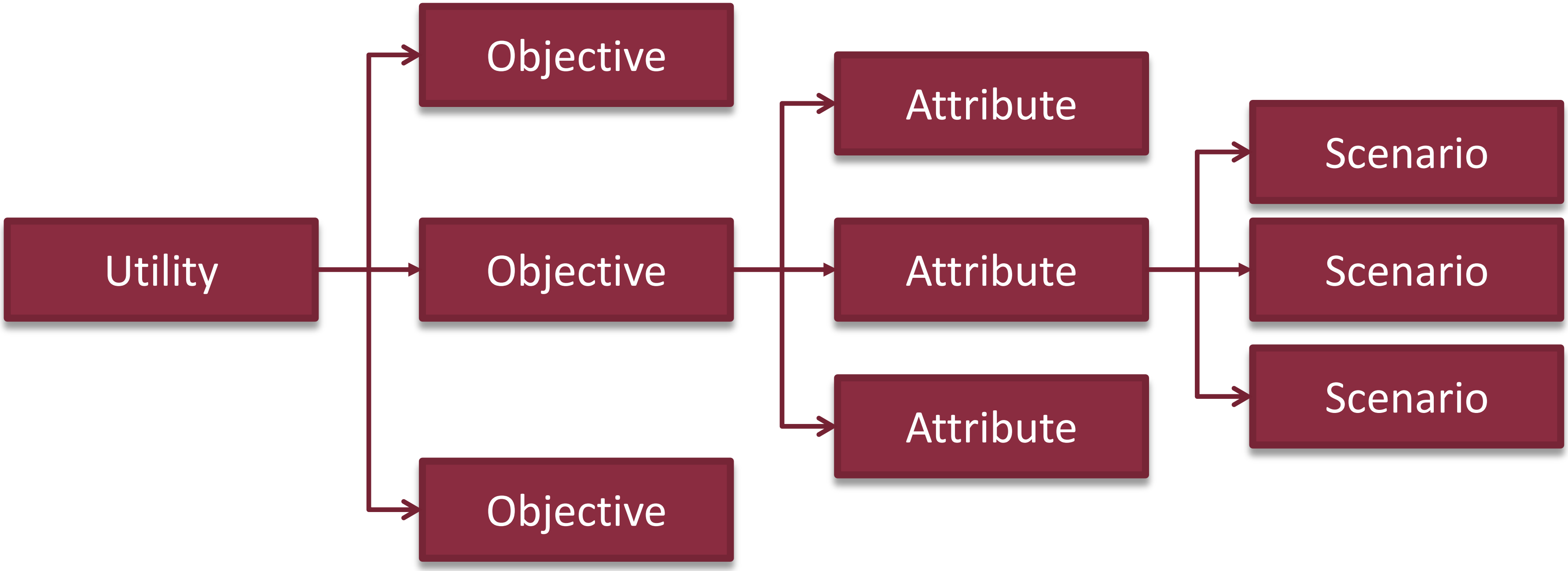
ATAM conceptual analysis process



http://www.sei.cmu.edu/architecture/tools/evaluate/atam.cfm

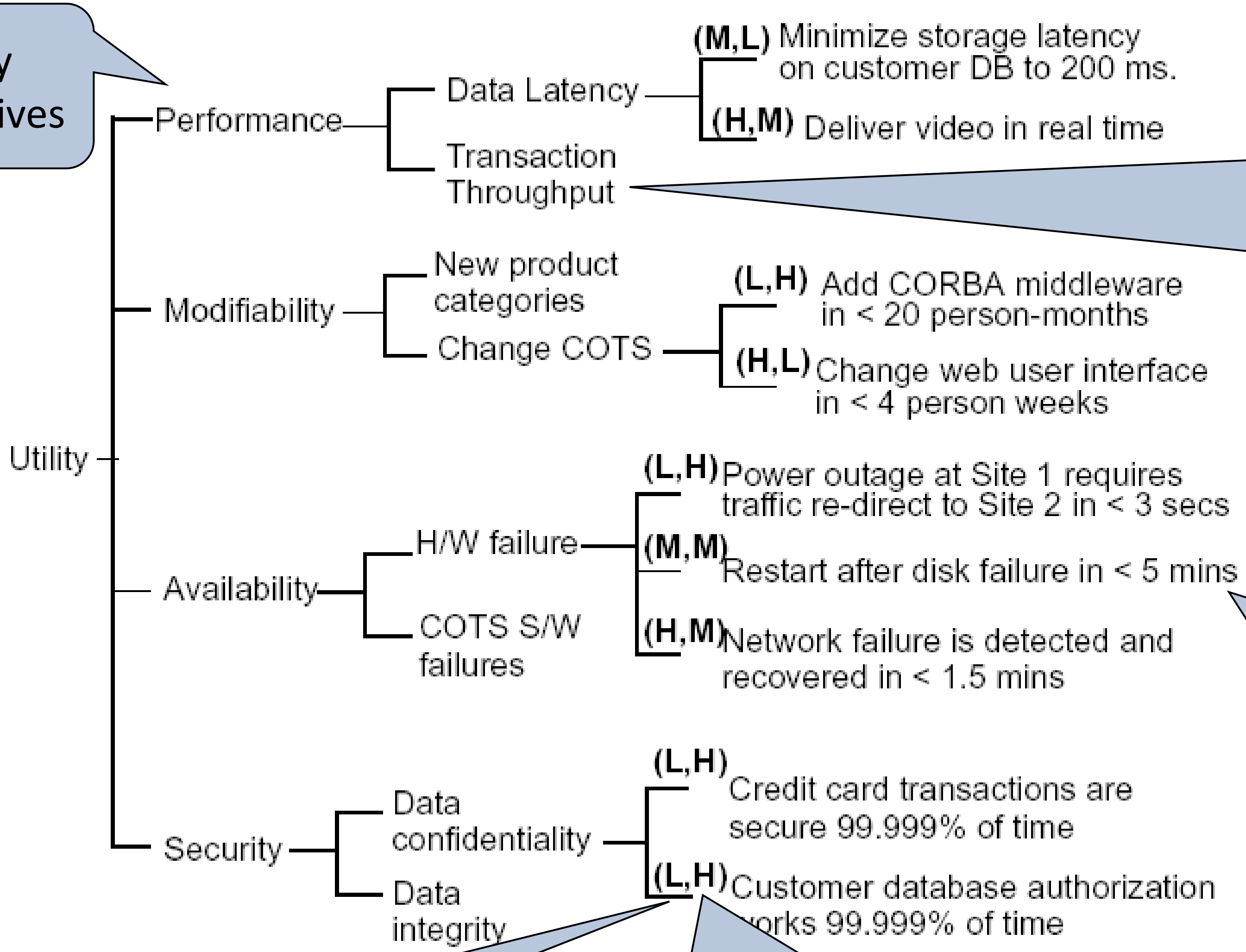
Collection of quality objectives: Utility tree structure

- Utility divided to quality objectives
- Quality objective is characterized by attributes
- Attributes are exemplified by scenarios



Collection of quality objectives: Utility tree

Quality objectives



Utility

Performance

Data Latency

(M,L) Minimize storage latency on customer DB to 200 ms.

(H,M) Deliver video in real time

Transaction Throughput

Modifiability

New product categories

Change COTS

(L,H) Add CORBA middleware in < 20 person-months

(H,L) Change web user interface in < 4 person weeks

Availability

H/W failure

COTS S/W failures

(L,H) Power outage at Site 1 requires traffic re-direct to Site 2 in < 3 secs

(M,M) Restart after disk failure in < 5 mins

(H,M) Network failure is detected and recovered in < 1.5 mins

Security

Data confidentiality

Data integrity

(L,H) Credit card transactions are secure 99.999% of time

(L,H) Customer database authorization works 99.999% of time

Attributes belonging to quality objectives and their refinements

Scenarios for capturing (refined) attributes

Priority:
Low, Medium, High

Implementation complexity:
Low, Medium, High

Steps of the analysis (with examples)

- Analysis of the architectural support for the scenarios
  - Scenario: Recovery in case of disk failure shall be performed in < 5 min
  - Reaction as design decision: Replica database is used
- Analysis of sensitivity points
  - The use of replica database influences availability
  - The use of replica database influences also performance
    - Synchronous updating of the replica database: Slow
    - Asynchronous updating of the replica database: Faster, but potential data loss
- Analysis and optimization of the tradeoffs
  - The use of replica database influences both availability and performance – depending on the updating strategy
  - Tradeoff (decision): Asynchronous updating of the replica database
- Analysis of the risks of tradeoffs
  - Replica database with asynchronous updating (as an architecture design decision) is a risk, if the cost of data loss is high
    - The decision is optimal only in context of the given needs and costs constraints

The process of ATAM 1/2

1. Presentation of the method <- evaluation leader
2. Presentation of business drivers <- development leader
   - Functions, quality objectives, stakeholders
   - Constraints: technical, economical, management
3. Presentation of the architecture <- designers
4. Identification of the design decisions <- designers
5. Construction of the utility tree <- designers, verifiers
   - Refinement of quality objectives and attributes
   - Assignment of scenarios to capture objectives
     - Inputs, effects that are relevant to the quality objective
     - Environment (e.g., design-time or run-time)
     - Expected reaction (support) from the architecture
   - Assignment of priorities to the scenarios (objectives)

The process of ATAM 2/2

6. Analysis of the architecture <- verifiers
   - Architectural support
   - Sensitivity points
   - Tradeoffs
   - Risks
7. Extending the scenarios <- stakeholders
   - Contribution of testers, users, etc.
   - Brainstorming: Aspects of testability, maintenance, ergonomics, etc.
   - Assignment of priorities
8. Continuing the architecture analysis <- verifiers
   - In case of scenarios with priorities that are high enough
9. Presentation of results <- verifiers
   - Preparation of a summary document

Advantages of ATAM

- Quality objectives are explicit and clarified
  - Refinement of objectives, assignment of scenarios
  - Assignment of priorities
- Early identification of risks
  - Explicit analysis of the effects of architecture design decisions (model based analysis may be used)
  - Investigation of tradeoffs
- Stakeholders are involved
  - Designer, tester, user, verifier
  - Communication among the stakeholders
- Documenting architecture related decisions and risks

Systematic analysis methods

Interface analysis

Fault effects analysis

Interface analysis

- Goals
  - Checking the conformance of component interfaces
  - Completeness: Systematic coverage of relations and interfaces
- Syntactic analysis
  - Checking function signatures (number and types of parameters)
- Semantic analysis
  - Based on the description of the functionality of the components
  - Analysis of contracts (contract based specifications)
- Behavioral analysis
  - Based on the behavior specification of components
  - Behavioral conformance is checked (e.g., in case of protocols)
  - Precise behavioral equivalence relations are defined (e.g., bisimulation), also timing can be checked

Example: Interface analysis

- „Contract-based” specification of component functionality: JML

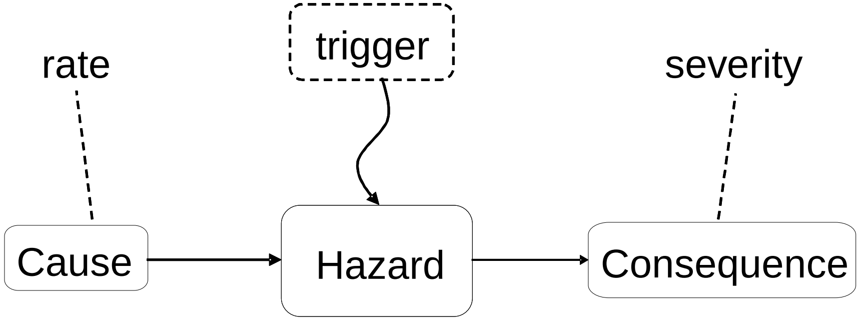
```
public class Purse {
    final int MAX_BALANCE;
    int balance;
      /*@ invariant pin != null && pin.length == 4  @*/
    byte[] pin;
      /*@ requires amount >= 0;
        @ assignable balance;
        @ ensures balance == \old(balance) – amount
                && \result == balance;
        @ signals (PurseException) balance == \old(balance);
        @*/
    int debit(int amount) throws PurseException {
      if (amount <= balance) {
        balance -= amount;
        System.out.println("Debit placed"); return balance; }
      else {
        throw new PurseException("overdrawn by " + amount); }}
```

- Contract based tools: for proving of properties (EscJava2), runtime verification (jmlc)

Fault effects analysis

- Goal: Analysis of the fault effects and the evolution of hazards on the basis of the architecture
  - What are the causes for a hazard?
  - What are the effects of a component fault?
- Results:
  - Hazard catalogue
  - Categorization of hazards
    - Rate of occurrence
    - Severity of consequences

    → Risk matrix
  - These results form the basis for risk reduction



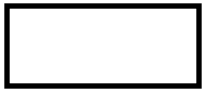
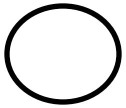
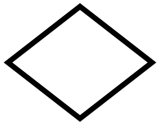
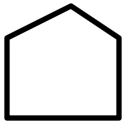
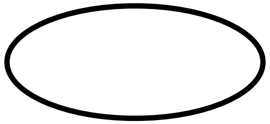
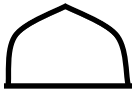
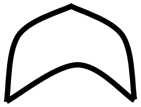
Categorization of the techniques

- Analysis approach:
  - Cause-consequence view
    - Forward (inductive): Analysis of the effects of faults and events
    - Backward (deductive): Analysis of the causes of hazards
  - System hierarchy view
    - Bottom-up: From the components to subsystems / system level
    - Top-down: From the system level down to the components
- Systematic techniques are used
  - Fault tree analysis
  - Event tree analysis
  - Cause-consequence analysis
  - Failure modes and effects analysis

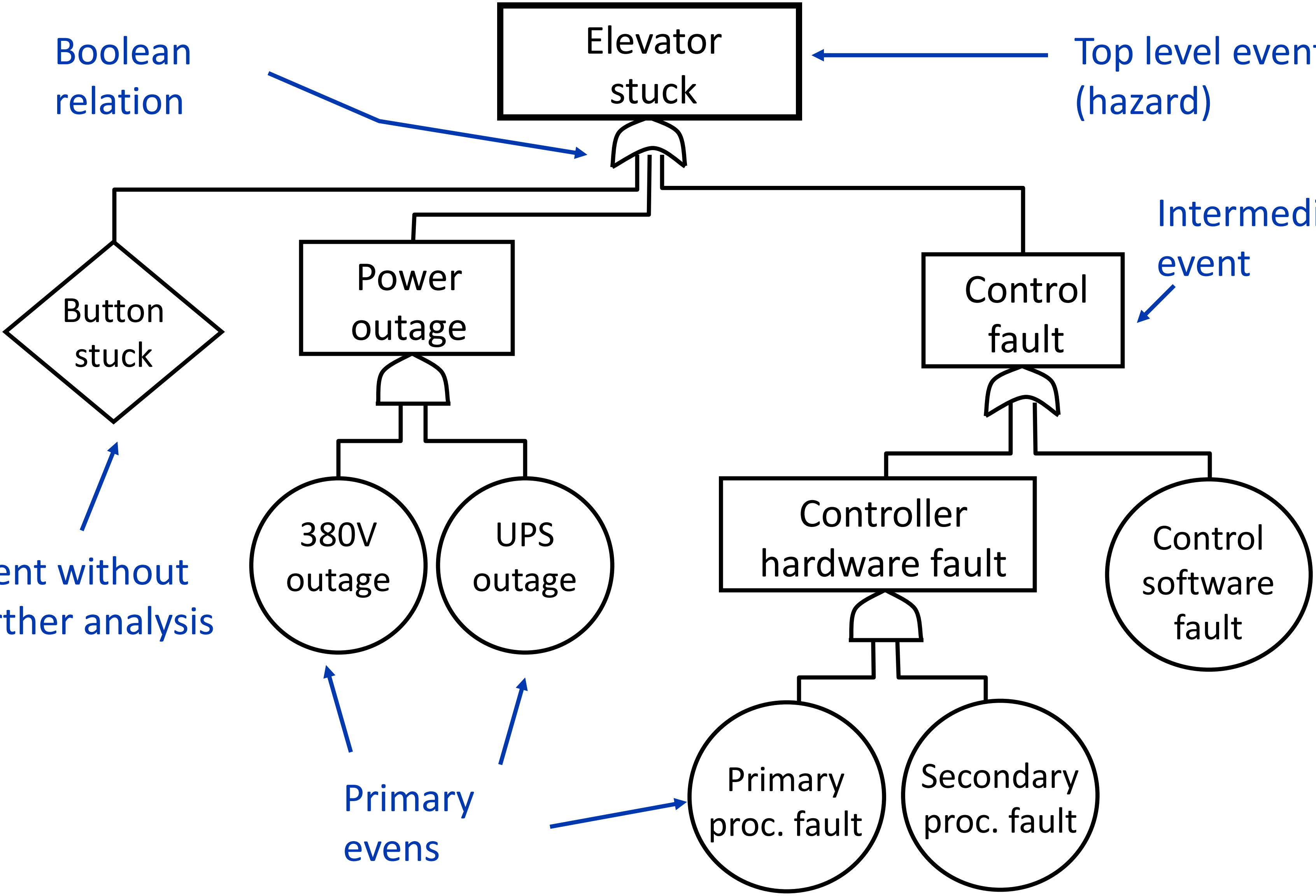
Fault tree analysis

- Analysis of the causes of system level hazards
  - Top-down analysis
  - Identifying the component level combinations of faults and events that may lead to hazard
- Construction of the fault tree
  1. Identification of the foreseen system level hazard: on the basis of environment risks, standards, etc.
  2. Identification of intermediate events (pseudo-events): Boolean (AND, OR) combinations of lower level events that may cause upper level events
  3. Identification of primary (basic) events: no further refinement is needed/possible

Set of elements in a fault tree

	Top level or intermediate event
	Primary (basic) event
	Event without further analysis
	Normal event (i.e., not a fault)
	Conditional event
	AND combination of events
	OR combination of events

Example: Fault tree of an elevator



Boolean relation

Top level event (hazard)

Intermediate event

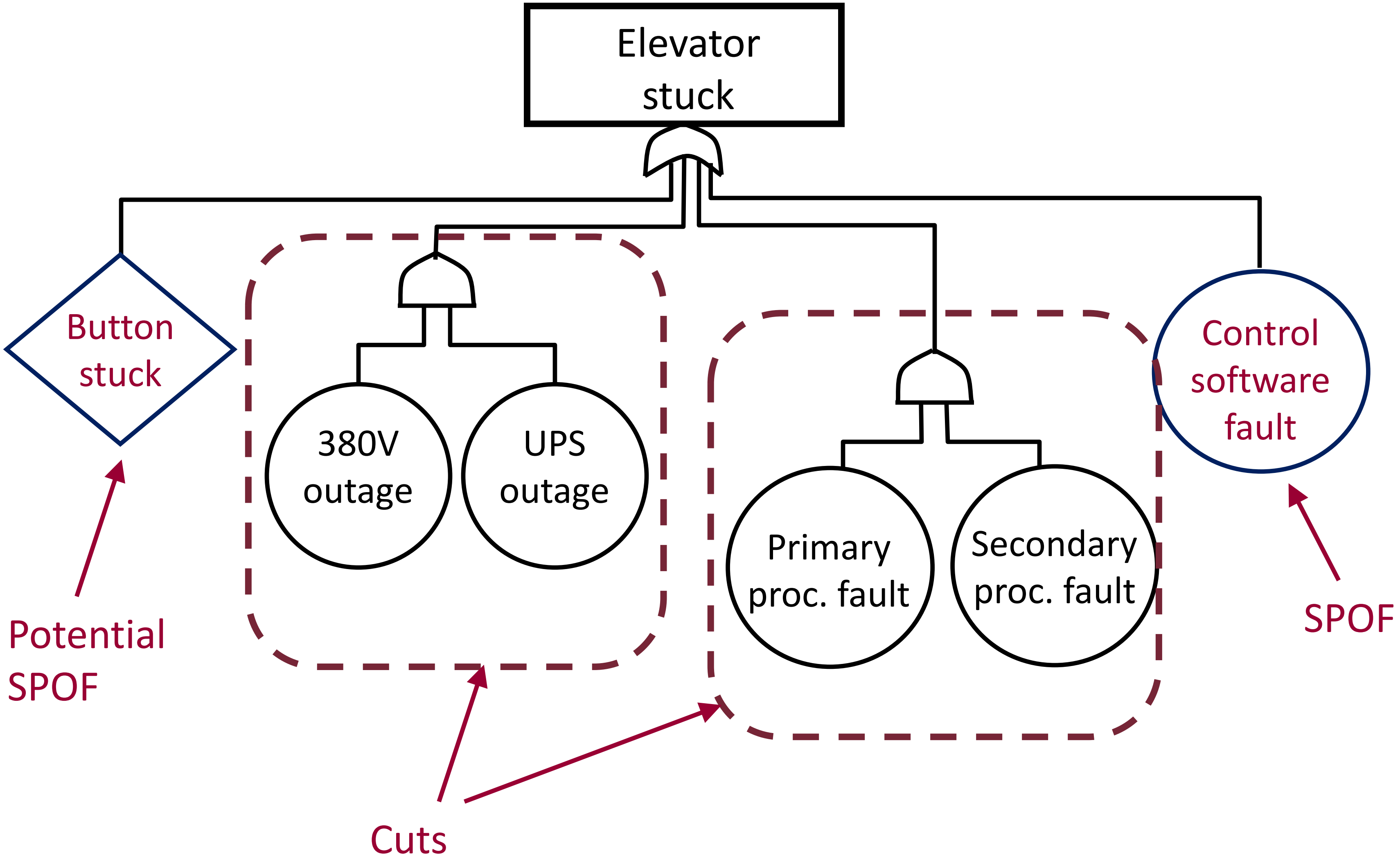
Event without further analysis

Primary evens

Qualitative analysis of the fault tree

- Fault tree reduction: Resolving intermediate events/pseudo-events using primary events
  → disjunctive normal form (OR on the top of the tree)
- Cut of the fault tree:
  AND combination of primary events
- Minimal cut set: No further reduction is possible
  - Minimal cut: There is no other cut that is its subset
- Outputs of the analysis of the reduced fault tree:
  - Single point of failure (SPOF)
  - Events that appear in several cuts

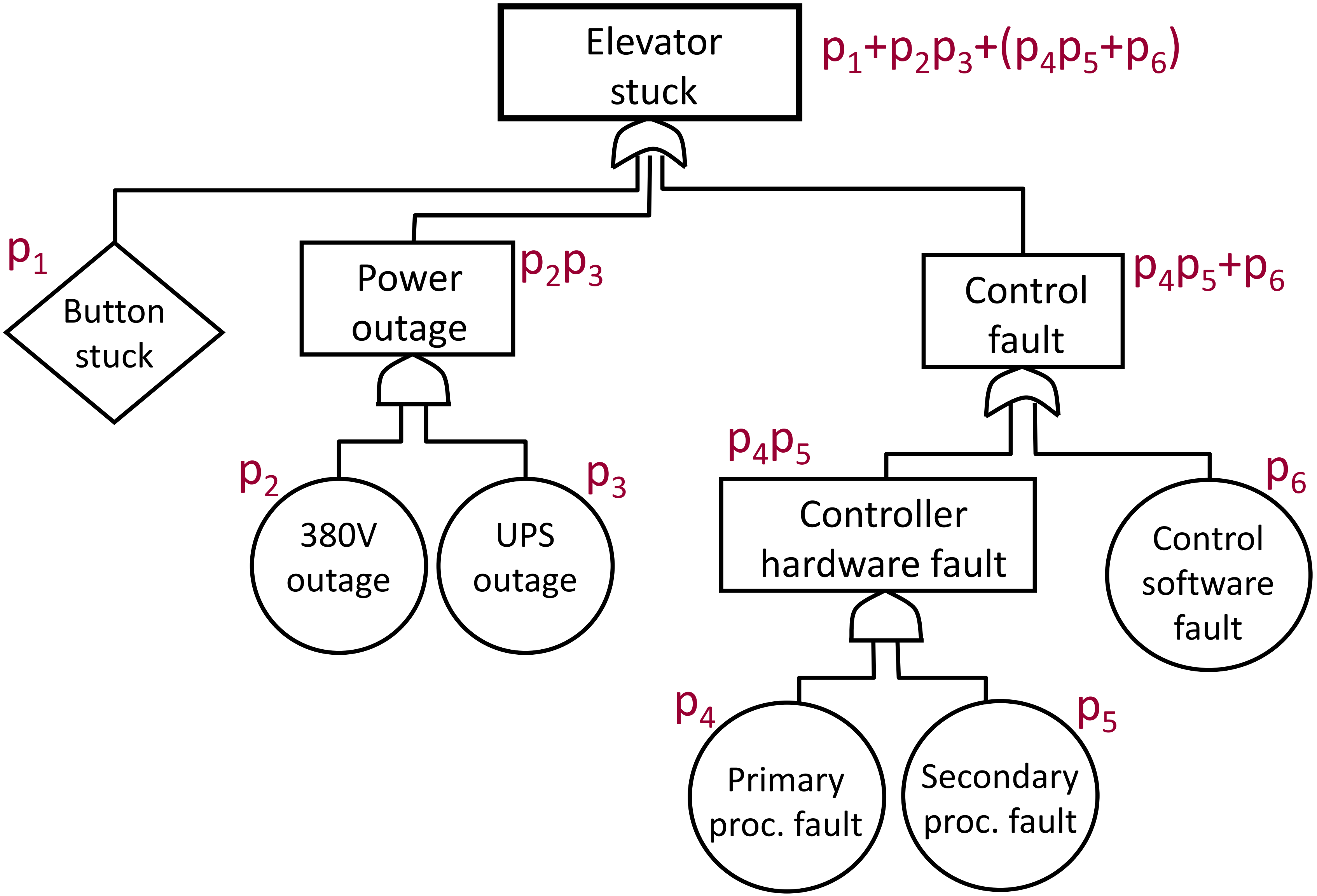
Example: Reduced fault tree of the elevator



Quantitative analysis of the fault tree

- Basis: Probabilities of the primary events
  - Component level data, experience, or estimation
- Result: Probability of the system level hazard
  - Computing probability on the basis of the probabilities of the primary events, depending on their combinations
  - AND gate: Product (if the events are independent)
    - Exact calculation: P{A and B} = P{A} · P{B|A}
  - OR gate: Sum (worst case estimation)
    - Exactly: P{A or B} = P{A} + P{B} - P{A and B} <= P{A} + P{B}
  - Probability as time function can also be used in computations (e.g., reliability, availability)
- Limitations of the analysis
  - Correlated faults (not independent), fault sequences

Example: Fault tree of the elevator with probabilities



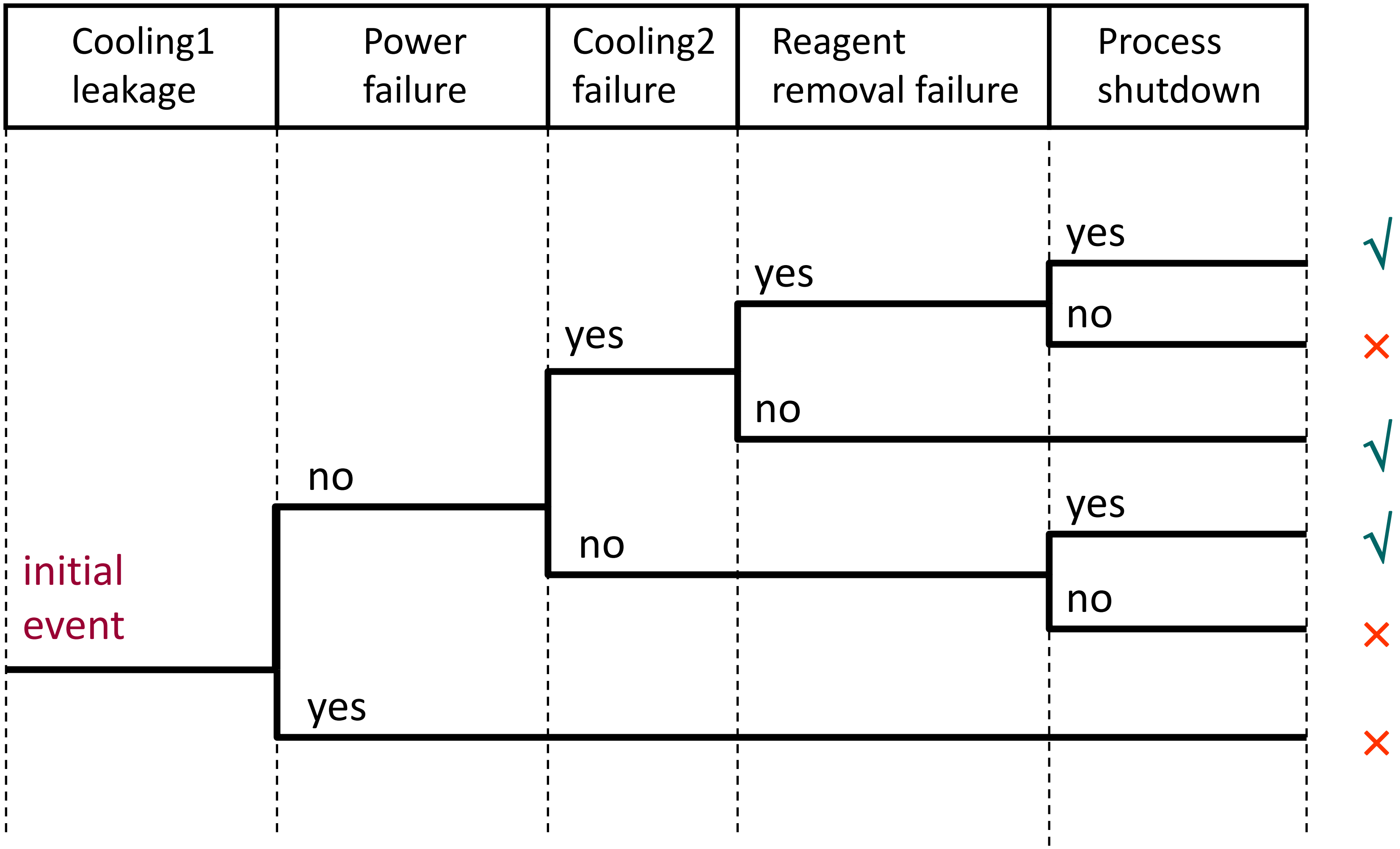
Event tree analysis

- Forward (inductive) analysis:
  Investigates the effects of an initial event

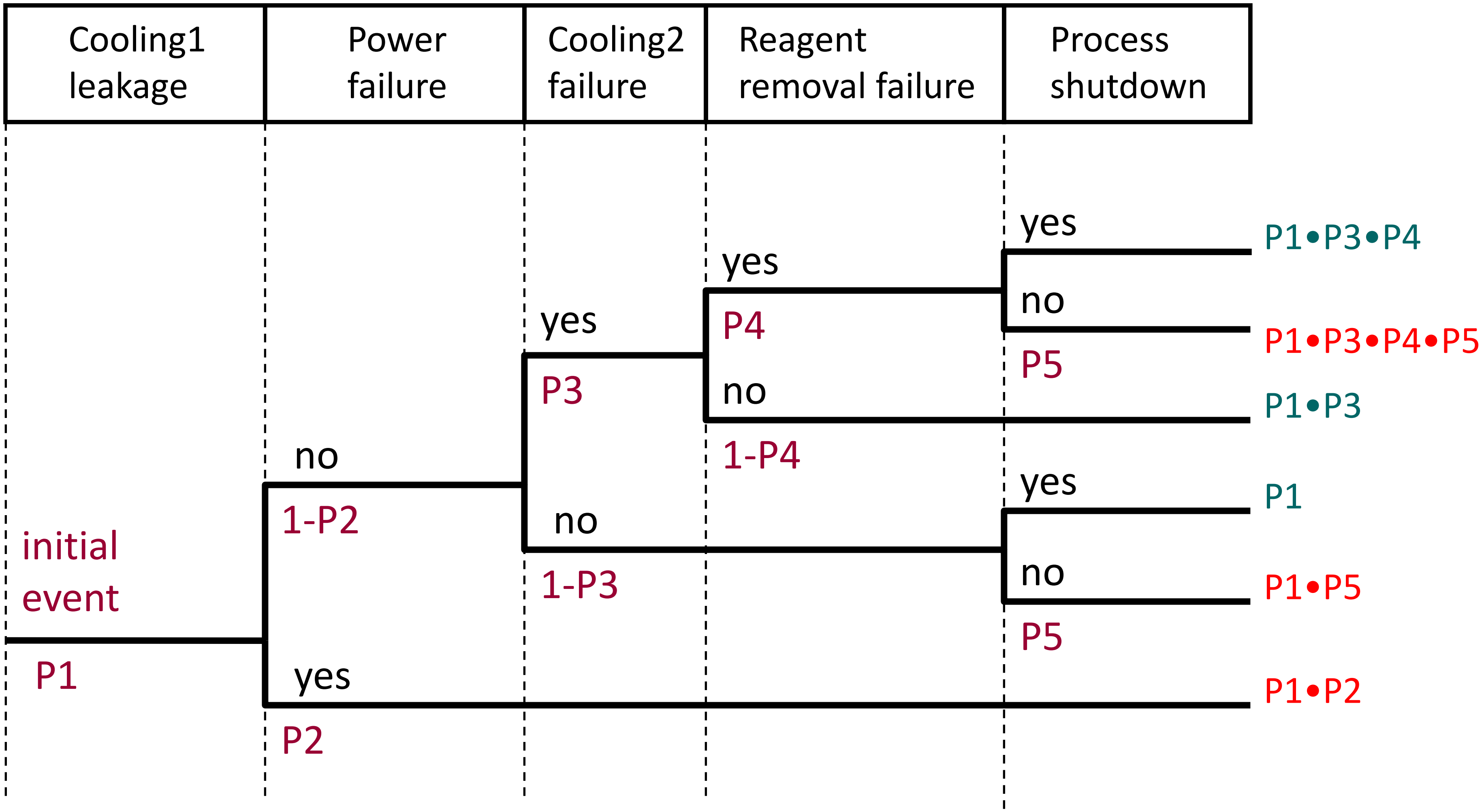
○ Initial event:	component level fault/event
○ Related events:	faults/events of other components
○ Ordering:	causality, timing
○ Branches:	depend on the occurrence of events

- Investigation of hazard occurrence „scenarios”
  - ○ Path probabilities (on the basis of branch probabilities)
- Advantages: Investigation of event sequences
  - Example: Checking protection systems (protection levels)
- Limitations of the analysis
  - ○ Complexity, multiplicity of events

Example: Event tree of a protection system



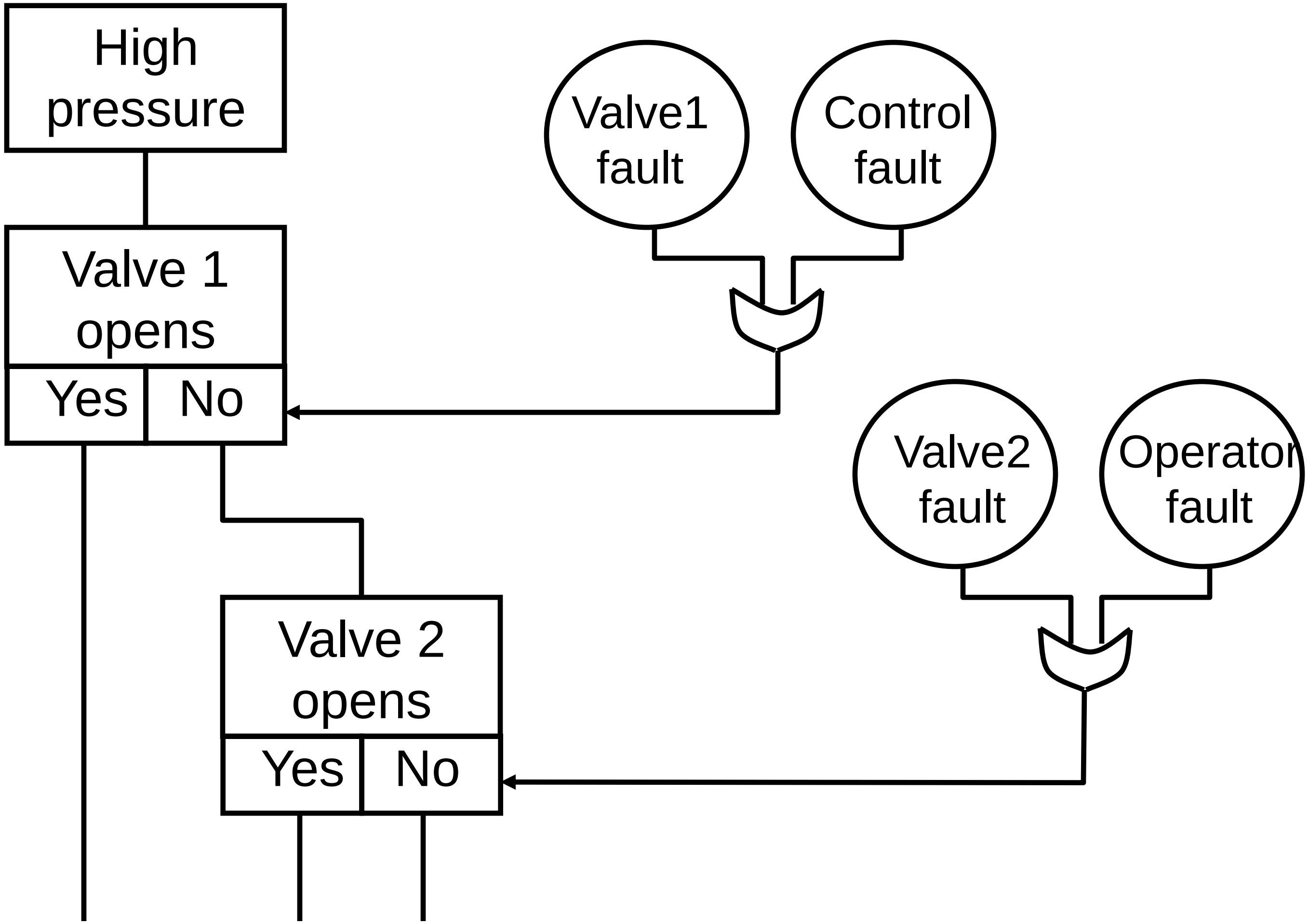
Example: Event tree of a protection system



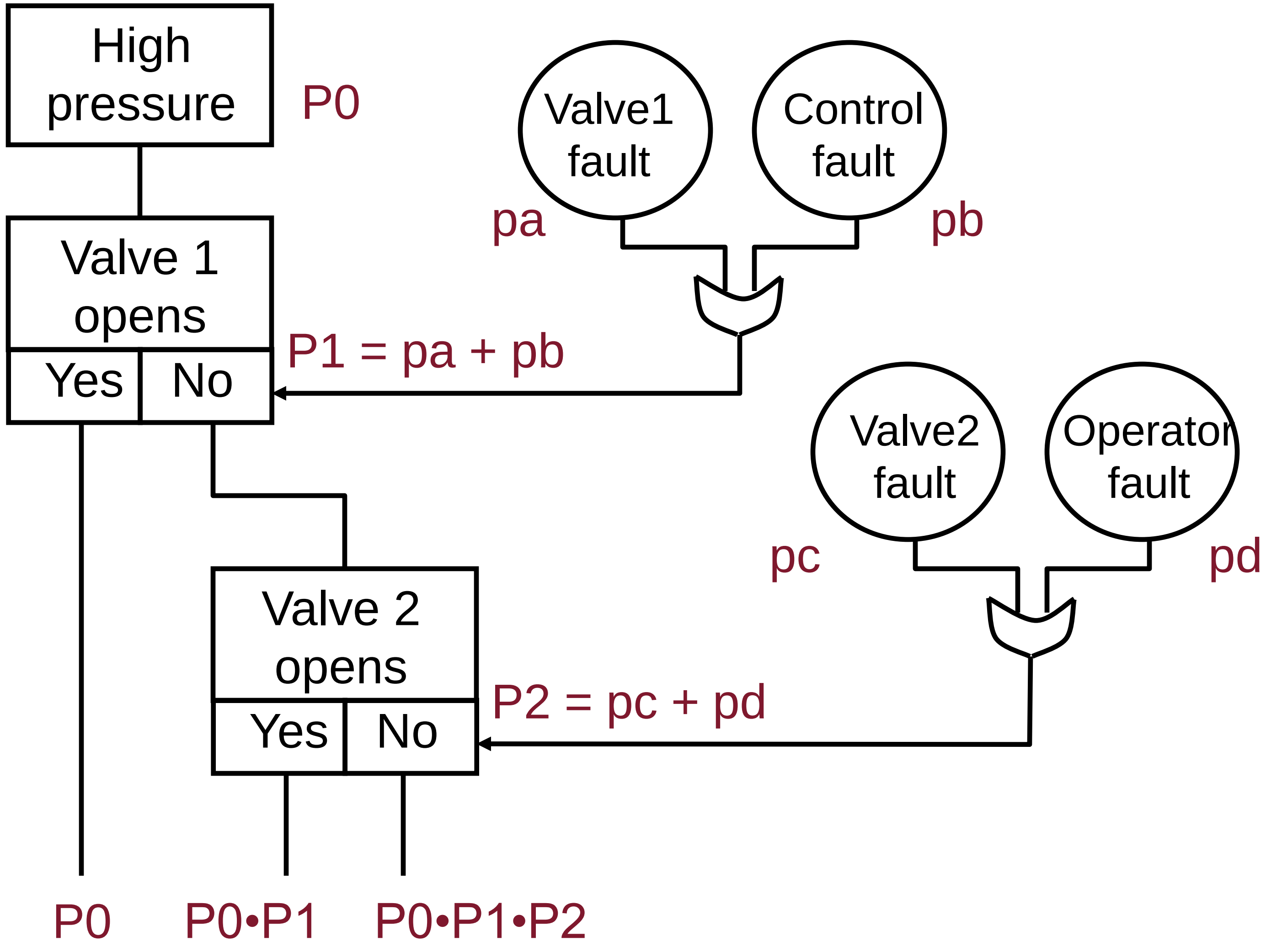
Cause-consequence analysis

- Connecting event tree with fault trees
  - Event tree: Scenarios (sequence of events)
  - Connected fault trees: Analysis of event occurrence, computing the probability of occurrence
- Advantages:
  - Sequence of events (forward analysis) together with analysis of event causes (backward analysis)
- Limitations of the analysis:
  - Complexity: Separate diagrams are needed for all initial events

Example: Cause-consequence analysis



Example: Cause-consequence analysis



Failure Modes and Effects Analysis (FMEA)

- Tabular representation and analysis of components, failure modes, probabilities (occurrence rates) and effects
- Advantages:
  - Systematic listing of components and failure modes
  - Analysis of redundancy
- Limitations of the analysis
  - Complexity of determining the fault effects (using simulators, analysis models, symbolic execution etc.)

Component	Failure mode	Probability	Effect
Detecting that a temperature value is greater than L	> L not detected	65%	Over-heating
	≤ L detected	35%	Process is stopped
…	…	…	…

Model based quantitative evaluation

Performance evaluation

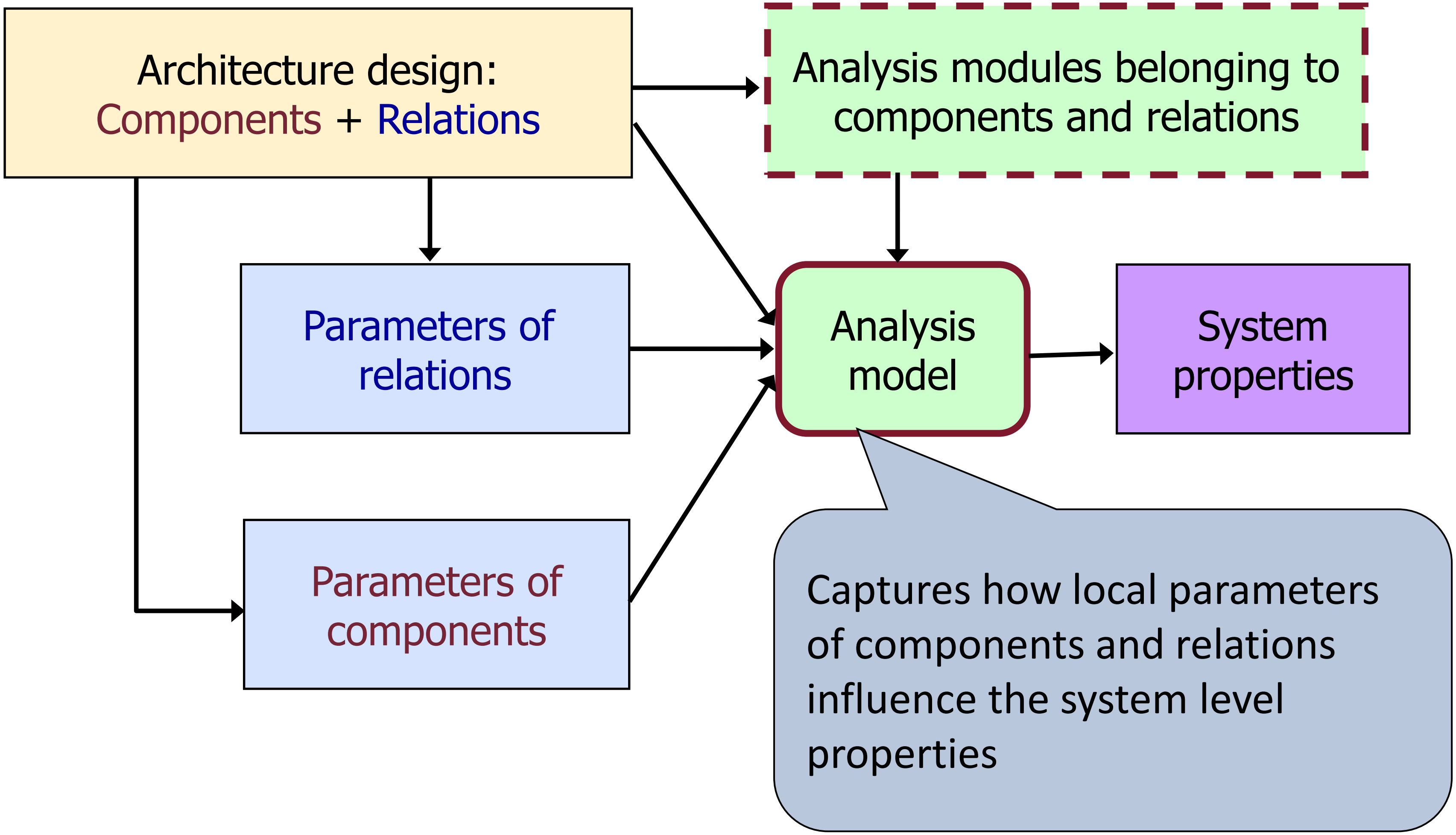
Dependability evaluation

Model based quantitative evaluation

Goal: Evaluation of architecture solutions

- Analysis models are constructed and solved on the basis of the architecture model, e.g.
  - Performance model
  - Dependability model
  - Safety analysis model
- Analysis models are mathematical models
  - Capture how local parameters of components and relations influence system level properties
  - The solution of the model (= computation of selected model characteristics) provide system level properties
- Modular construction of analysis models (possibly automated)
  - Architecture: Component and relations
  - Analysis model: Submodels (modules) for components and relations

General approach for model based evaluation



Captures how local parameters of components and relations influence the system level properties

Typical analysis models

	Performance model	Dependability model	Safety analysis model
Component parameters	Local execution time of functions, priorities, scheduling	Fault occurrence rate, error delay, repair rate, error detection coverage, …	Fault and hazardous event occurrence rate
Relation parameters	Call forwarding rate, call synchronization	Error propagation probability, conditions of error propagation, repair strategy	Hazard scenario, hazard combinations
Model	Queuing network	Markov chain, Petri net	Markov chain, Petri net
System properties (computed)	Request handling time, throughput, processor utilization	System level reliability, availability, MTTF, MTTR, MTBF	System level hazard occurrence rate, criticality

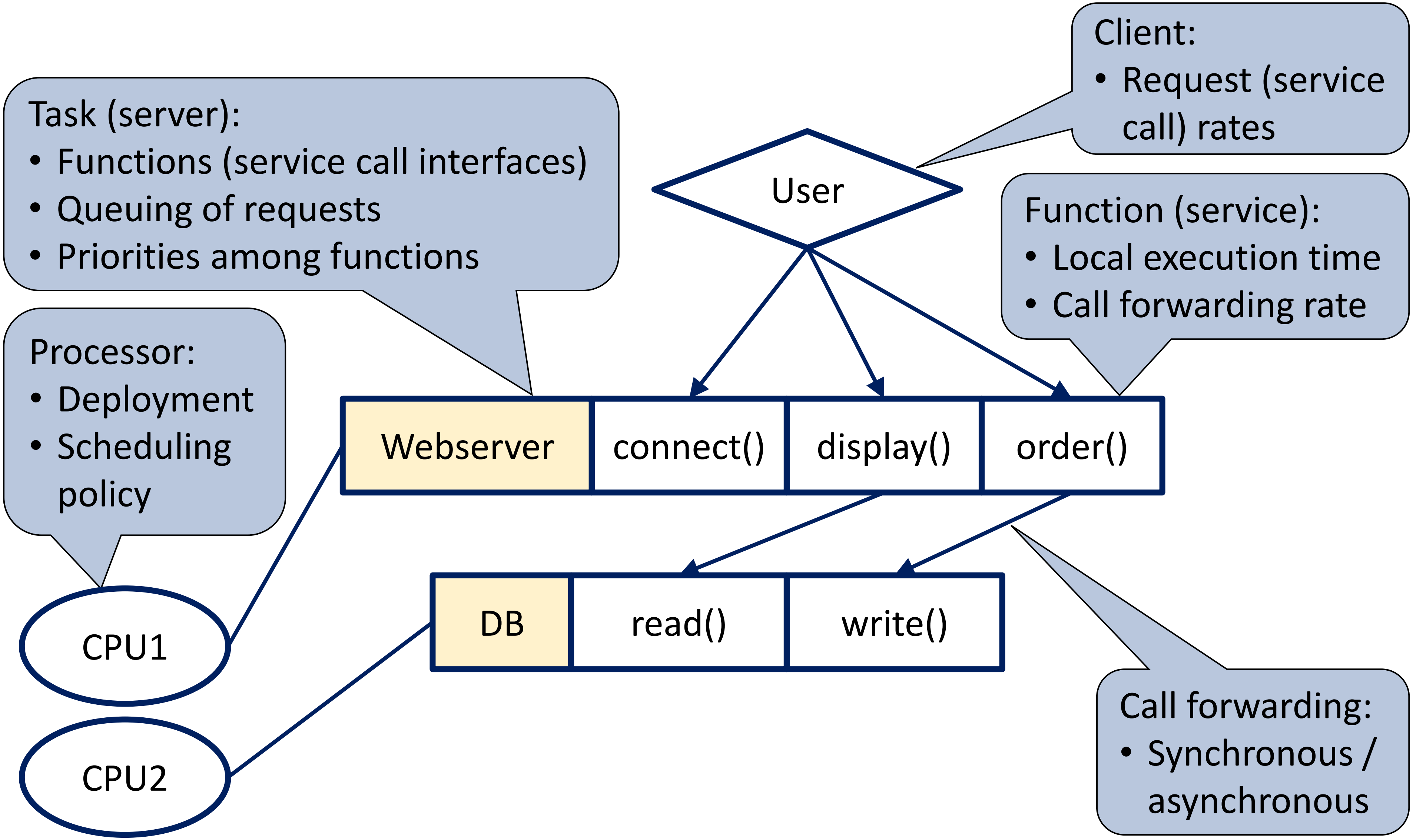
Performance modeling

	Performance model	Dependability model	Safety analysis model
Component parameters	Local execution time of functions, priorities, scheduling	Fault occurrence rate, error delay, repair rate, error detection coverage, …	Fault and hazardous event occurrence rate
Relation parameters	Call forwarding rate, call synchronization	Error propagation probability, conditions of error propagation, repair strategy	Hazard scenario, hazard combinations
Model	Queuing network	Markov chain, Petri net	Markov chain, Petri net
System properties (computed)	Request handling time, throughput, processor utilization	System level reliability, availability, MTTF, MTTR, MTBF	System level hazard occurrence rate, criticality

Performance modeling: Formalisms

- Typical formalism: Queuing networks
  - Servers, hosts, requests and replies, waiting queues
- Example: Layered Queuing Network (LQN)
  - Suitable for distributed client-server applications
- Model elements
  - Client submitting requests to (remote) servers
  - Servers (called “tasks” by convention)
    - Queuing of incoming requests
    - Entry points for service threads (called “functions”) with priorities
    - Forwarding function calls to other servers
  - Hosts (called “processors”)

Example: Elements of an LQN model



Task (server):
- Functions (service call interfaces)
- Queuing of requests
- Priorities among functions

Processor:
- Deployment
- Scheduling policy

Client:
- Request (service call) rates

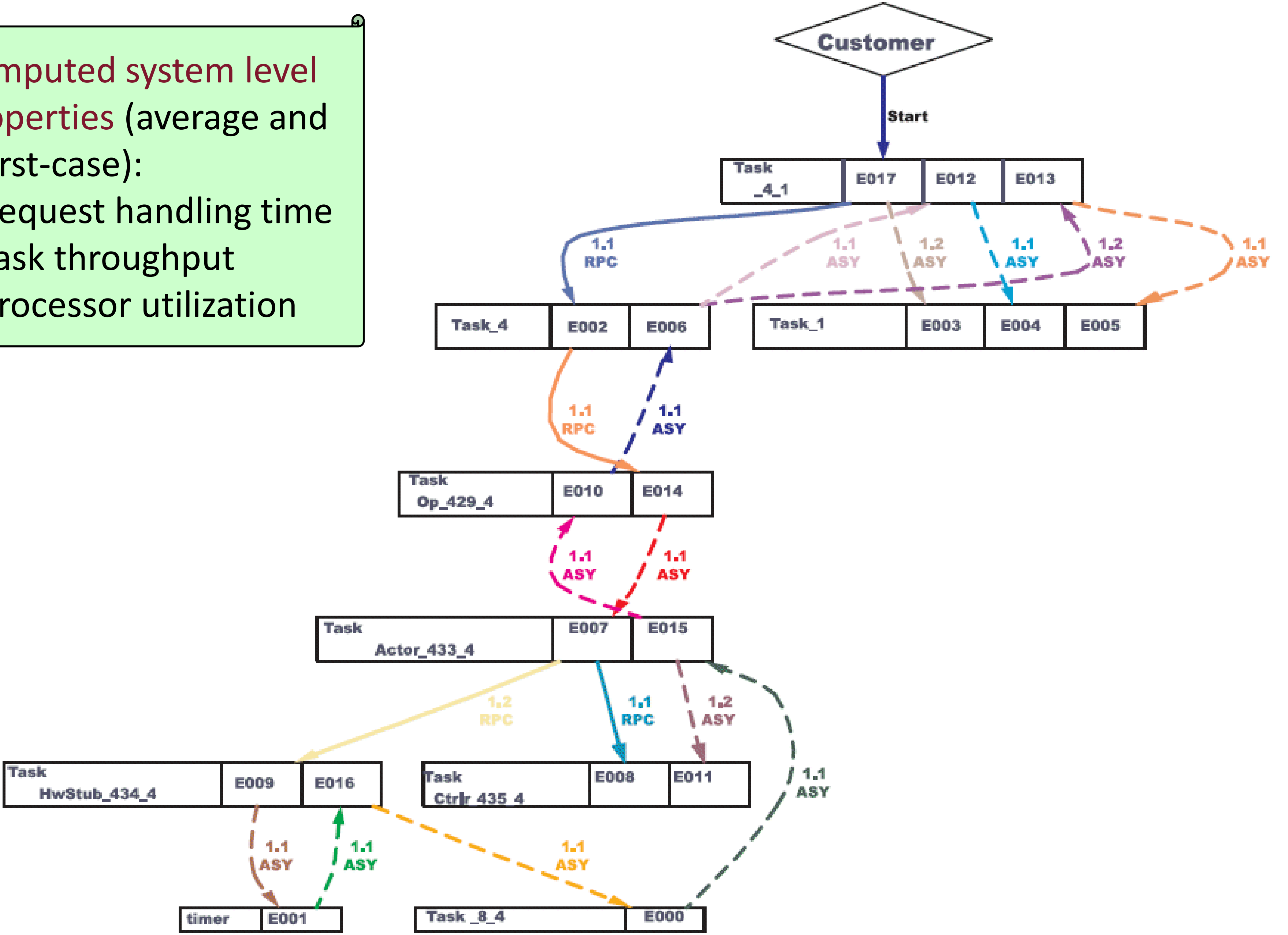
Function (service):
- Local execution time
- Call forwarding rate

Call forwarding:
- Synchronous / asynchronous

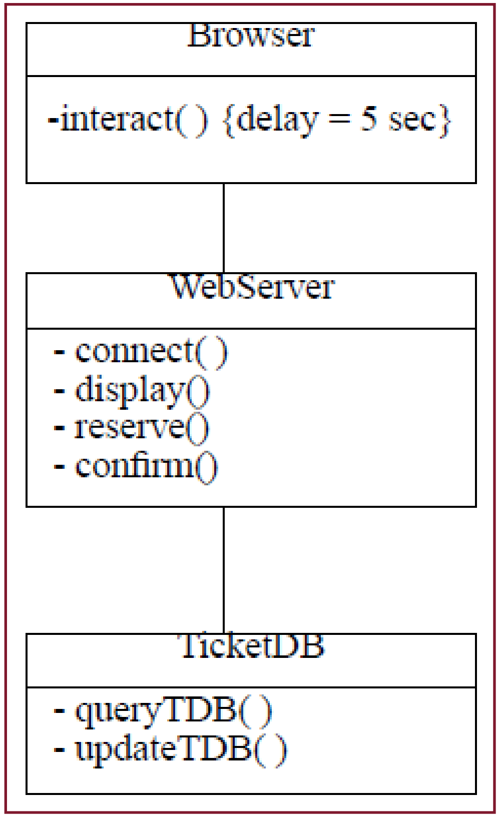
Example: Layers of LQN models

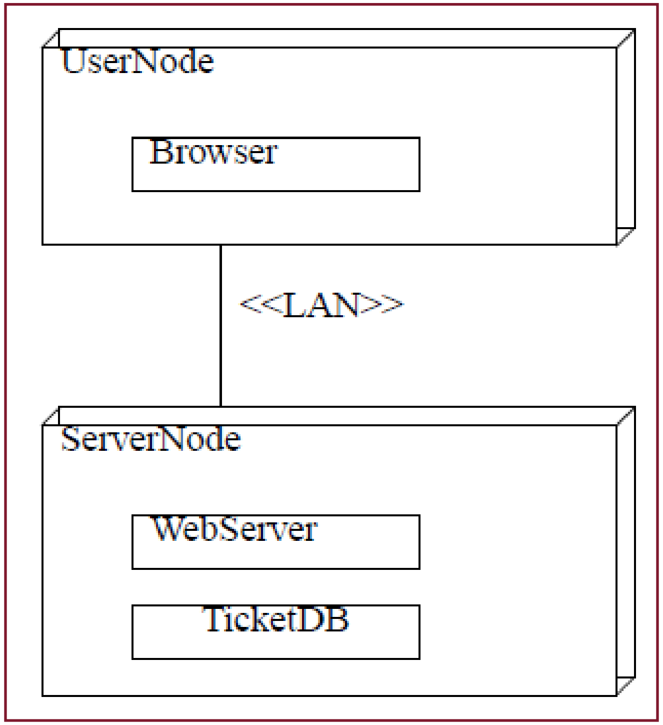
Computed system level properties (average and worst-case):

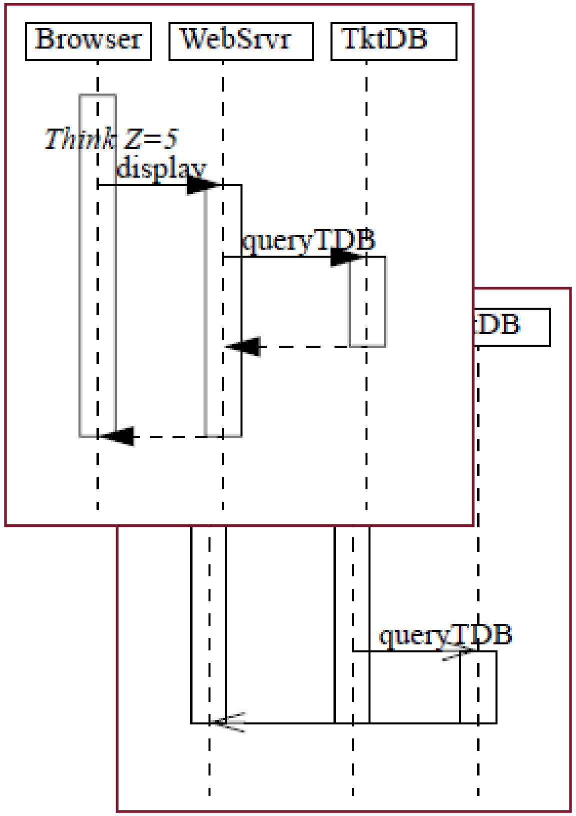
- Request handling time
- Task throughput
- Processor utilization



Example: Architecture model with interactions





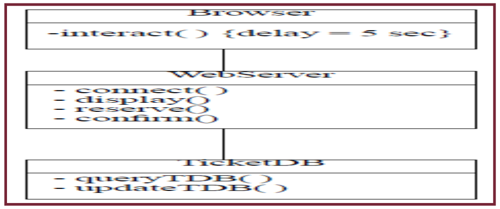


Classes and objects
with local parameters

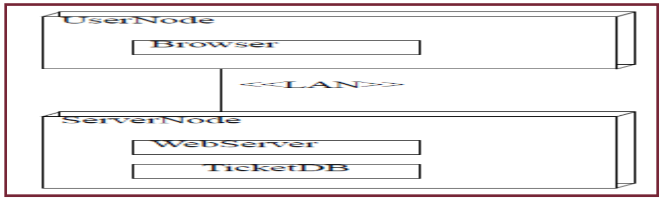
Servers and
deployment

Interactions
(calls)

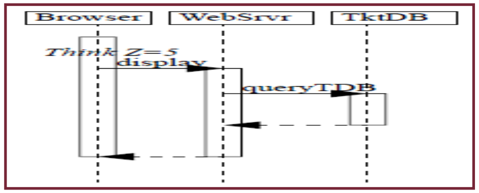
Example: Mapping architecture to analysis model



Classes (objects)

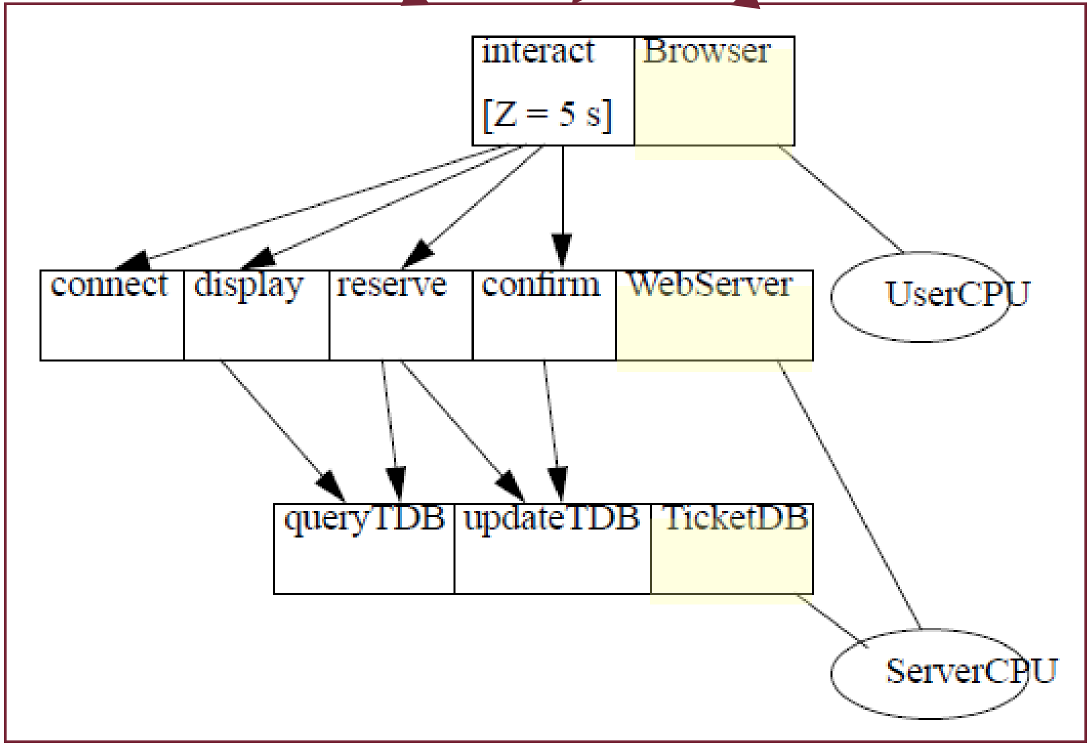


Deployment



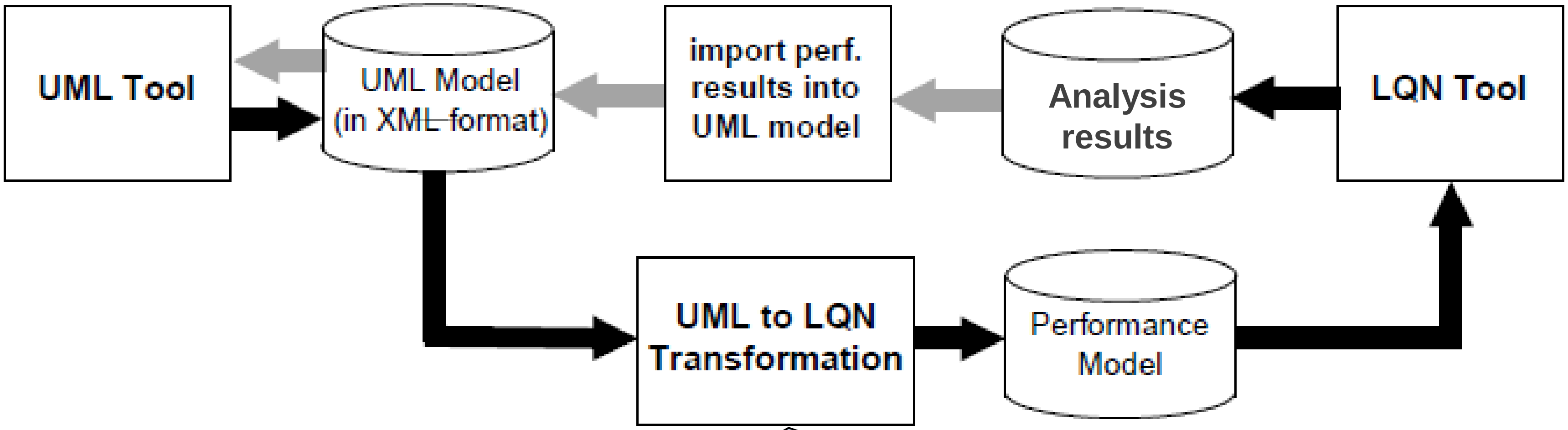
Interactions

Model transformation

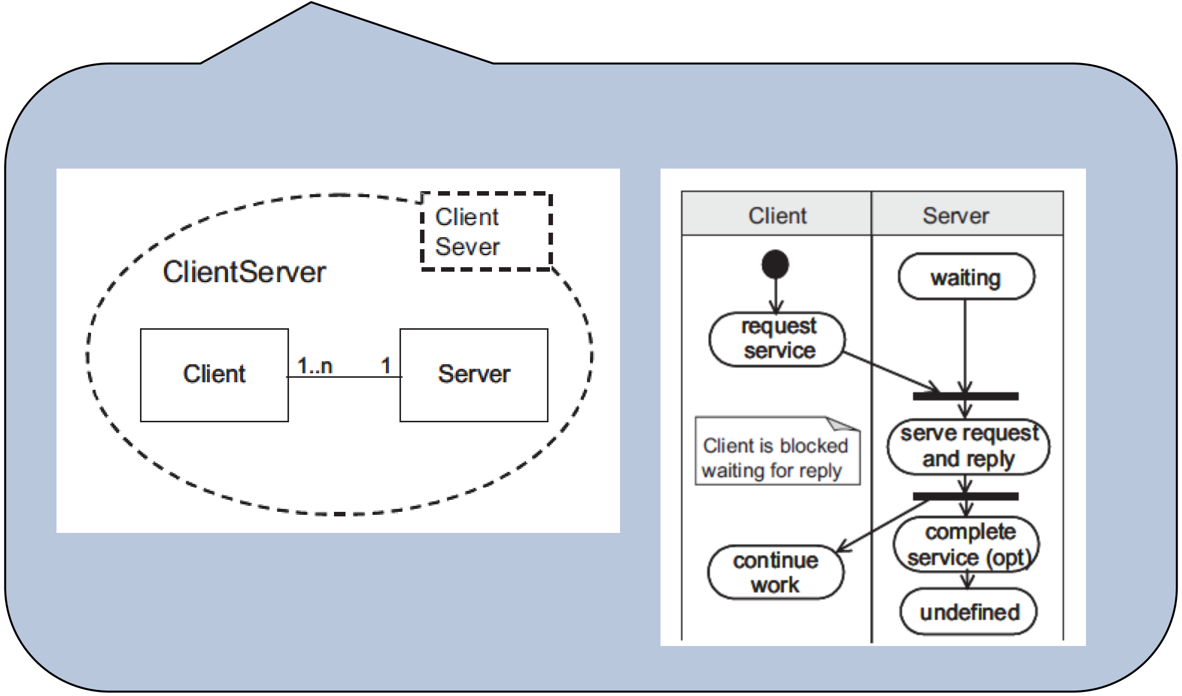


LQN performance model

Example: Analysis workfow


UML Tool
UML Model (in XML format)
import perf. results into UML model
Analysis results
LQN Tool
UML to LQN Transformation
Performance Model

Architecture design patterns can be identified to assign analysis modules

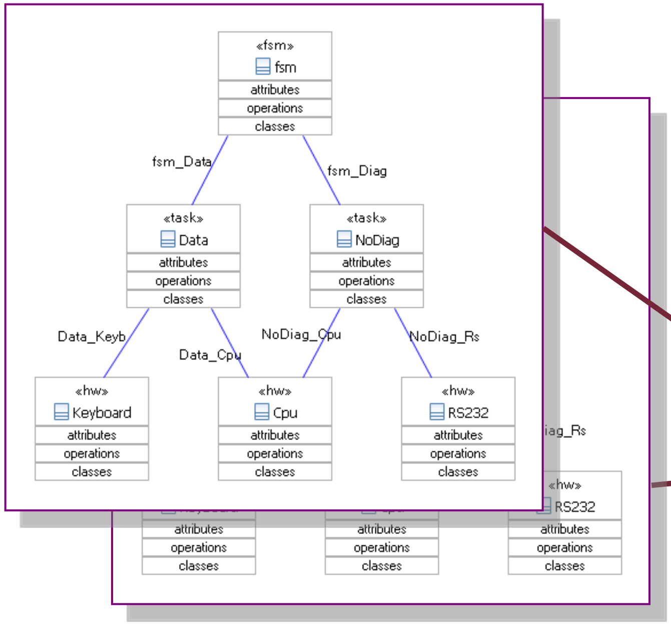


Dependability modeling

	Performance model	Dependability model	Safety analysis model
Component parameters	Local execution time of functions, priorities, scheduling	Fault occurrence rate, error delay, repair rate, error detection coverage, …	Fault and dangerous event occurrence rate
Relation parameters	Call forwarding rate, call synchronization	Error propagation probability, conditions of error propagation, repair strategy	Hazard scenario, hazard combinations
Model	Queuing network	Markov chain, Petri net	Markov chain, Petri net
System properties (computed)	Request handling time, throughput, processor utilization	System level reliability, availability, MTTF, MTTR, MTBF	System level hazard occurrence rate, criticality

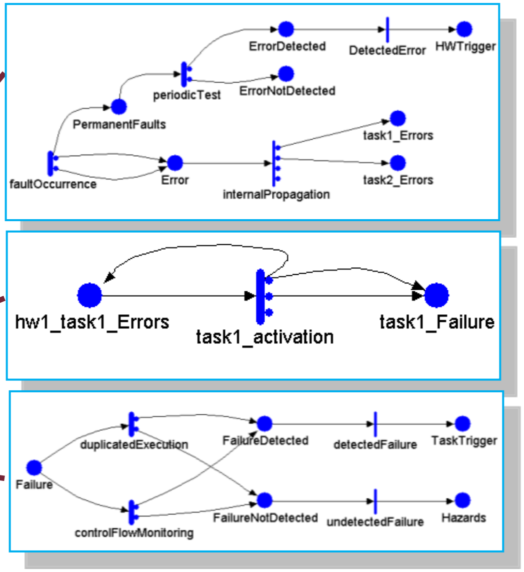
Example: UML based dependability modeling

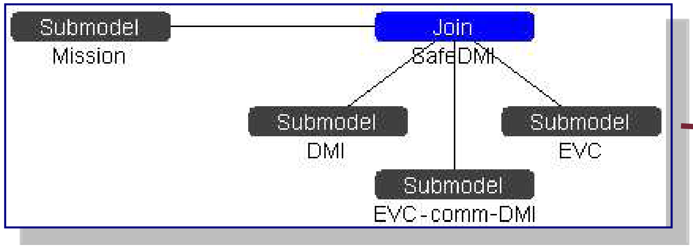
UML architecture model



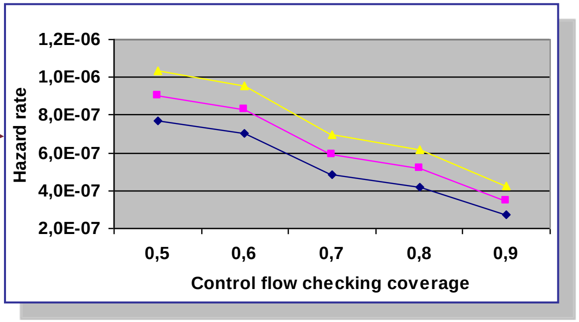
Dependability model construction

Analysis subnets





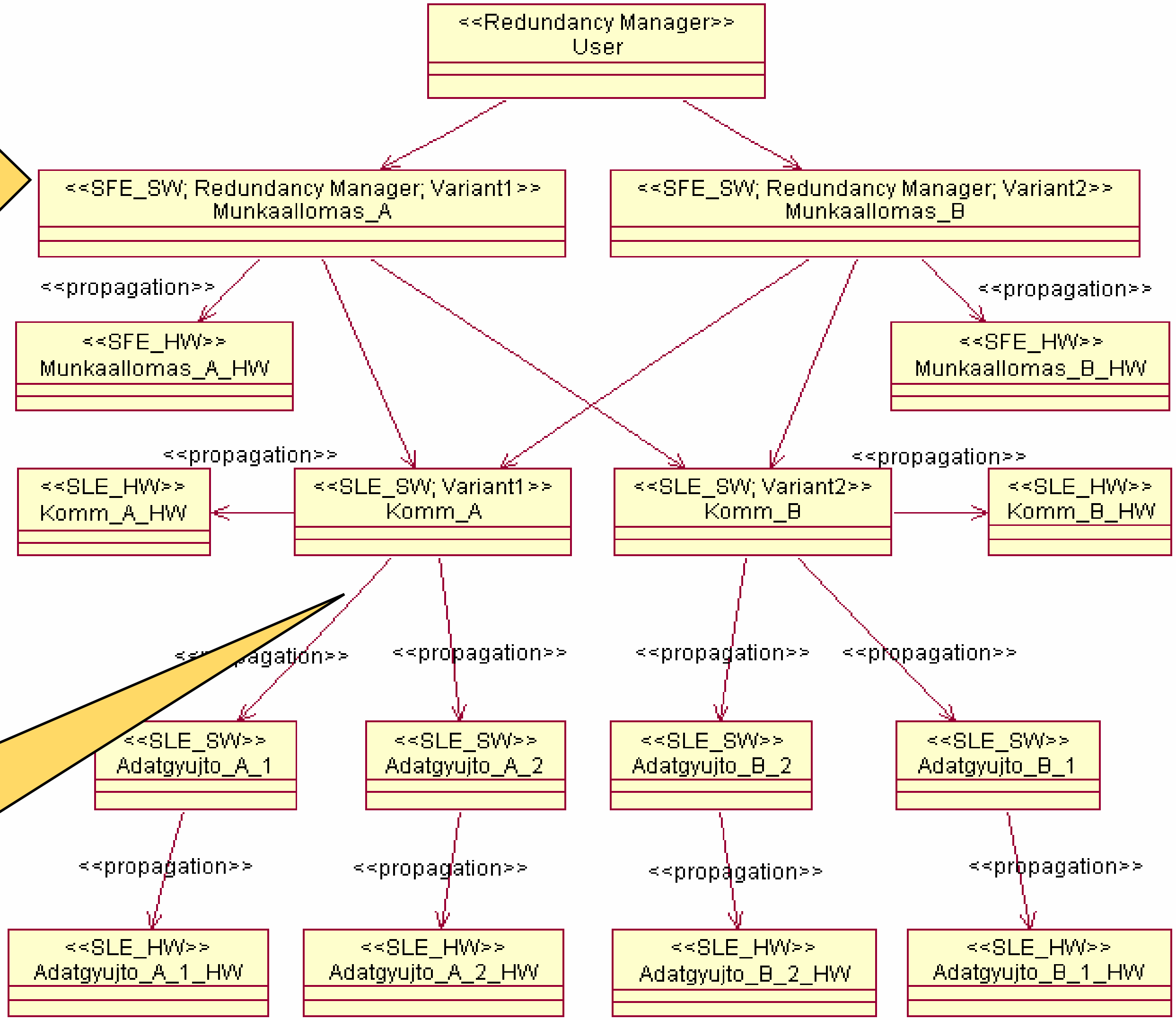
System level dependability model (Stochastic Activity Network)



Analysis results

Example: An extended architecture model

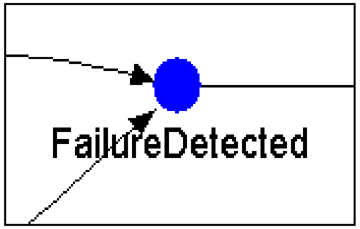
Components:
- Type (HW, SW)
- Role
  * variant,
  * manager
    in a redundancy
    structure
- Fault occurrence
  properties:
  * fault rate,
  * latency,
  * repair time



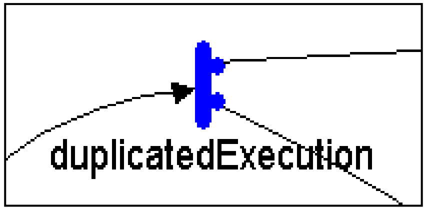
Relations:
- Fault propagation
  properties:
  * propagation
    probability

Example: Elements of a SAN analysis model

- Stochastic Activity Network (SAN)
- Places: Represent conditions
  - Valid if marked with a token



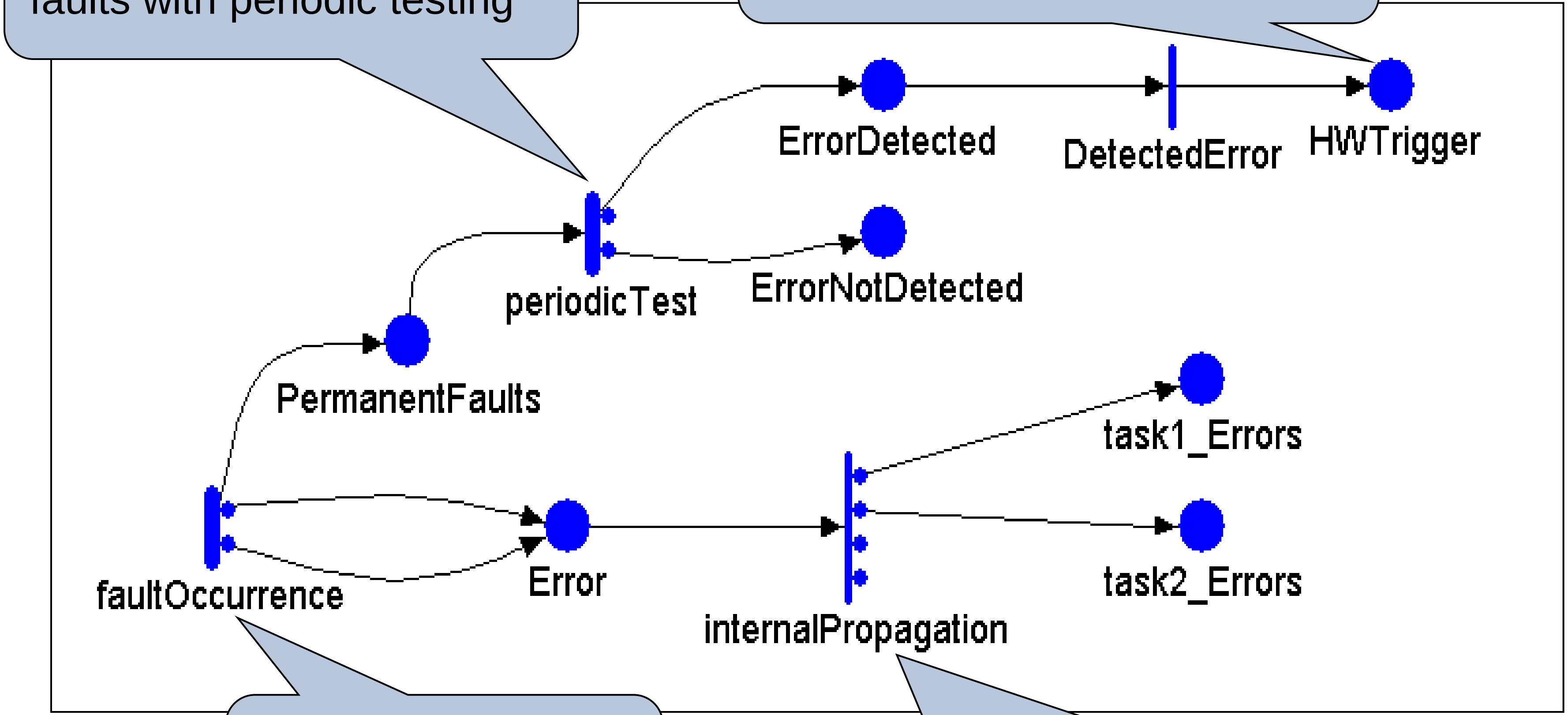
- Transitions: Events with cases
  - Occurrence of a case removes a token from each input place and puts a token to each output place
  - Rate of the event (or delay distribution)
  - Probabilities of different cases



Example: Analysis model of a hardware resource

Detection of permanent faults with periodic testing

Detected errors trigger a fault handling (e.g., stopping)

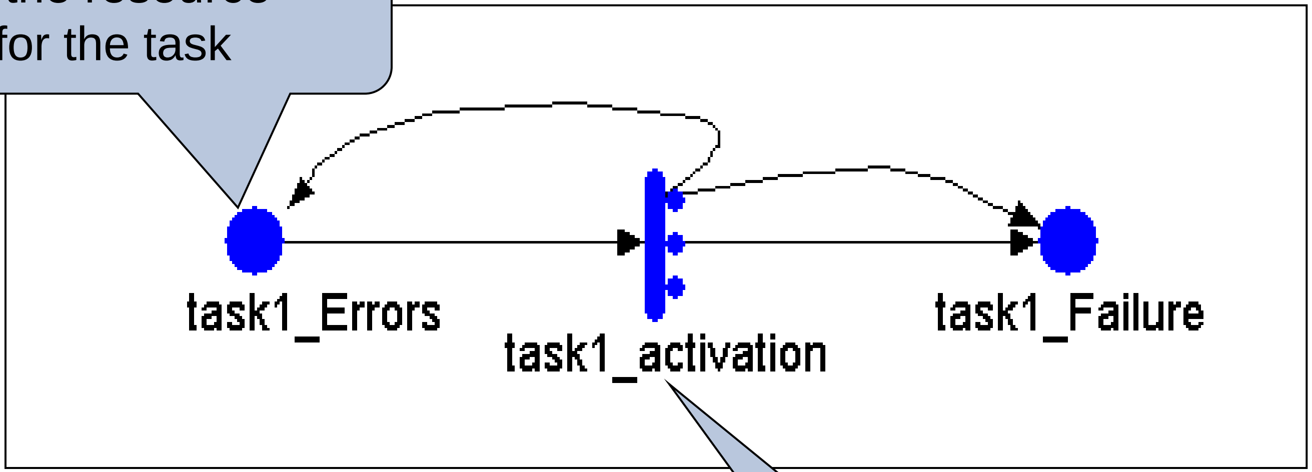


Occurrence of permanent or transient faults

Propagation of errors towards tasks that use this resource (according to the proportion of usage)

Example: Analysis model of error propagation

Errors in the resource relevant for the task



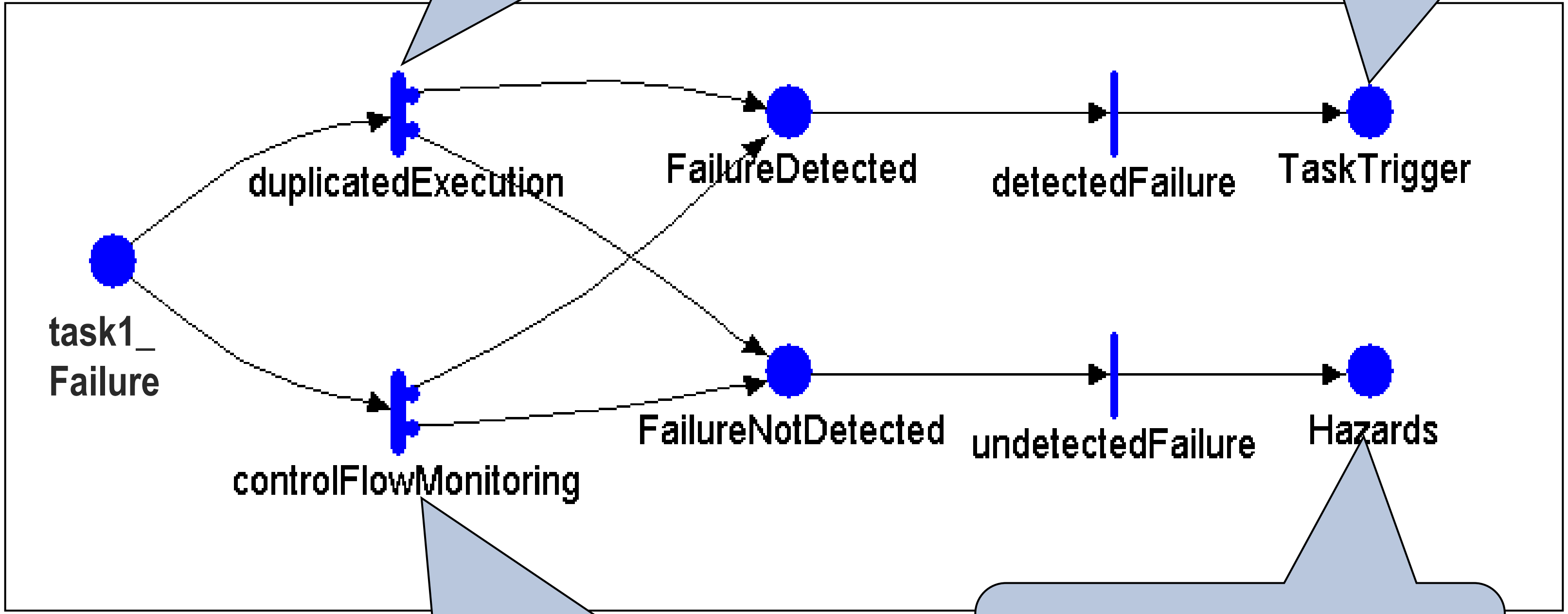
Task execution rate with potential error activation:

- Activated error, remaining in the system
- Activated error, overwritten
- Overwritten error with no effect

Example: Analysis model of a task

Error detection technique with given rate and coverage

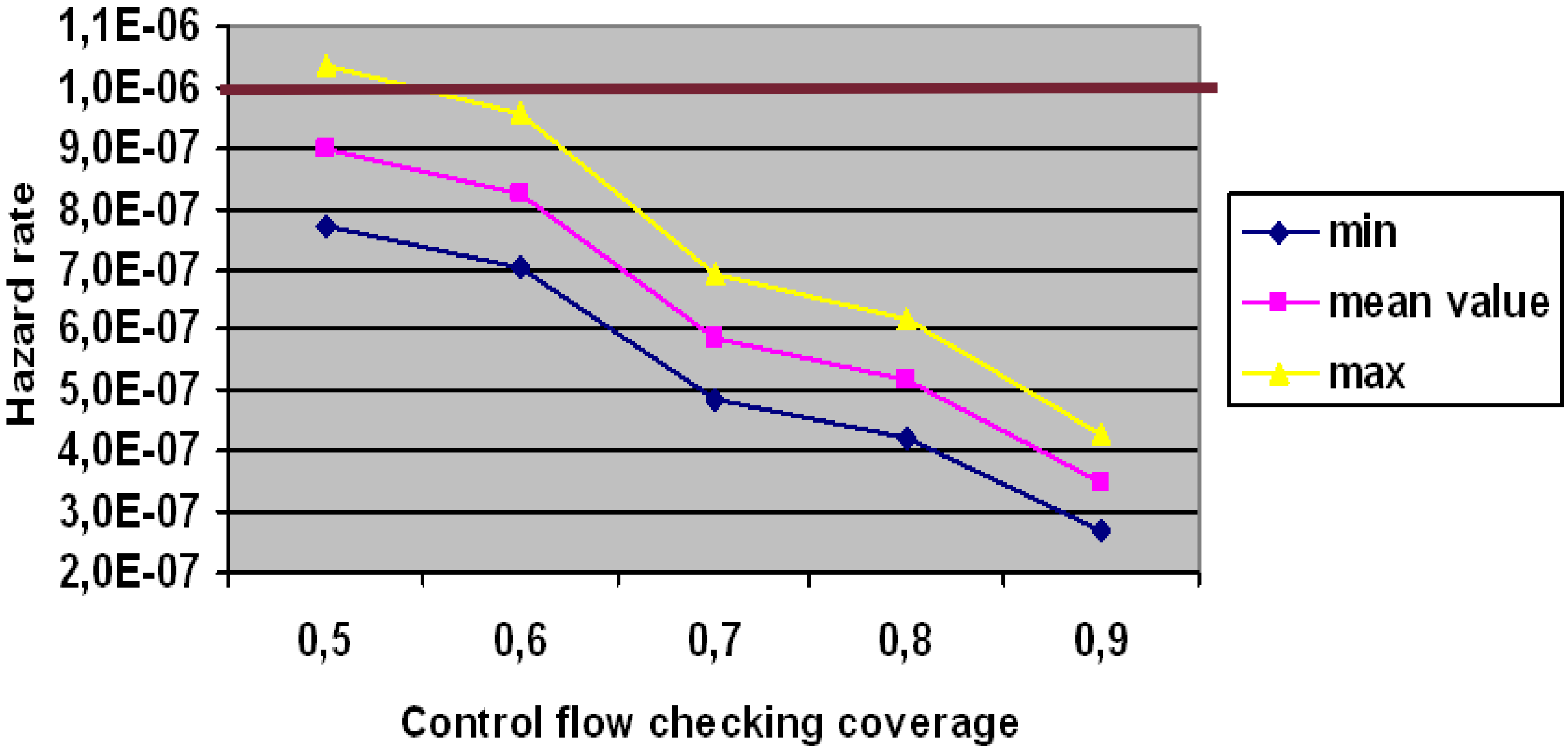
Detected failures will trigger fault handling (e.g., stopping)



Error detection technique with given rate and coverage

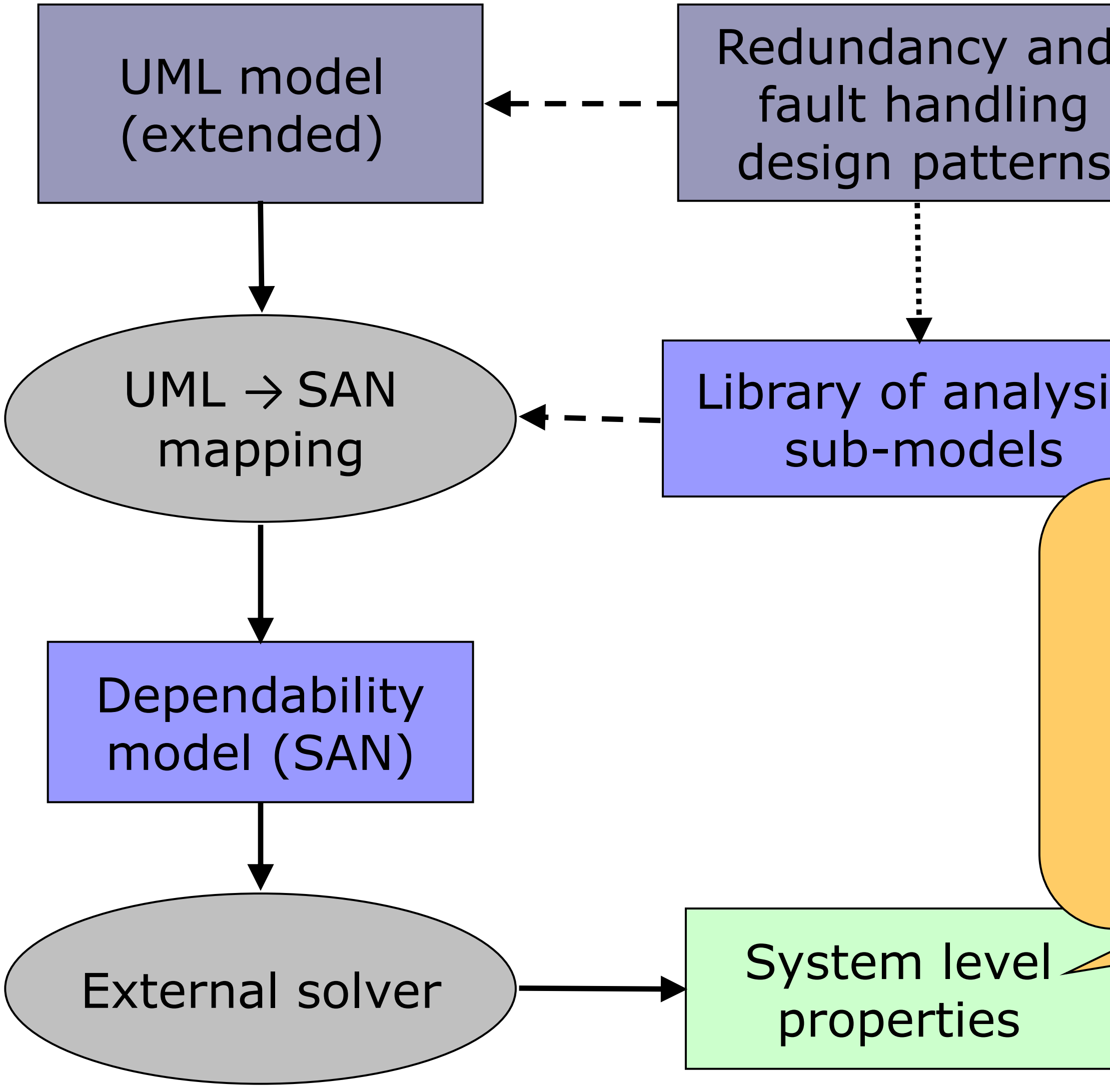
Undetected failure becomes a hazard

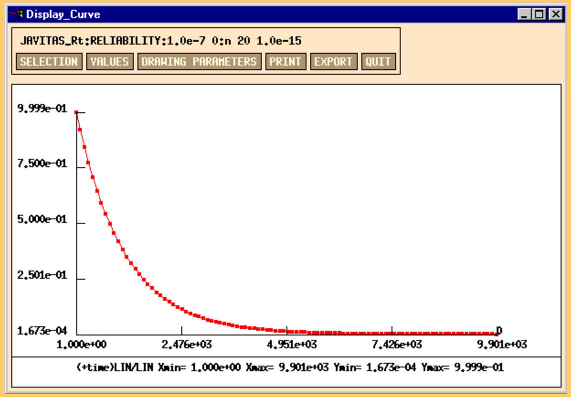
Example: Analysis of hazard rate



Outcome: If the coverage falls below 50% then the SIL2 requirement (10^{-7} < Hazard rate < 10^{-6}) is not satisfied

Example: Summary of the analysis steps


UML model (extended)
Redundancy and fault handling design patterns
UML → SAN mapping
Library of analysis sub-models
Dependability model (SAN)
External solver
System level properties



```
JAVITAS_Rt:RELIABILITY:1,0e-7 0:n 20 1,0e-15
```

```
(+time)LIN/LIN Xmin= 1,000e+00 Xmax= 9,901e+03 Ymin= 1,673e-04 Ymax= 9,999e-01
```

Summary

- Motivation
  - What is determined by the architecture?
  - What kind of verification methods can be used?
- Requirements based architecture analysis
  - ATAM: Architecture Trade-off Analysis
- Systematic analysis methods
  - Interface analysis
  - Fault effects analysis
- Model based evaluation
  - Performance evaluation
  - Dependability modeling and analysis