Safety-critical systems: Evaluation

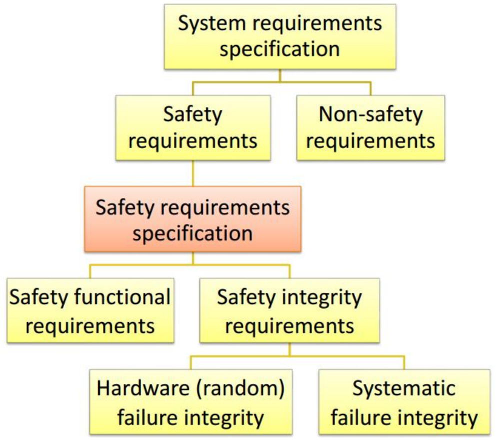
Systems Engineering course

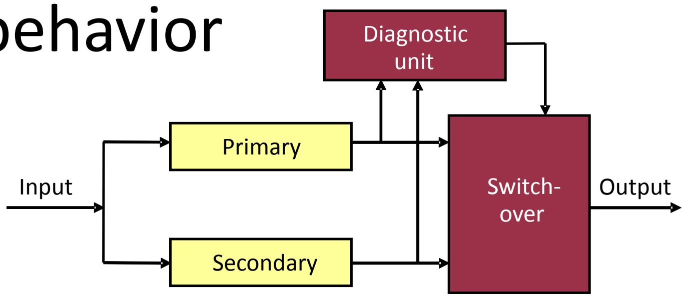
András Vörös
(slides: István Majzik)

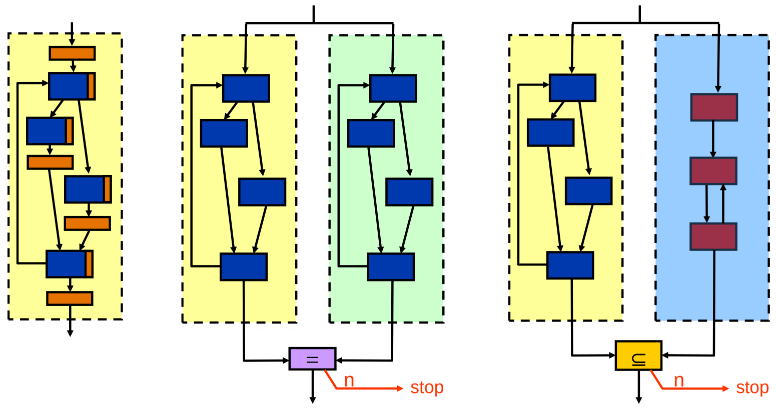
Overview of the goals

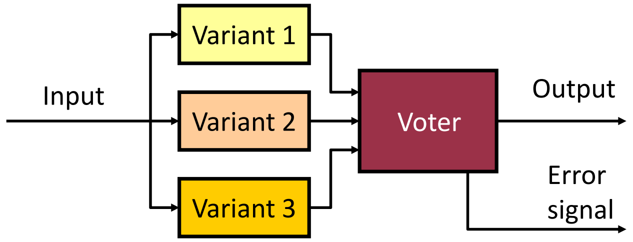
Previous topics

- Specification in safety-critical systems
  - Safety function requirements
  - Safety integrity requirements
  - Dependability requirements
- Architecture design (patterns)
  - Error detection for fail-stop behavior
  - Fault tolerance for fail-operational behavior


System requirements specification
Safety requirements
Non-safety requirements
Safety requirements specification
Safety functional requirements
Safety integrity requirements
Hardware (random) failure integrity
Systematic failure integrity







Goals

- Safety critical systems study block
  1. Requirements in critical systems: Safety, dependability
  2. Architecture design (patterns) in critical systems
  3. Evaluation of system architecture

- Focus: Evaluation of the system architecture to ...
  - Analyze the causes of potential hazards
  - Analyze the effects of component faults
  - Estimate risk: Hazards with rate (probability) and severity

    $\rightarrow$ check with respect to tolerable hazard rate (THR)
  - Calculate reliability and availability

Learning objectives

Evaluation of hazards and fault effects

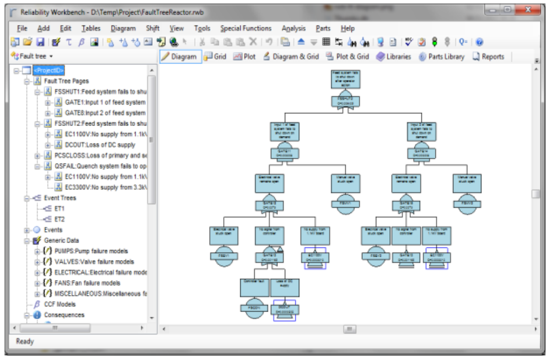
- Understand the role of architecture evaluation
- Know the typical techniques for the analysis
- Understand the method of risk estimation
- Perform evaluation of a concrete architecture

Evaluation of reliability and availability

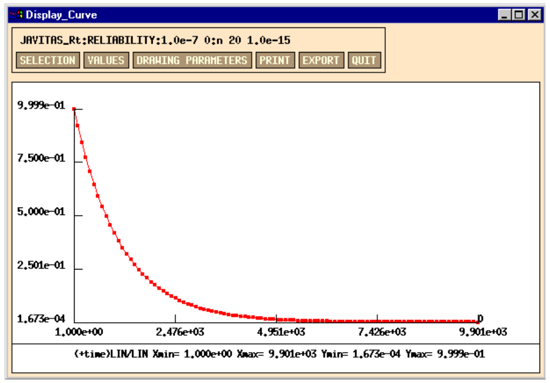
- Know the reliability block diagram technique
- Understand the limitations of the technique
- Perform evaluation in canonical systems

Overview: Evaluation techniques

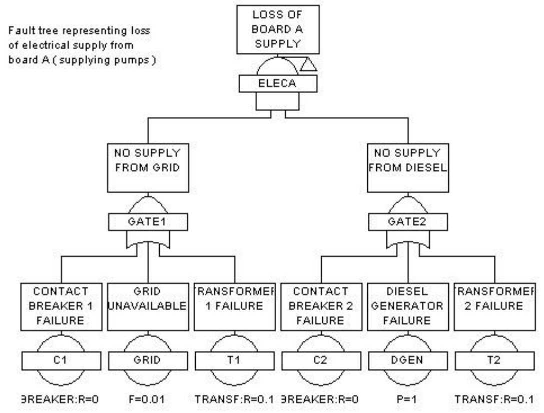
- Systematic analysis of hazard causes and fault effects (with risk estimation):
  - Fault tree analysis (FTA)
  - Event tree analysis (ETA)
  - Failure modes and effects analysis (FMEA)



- Quantitative reliability analysis:
  - Reliability block diagram (RBD) based calculation

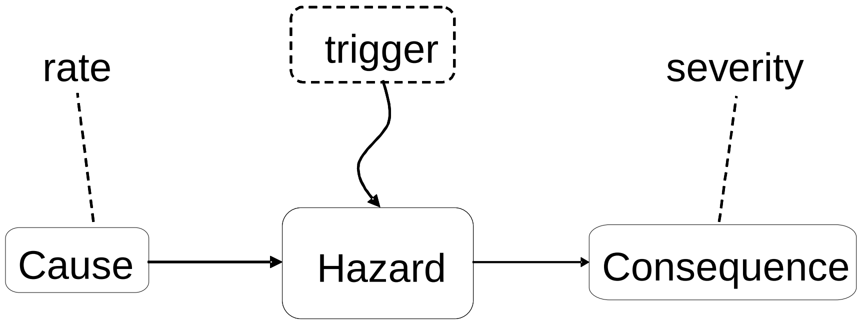


Fault tree analysis



Introduction: Hazard analysis

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



- These results form the basis for risk reduction

Categorization of the techniques

- On the basis of the development phase (tasks):
  - Design phase: Identification and analysis of hazards
  - Delivery phase: Demonstration of safety
  - Operation phase: Checking the modifications
- On the basis of the 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 (subsystems) to system level
    - Top-down: From the system level down to the components
- Systematic techniques are needed

Fault tree analysis

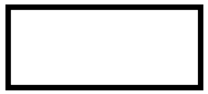
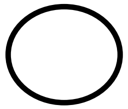
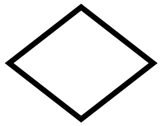
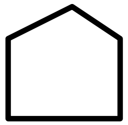
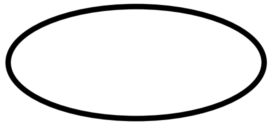
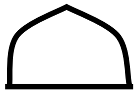
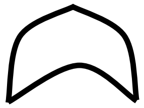
Analysis of the causes of system level hazards

- Top-down analysis
- Identifying the component level combinations of faults/events that may lead to hazard

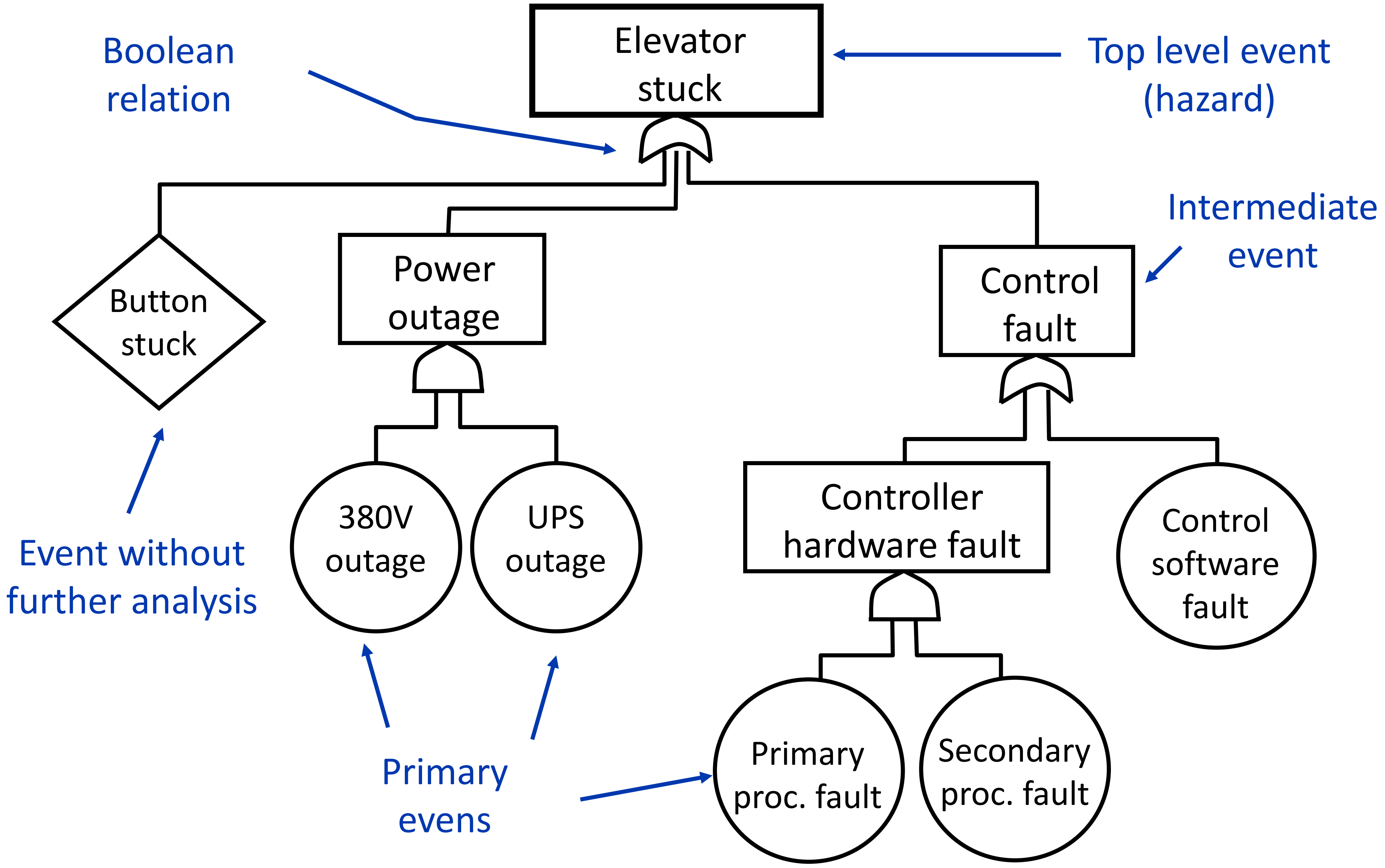
Construction of the fault tree

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

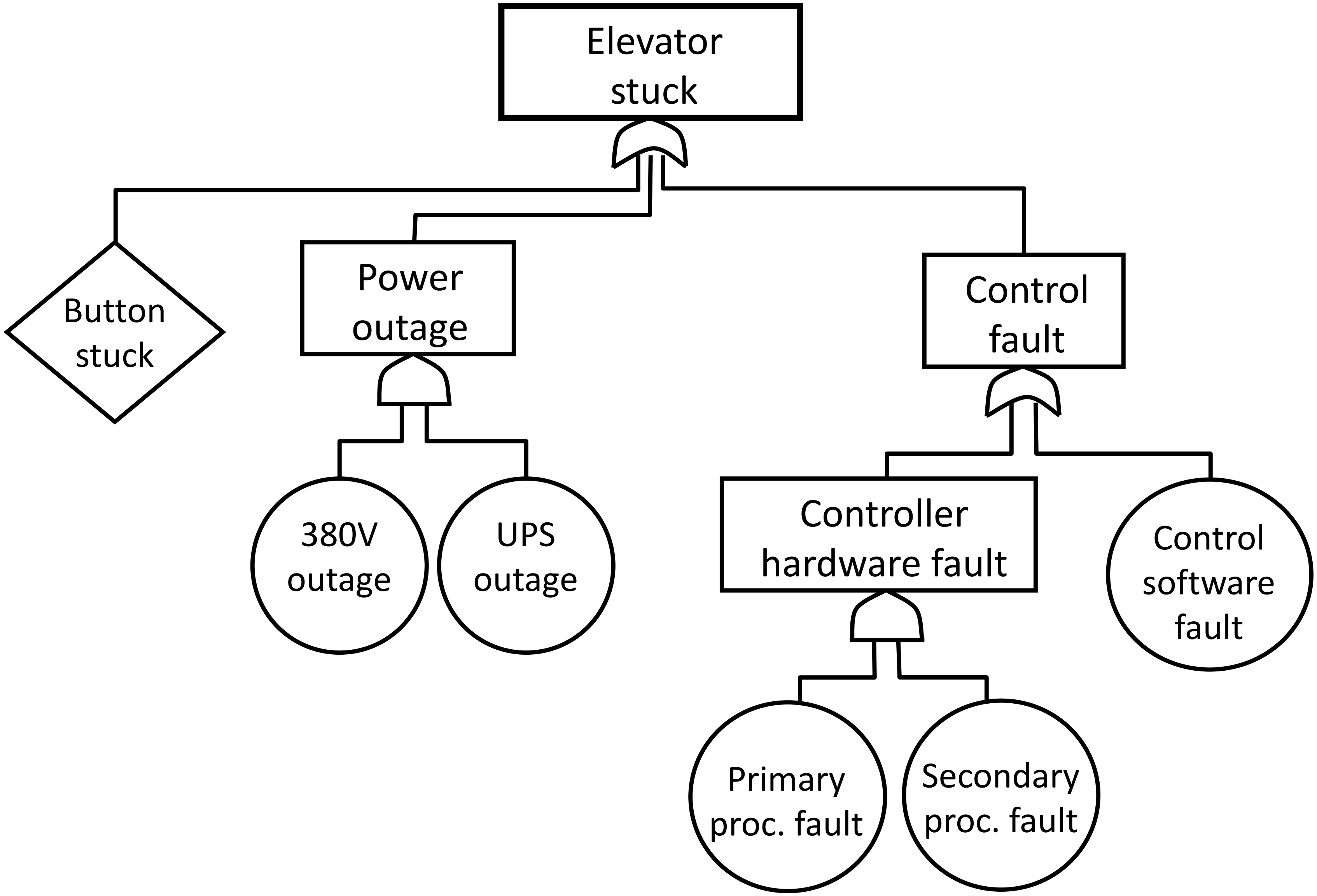
Fault tree example: Elevator



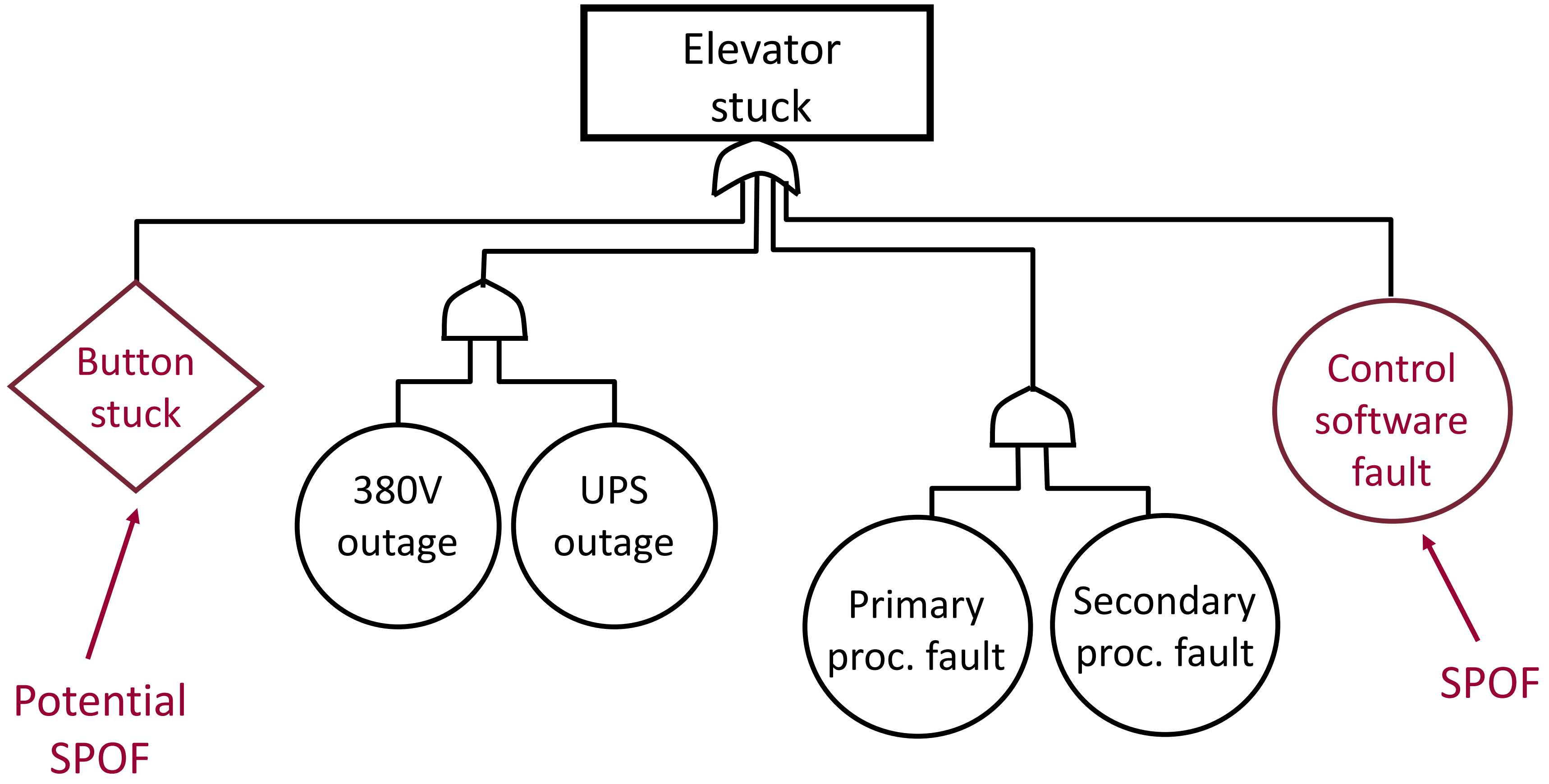
Qualitative analysis of the fault tree

- Fault tree reduction: Resolving intermediate events/pseudo-events using primary events
  $\rightarrow$ 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 a subset
- Outputs of the analysis of the reduced fault tree:
  - Single point of failure (SPOF)
  - Critical events that appear in several cuts

Original fault tree of the elevator example



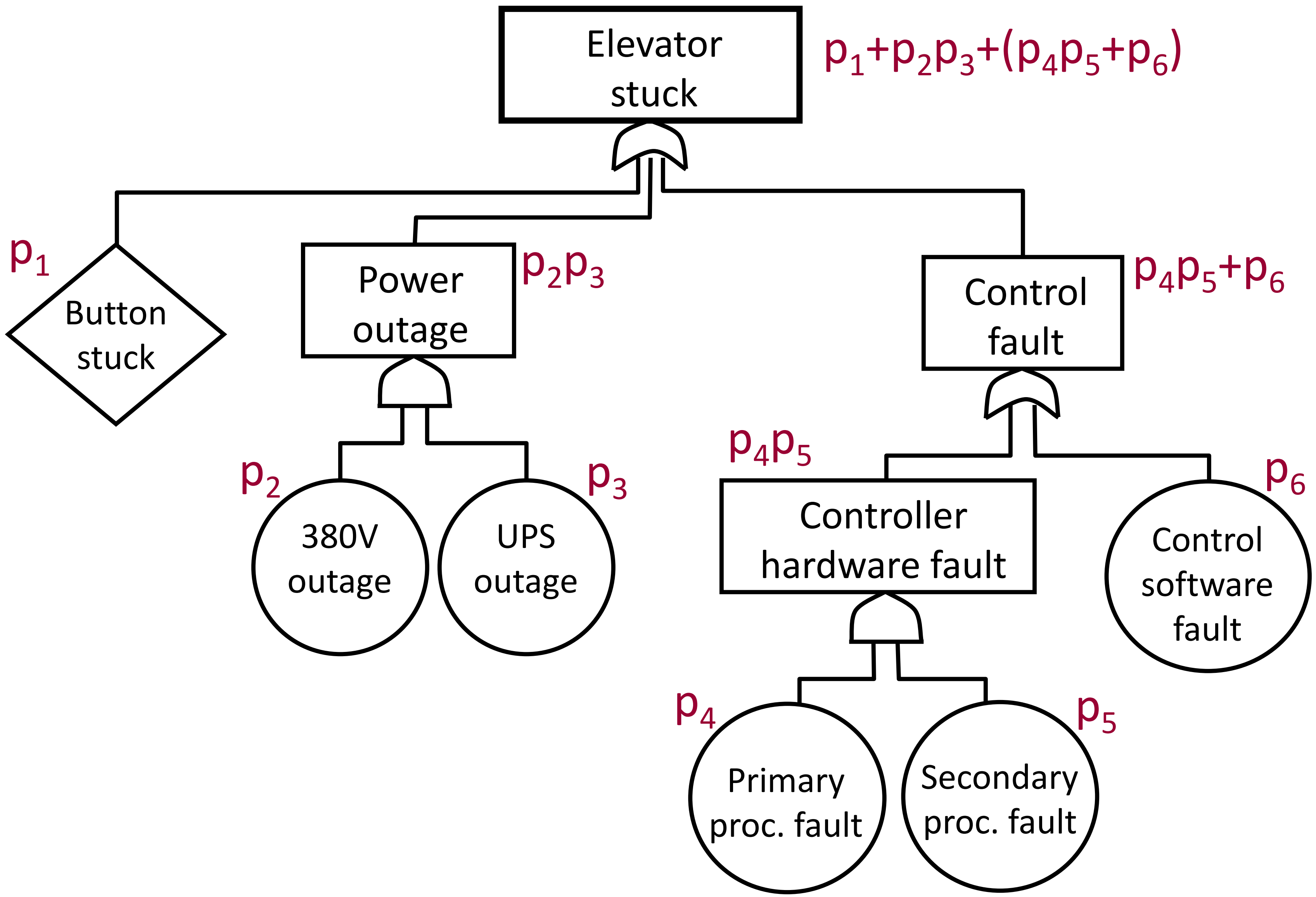
Reduced fault tree of the elevator example



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)
- Typical problems:
  - Correlated faults (not independent)
  - Handling of fault sequences

Fault tree of the elevator with probabilities

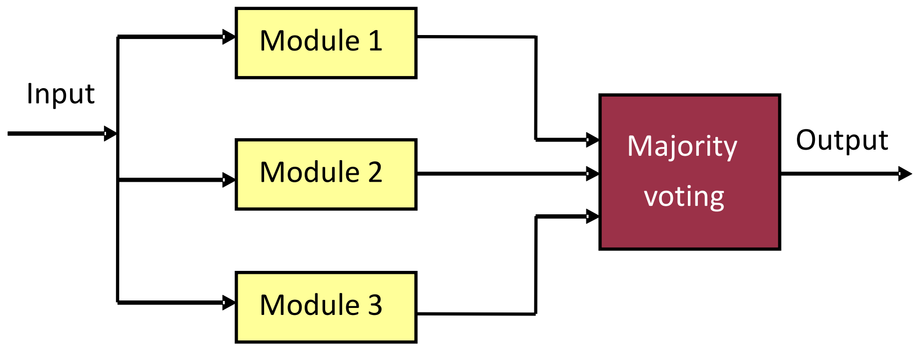


Exercise: Evaluation of an intrusion detection system

The intrusion detection system of a flat includes as detectors a door opening sensor, a pressure detector on the floor and a sound detector with an analogue sound filter.

These detectors are operated in a TMR structure with a voter component that is implemented using a microcontroller.

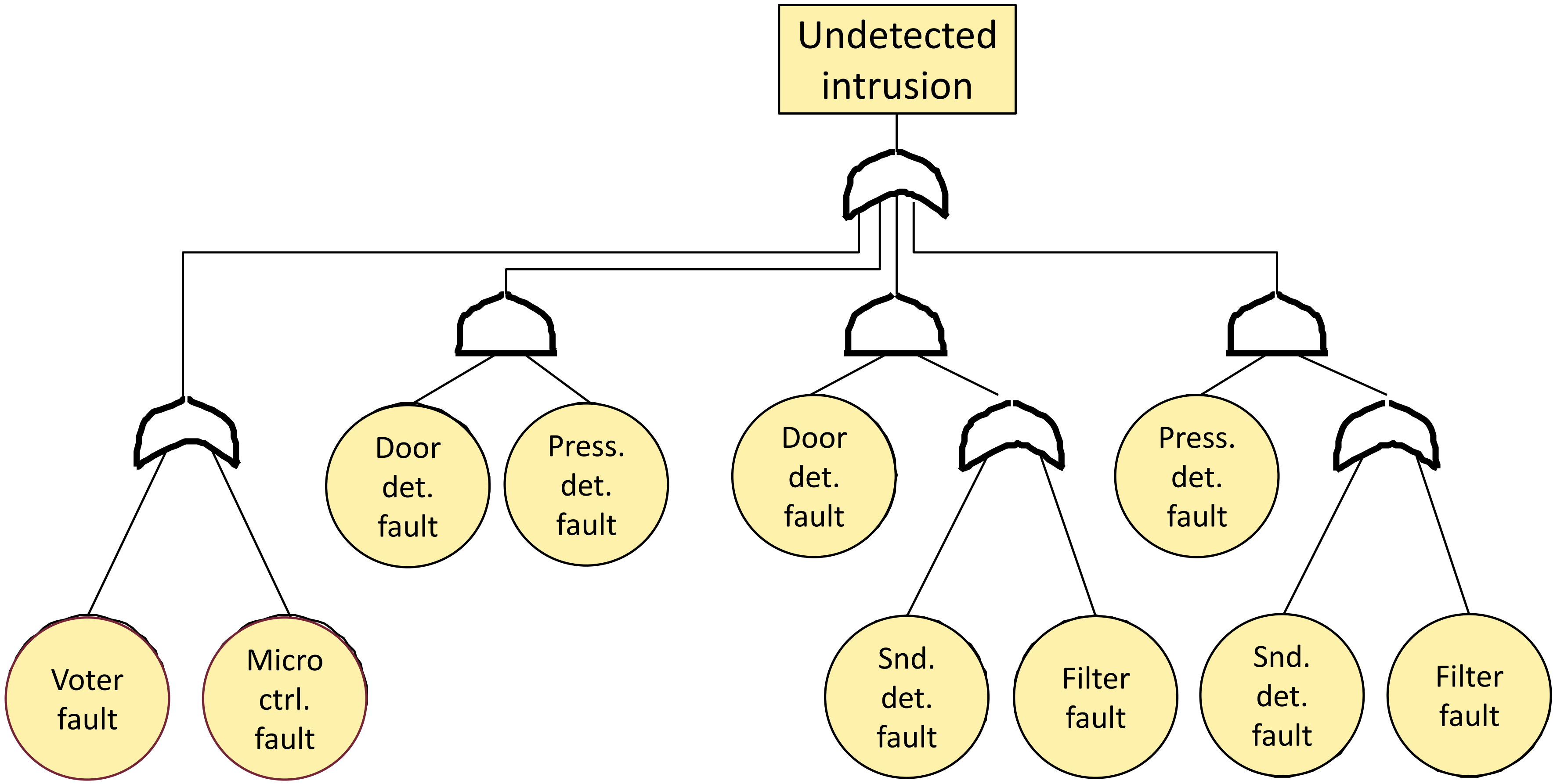
TMR:



Exercise:

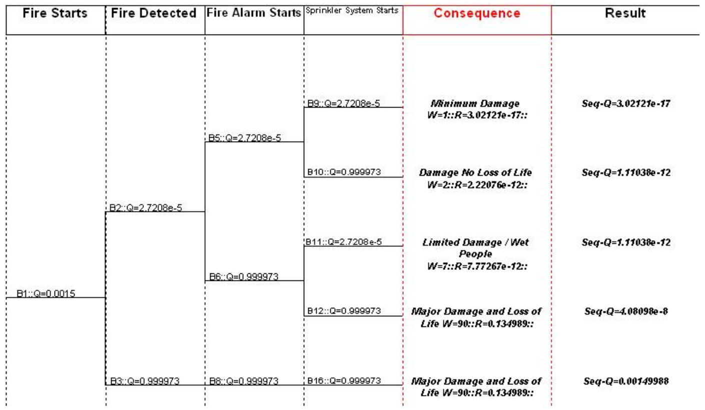
- Draw up the fault tree that belongs to the undetected intrusion as the top level hazard. The basic events are the faults of the above mentioned components (these faults are considered as independent).
- Indicate the single point of failure (if any).
- Is it possible to implement the recovery block structure on the microcontroller in order to tolerate the faults of the detectors?

Solution of the exercise



Single point of failure: Voter fault, microcontroller fault

Event tree analysis



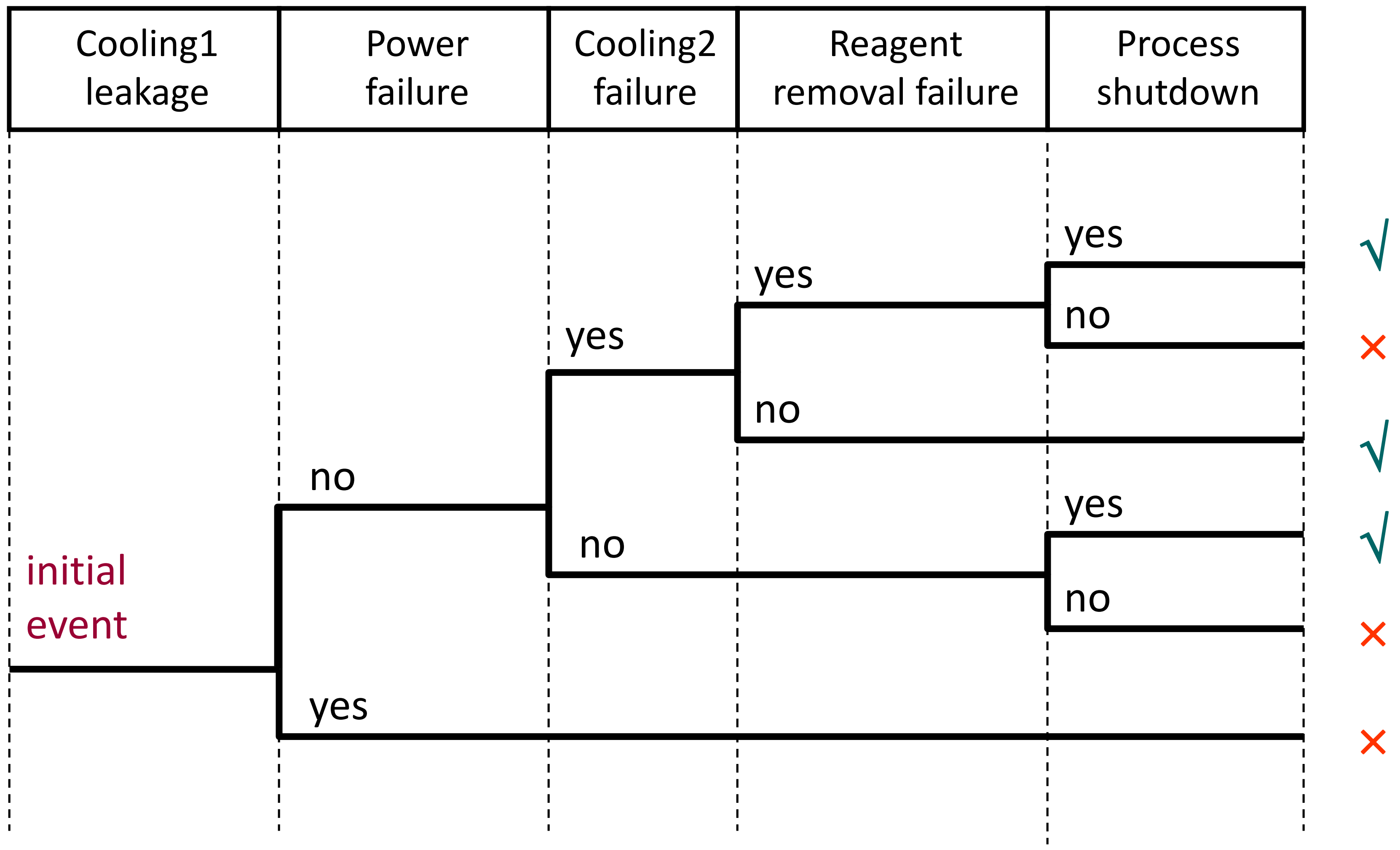
Event tree analysis

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

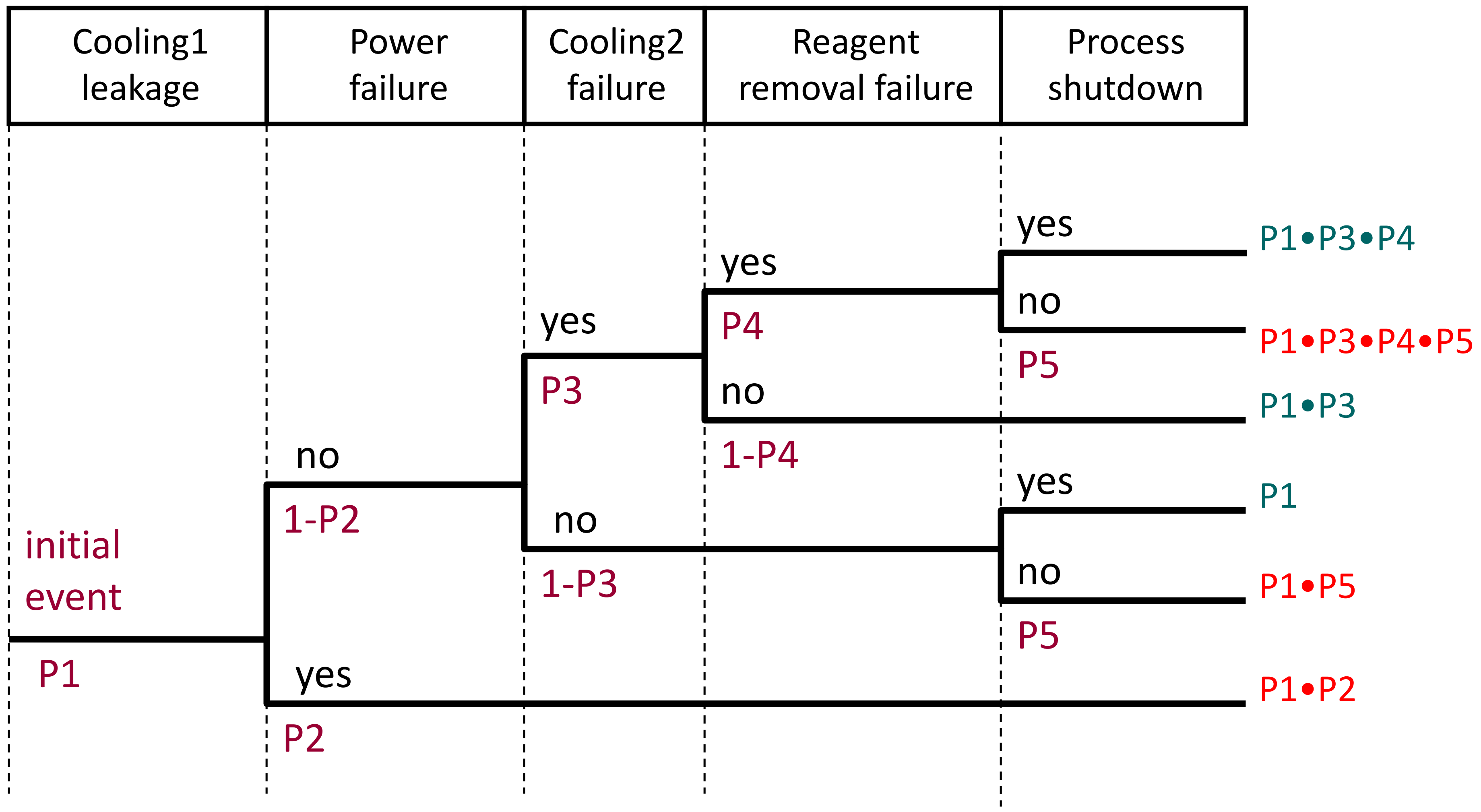
Initial event:	component level fault/event
Related events:	faults/events of other components
Ordering:	causality, timing
Branches:	depend on the occurrence of events

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

Event tree example: Reactor cooling



Event tree example: Reactor cooling



Exercise: Evaluation of sensor subsystem

The temperature of a hot water storage is measured using two sensors.

- The two sensors may be faulty with probability p1 and p2, in this case they report the invalid temperature +255°C.
- The faults of the sensors are checked by the controller performing an acceptance check.
- The sensor with p1 fault probability is the primary sensor. The secondary sensor is read only in case of detecting the fault of the primary sensor.
- In case of a faulty sensor, the acceptance check always detects the fault.
  However, due to a program bug, the acceptance check detects a sensor fault with probability pe even in case of a non-faulty sensor.

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  However, due to a program bug, the acceptance check detects a sensor fault with probability pe even in case of a non-faulty sensor.

Draw the event tree belonging to this system and calculate the probabilities of the scenarios.

The events:

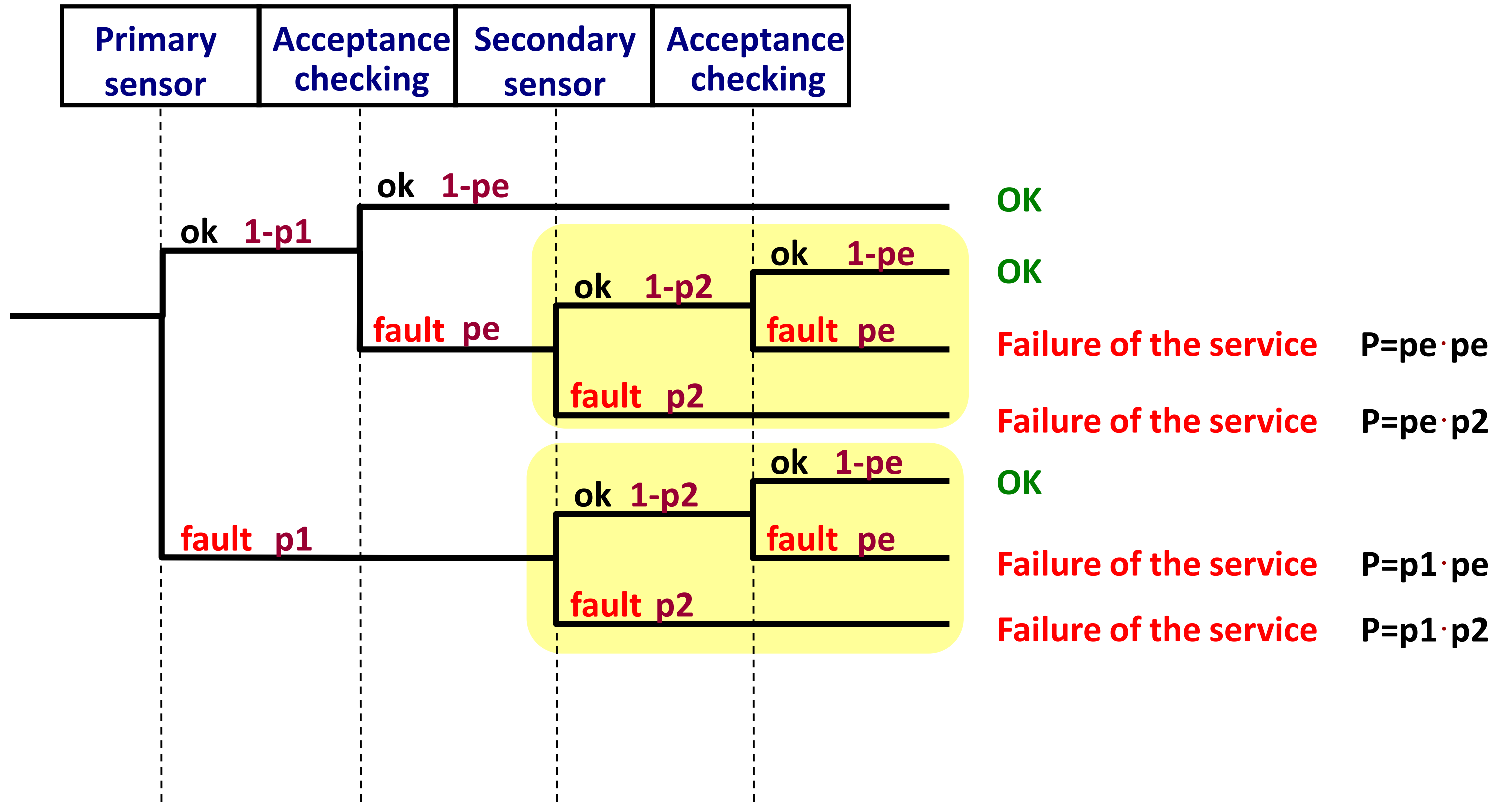
- Initial event: Starting the temperature measurement
- Further events: Faults of the sensors, fault of the acceptance checking

Ordering of events:

Primary sensor	← may be faulty with probability p1
Acceptance checking	← may be faulty with probability pe (in case of a non-faulty sensor)
Secondary sensor	← may be faulty with probability p2
Acceptance checking	← may be faulty with probability pe (in case of a non-faulty sensor)

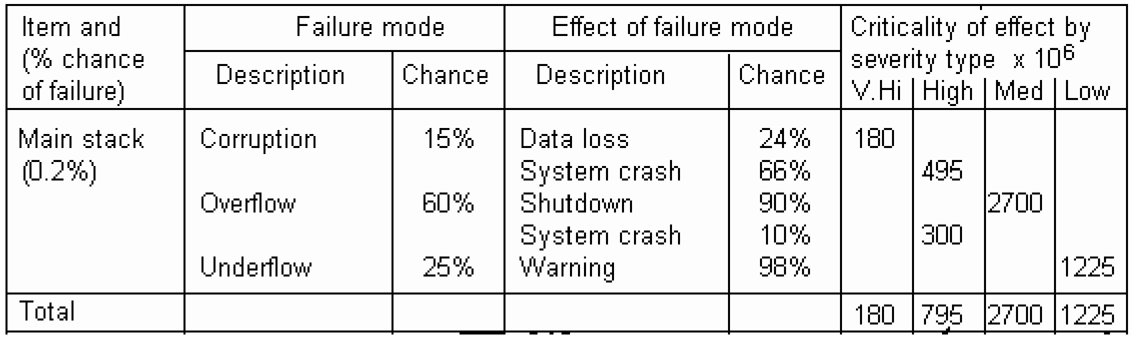
Solution of the exercise

Event tree:



Failure of the service at system level: pe·pe + pe·p2 + p1·pe + p1·p2

Failure modes and effects analysis



Item and (% chance of failure)	Failure mode		Effect of failure mode		Criticality of effect by severity type x 10^6			
	Description	Chance	Description	Chance	V.Hi	High	Med	Low
Main stack (0.2%)	Corruption	15%	Data loss	24%	180			
			System crash	66%		495		
	Overflow	60%	Shutdown	90%			2700	
			System crash	10%		300		
	Underflow	25%	Warning	98%				1225
Total					180	795	2700	1225

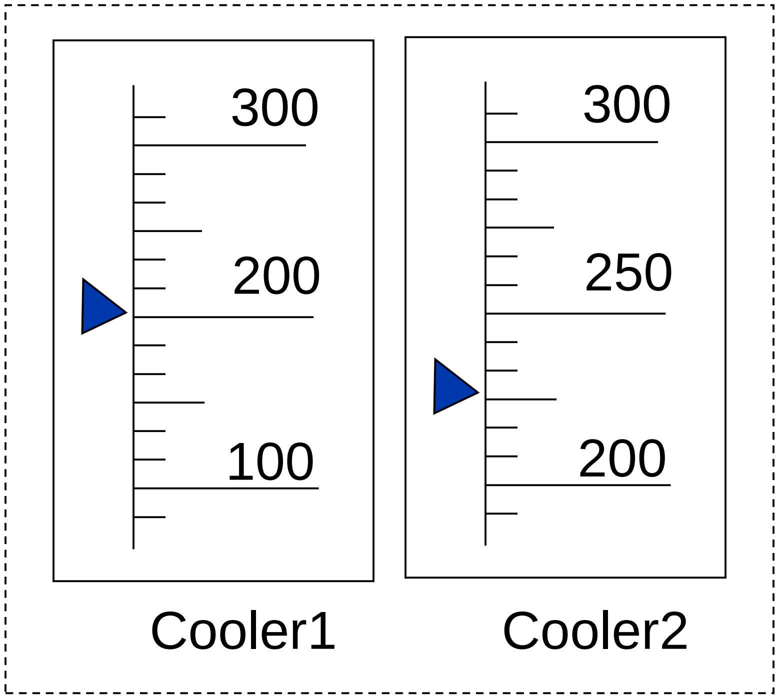
Failure modes and effects analysis (FMEA)

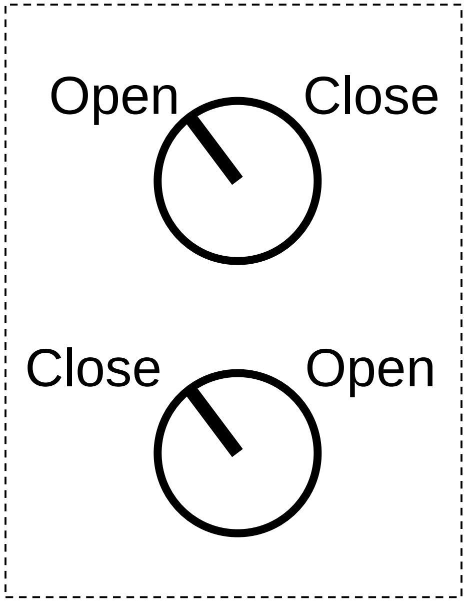
- Systematic investigation of component failure modes and their effects
- Advantages:
  - Known faults of components are included
  - Criticalities of effects can also be estimated (FMECA)

Component	Failure mode	Probability	Effect
D1 diode	Open circuit	65%	Over-heating
	Short circuit	35%	Missing output
…	…	…	…

Analysis of operator faults

- Qualitative techniques:
  - Operation – hazards – effects – causes – mitigations
  - Analysis of physical and mental demands
  - Fault causes ← human-machine interface problems





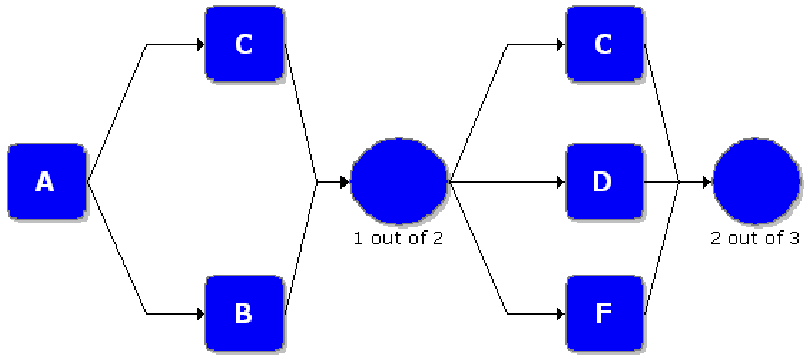
Outcome of hazard analysis

- Categorization of hazards on the basis of hazard analysis (e.g., MIL-STD-822b, NASA):
  - Probability / rate of hazard occurrence calculated: Frequent, probable, occasional, remote, improbable, incredible
  - Severity level of hazard consequences estimated: Catastrophic, critical, marginal, insignificant
- Identification of risks
- Output of the rate and severity analysis:
  - Risk matrix
  - Protection level: Identifies the risks to be handled

Example: Risk matrix (railway control systems)

	Frequency of Occurrence of a Hazardous Event	**RISK LEVELS**			
Daily to monthly	**FREQUENT (FRE)**	Undesirable (UND)	Intolerable (INT)	Intolerable (INT)	Intolerable (INT)
Monthly to yearly	**PROBABLE (PRO)**	Tolerable (TOL)	Undesirable (UND)	Intolerable (INT)	Intolerable (INT)
Between once a year and once per 10 years	**OCCASIONAL (OCC)**	Tolerable (TOL)	Undesirable (UND)	Undesirable (UND)	Intolerable (INT)
Between once per 10 years and once per 100 years	**REMOTE (REM)**	Negligible (NEG)	Tolerable (TOL)	Undesirable (UND)	Undesirable (UND)
Less than once per 100 years	**IMPROBABLE (IMP)**	Negligible (NEG)	Negligible (NEG)	Tolerable (TOL)	Tolerable (TOL)
	INCREDIBLE (INC)	Negligible (NEG)	Negligible (NEG)	Negligible (NEG)	Negligible (NEG)
		INSIGNIFICANT (INS)	**MARGINAL (MAR)**	**CRITICAL (CRI)**	**CATASTROPHIC (CAT)**
		Severity Levels of Hazard Consequence			

Reliability block diagrams



Boole model for calculating dependability

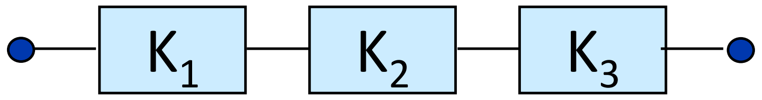
- Boole model of components
  - Two states: Fault-free (good) or faulty (bad)
  - No dependences regarding faults or repairing
- Relation of components from the point of view of dependability: What kind of redundancy is used?
  - Serial connection:
    - If both components are necessary for the operation of the system
    - I.e., the components are not redundant
  - Parallel connection:
    - If the components may replace each other in case of their failure
    - I.e., the components are redundant

The connection may depend on the failure modes

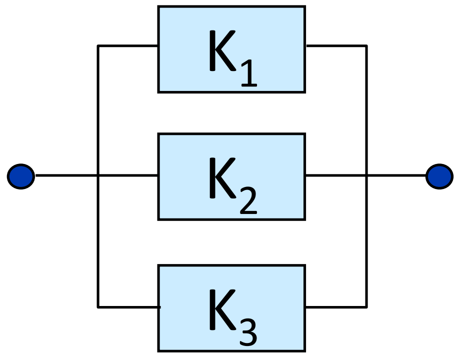
Reliability block diagram

- Blocks: Components
- Connections: Serial or parallel (redundancy)
- Paths: Operational system configurations
  - The system is operational (correct) if there is a path from the start point to the end point of the diagram through fault-free components

Serial:

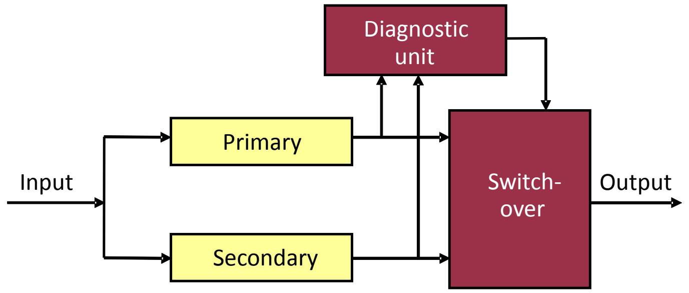


Parallel:

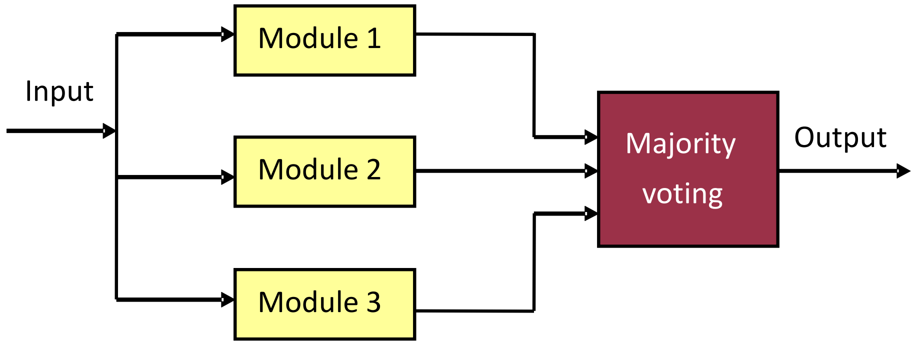


Overview: Typical system configurations

- Serial system model: no redundancy
- Parallel system model: redundancy (replication)



- Complex canonical system: redundant subsystems
- M faulty out of N components: Majority voting (TMR)



Previous topic: Attributes of components

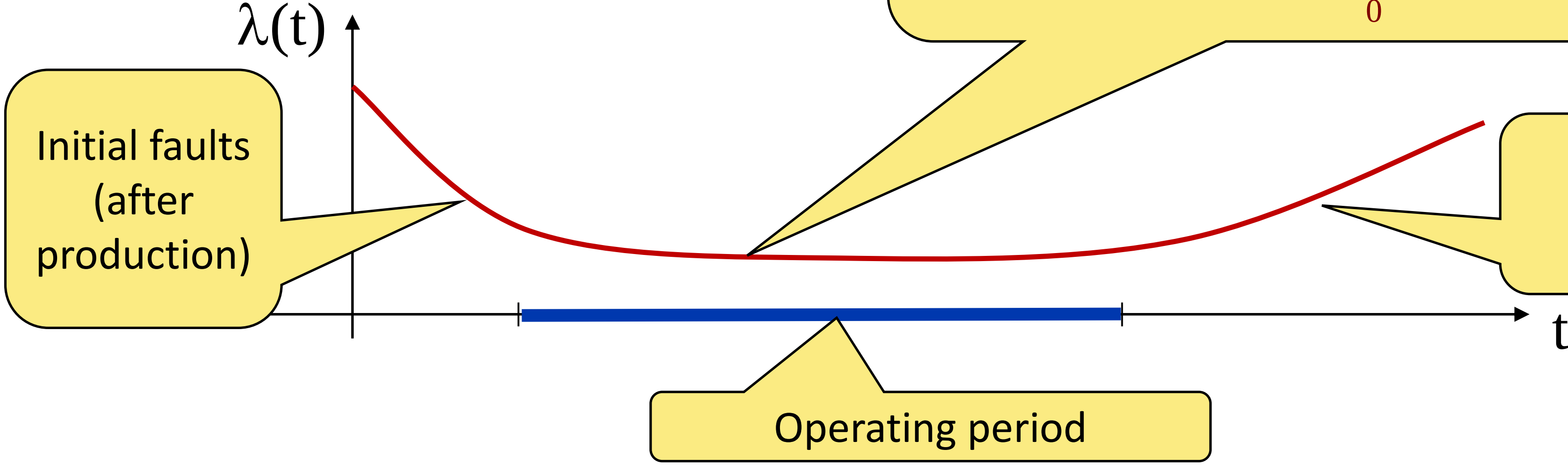
- Data from product sheet / reliability handbook:

  Fault rate: $\lambda(t)$

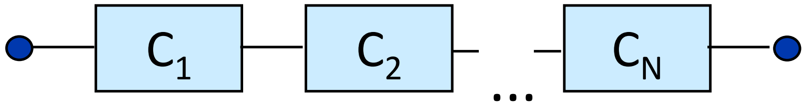
- Reliability of components: $r(t) = e^{-\int_0^t \lambda(t)dt}$
- For electronic components:

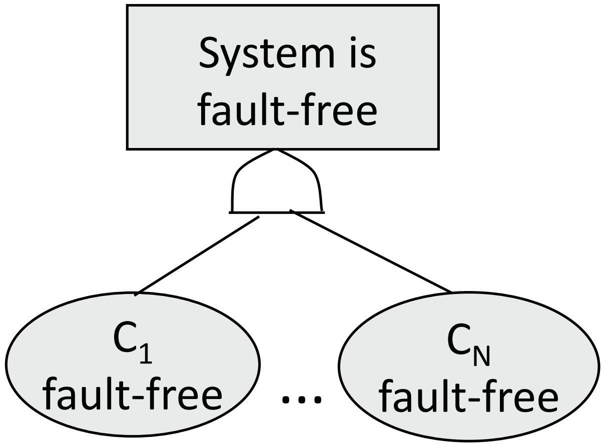
Here $r(t) = e^{-\lambda t}$

$$MTFF = E\{u1\} = \int_0^\infty r(t)dt = \frac{1}{\lambda}$$



Serial system





P(A∧B)=P(A)P(B)
if independent

- Reliability:

$$r_R(t) = \prod_{i=1}^{N} r_i(t)$$

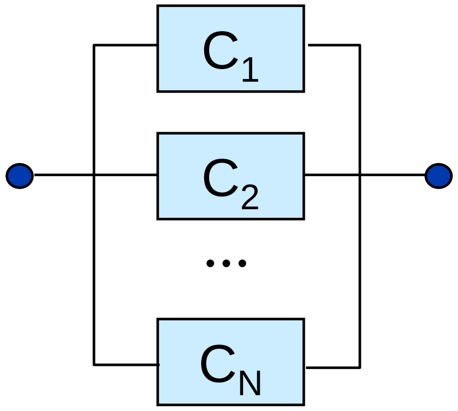
System level reliability

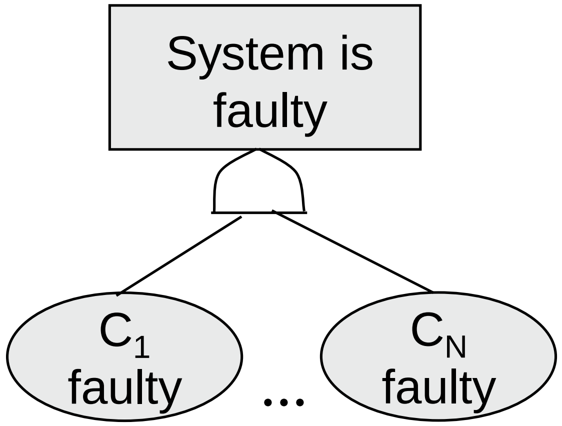
Component reliability

- MTFF:

$$MTFF = \frac{1}{\sum_{i=1}^{N} \lambda_i}$$

Parallel system





P(A∧B)=P(A)P(B) if independent

- Reliability:

$$1 - r_R(t) = \prod_{i=1}^{N} (1 - r_i(t))$$

- Uniform N components:

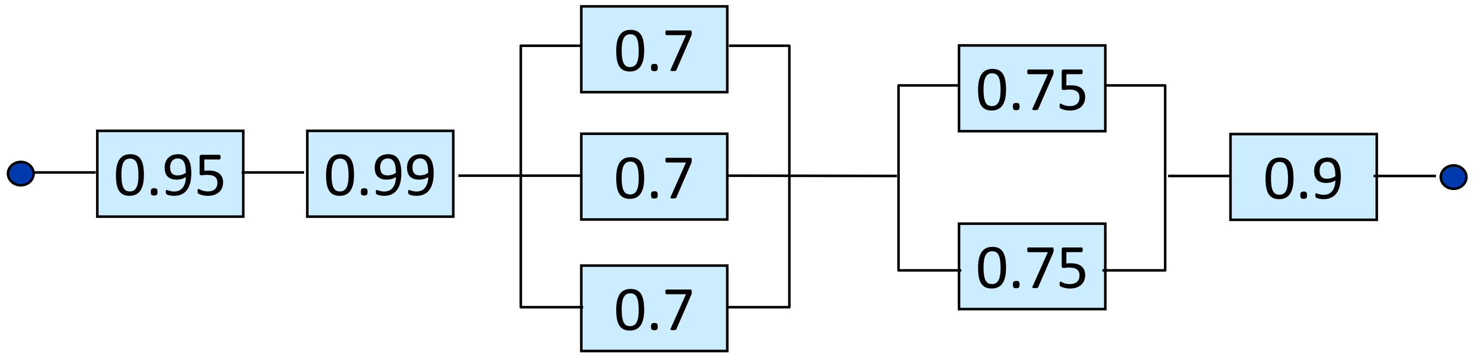
$$r_R(t) = 1 - (1 - r_K(t))^N$$

- MTFF (without explanation):

$$MTFF = \frac{1}{\lambda} \sum_{i=1}^{N} \frac{1}{i}$$

Complex canonical system

- Calculation on the basis of parts with basic connections
  - Example: Calculation of asymptotic availability



$$K_R = 0.95 \cdot 0.99 \cdot \left[1-(1-0.7)^3\right] \cdot \left[1-(1-0.75)^2\right] \cdot 0.9$$

M faulty out of N components

- N replicated components;
  If M or more components faulty: the system is faulty

$$r_R = \sum_{i=0}^{M-1} P\left\{\text{"there are i faults"}\right\}$$

$$r_R = \sum_{i=0}^{M-1} \binom{N}{i} (1-r)^i \cdot r^{N-i}$$

- Application: Majority voting (TMR): N=3, M=2

$$r_R = \sum_{i=0}^{1} \binom{3}{i} (1-r)^i \cdot r^{3-i} = \binom{3}{0} (1-r)^0 \cdot r^3 + \binom{3}{1} (1-r)^1 \cdot r^2 = 3r^2 - 2r^3$$

$$MTFF = \int_0^\infty r_R(t)dt = \int_0^\infty (3r^2 - 2r^3)dt = \frac{5}{6} \cdot \frac{1}{\lambda}$$

Less than in the case of a single component!

Exercise: Availability of a SCADA system

A SCADA system consists of the following components:
4 data collector units, 3 control units, 2 supervisory servers, 1 logging server and the corresponding network

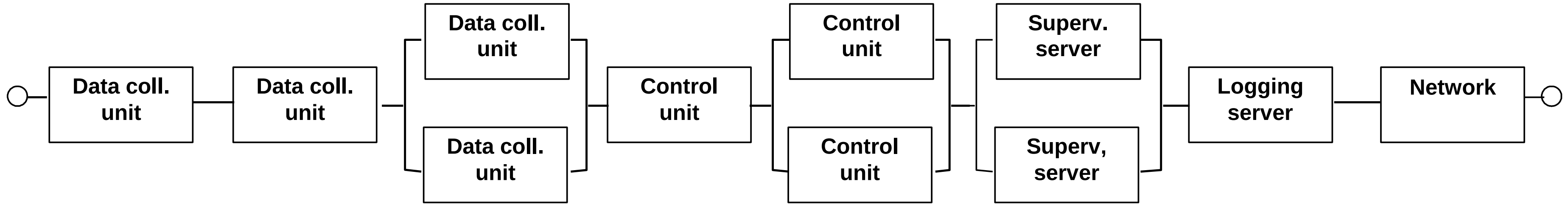
- The 2 supervisory servers are in a hot redundancy structure.
- Critical data collector and control units are in a hot redundancy structure: 2 data collector units and 2 control units are hot redundant units
- The reliability data of the system components are given as follows (measured in hours, with independent repairs in case of faults):

	Data coll. unit	Control unit	Superv. server	Logging server	Network
MTTF	9000	12000	4500	2000	30000
MTTR	2	3	5	1	2

- Evaluate the system level availability using a reliability block diagram.
- Compute the asymptotic availability of the system using the above given parameters of the system components.
- How many hours is the system out of service per year?

Solution of the exercise

Reliability block diagram:



Component level asymptotic availability: K = MTTF / (MTTF+MTTR)

	Data coll. unit (D)	Control unit (C)	Superv. server (S)	Logging server (L)	Network (N)
MTTF	9000	12000	4500	2000	30000
MTTR	2	3	5	1	2
K	KD=0.99977	KC=0.99975	KS=0.99889	KL=0.9995	KN=0.99993

System level asymptotic availability:

KD*KD*(1-(1-KD)*(1-KD))*KC*(1-(1-KC)*(1-KC))*(1-(1-KS)*(1-KS))*KL*KN = 0.9987362

Approx. 11 hours out of service per year

Summary

- Hazard analysis
  - Fault tree analysis
  - Event tree analysis
  - Failure modes and effects analysis (FMEA)
  - Risk matrix:
    - Severity level of hazard consequences
    - Rate of hazard occurrence
- Reliability analysis
  - Reliability block diagrams