Safety-critical systems: Basic definitions

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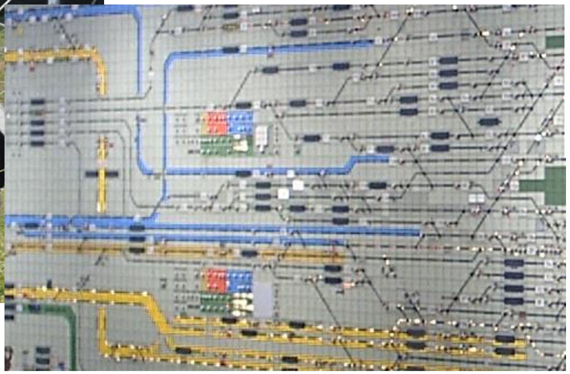
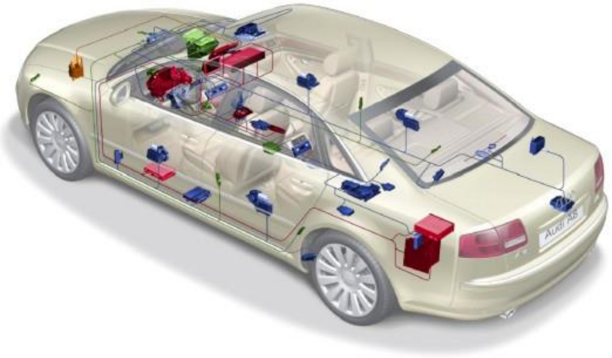
Introduction

- Safety-critical systems
  - Informal definition: Malfunction may cause injury of people
- Safety-critical computer-based systems
  - E/E/PE: Electrical, electronic, programmable electronic systems
  - Control, protection, or monitoring
  - EUC: Equipment under control





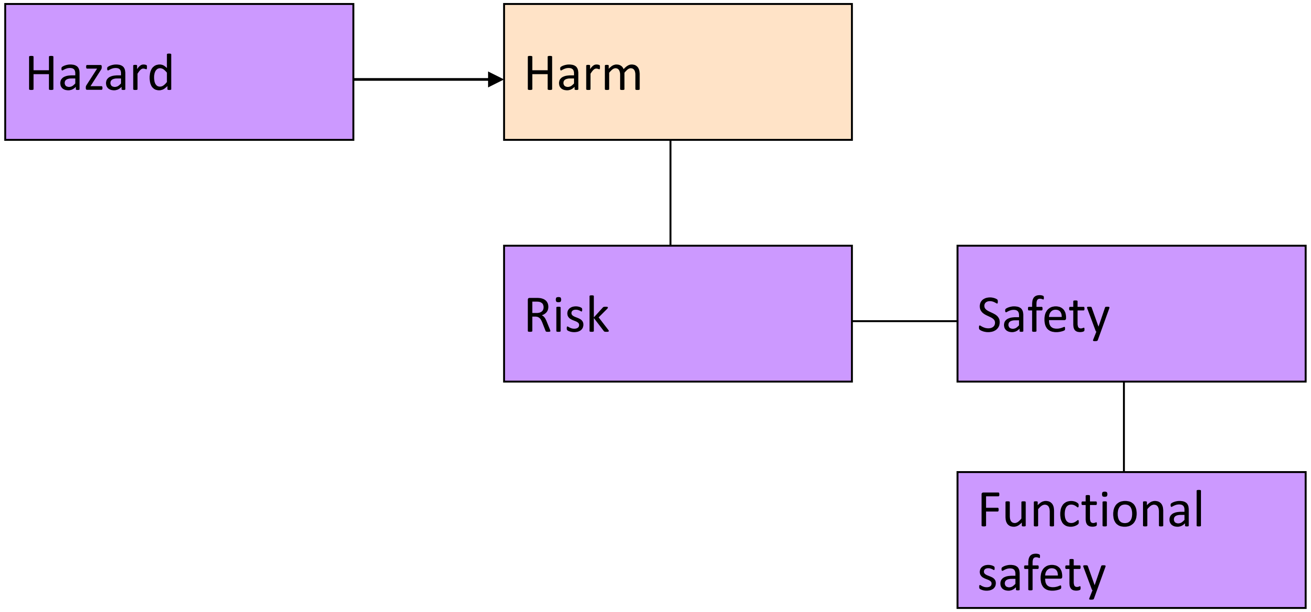
Railway signaling, x-by-wire, interlocking, emergency stopping, engine control, …

Specialities of safety critical systems

- Special solutions to achieve safe operation
  - Design: Requirements, architecture, tools, …
  - Verification, validation, and independent assessment
  - Certification (by safety authorities)
- Basis of certification: Standards
  - IEC 61508: Generic standard (for electrical, electronic or programmable electronic systems)
  - DO178B/C: Software in airborne systems and equipment
  - EN50129: Railway (control systems)
  - EN50128: Railway (software)
  - ISO26262: Automotive
  - Other sector-specific standards: Medical, process control, etc.

Definition of safety

- Central concepts: Hazard, risk and safety



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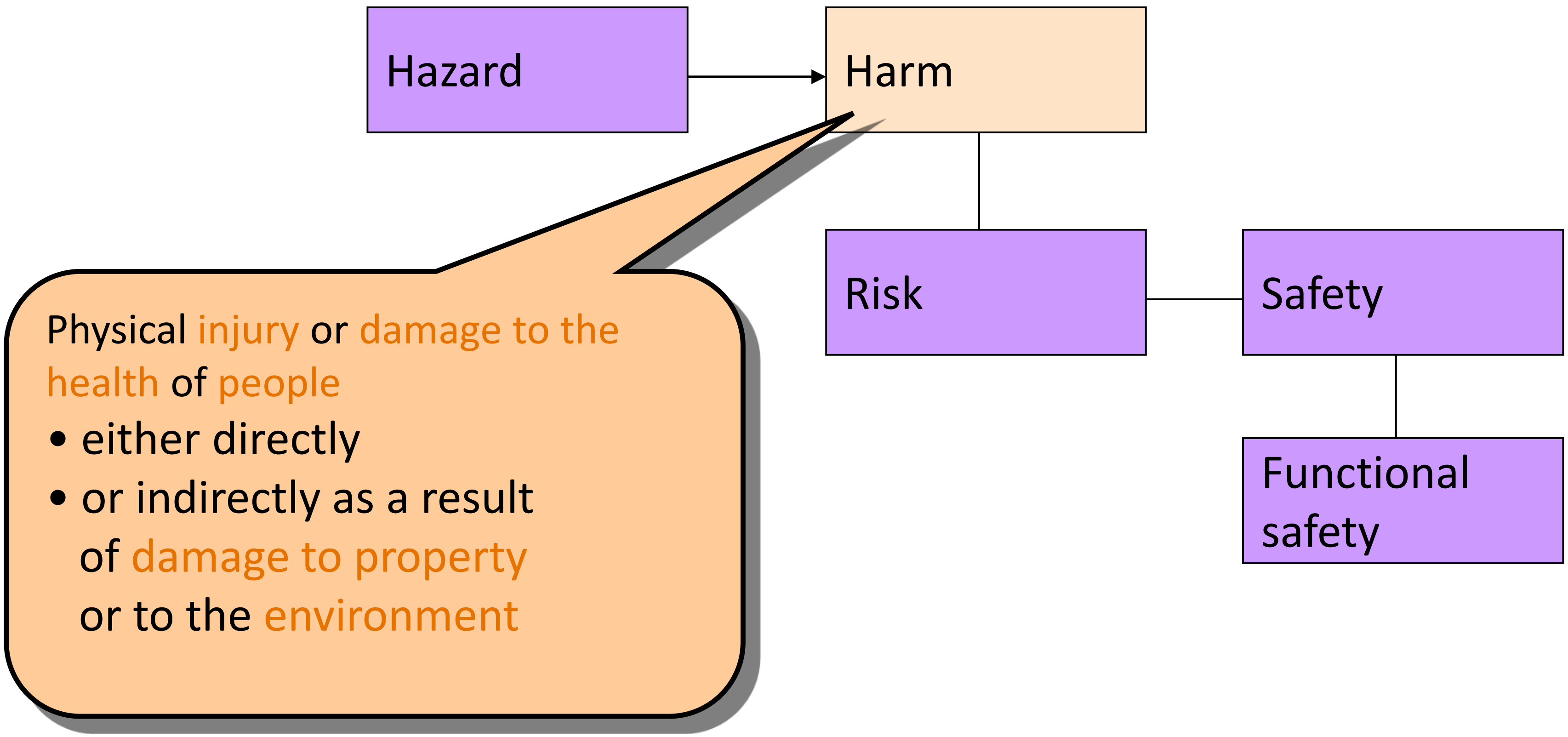

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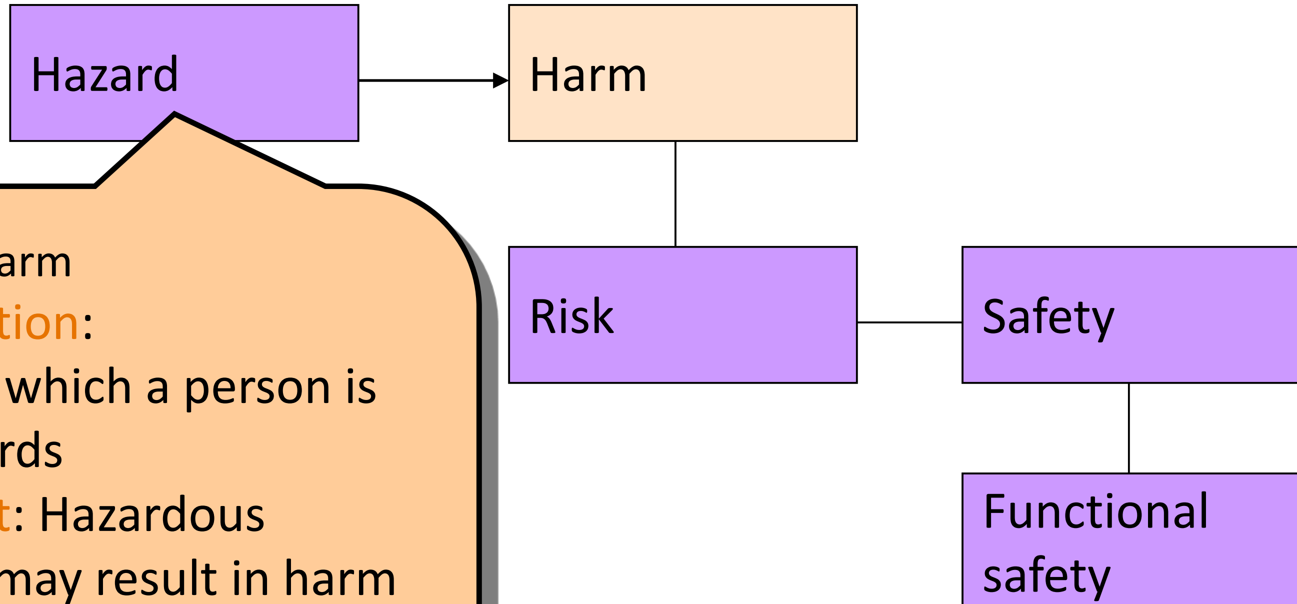

Potential cause of harm

- Hazardous situation: Circumstance in which a person is exposed to hazards
- Hazardous event: Hazardous situation which may result in harm
- Accident: Unintended event that results in harm
- Incident (near miss): Event that has the potential of harm

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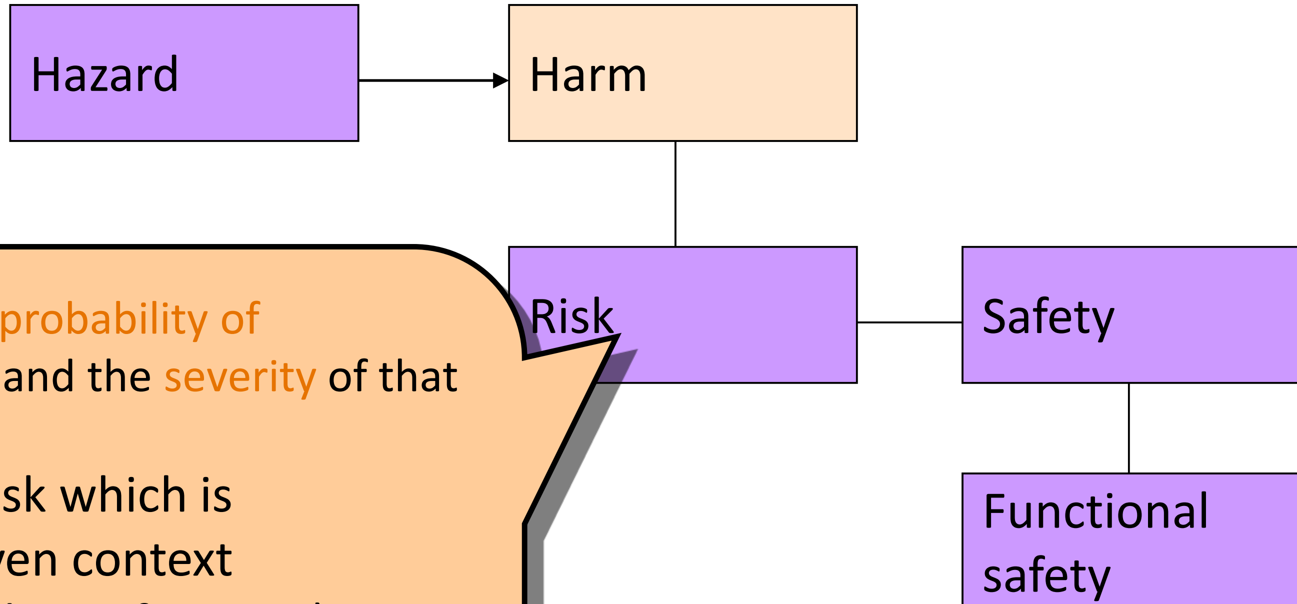
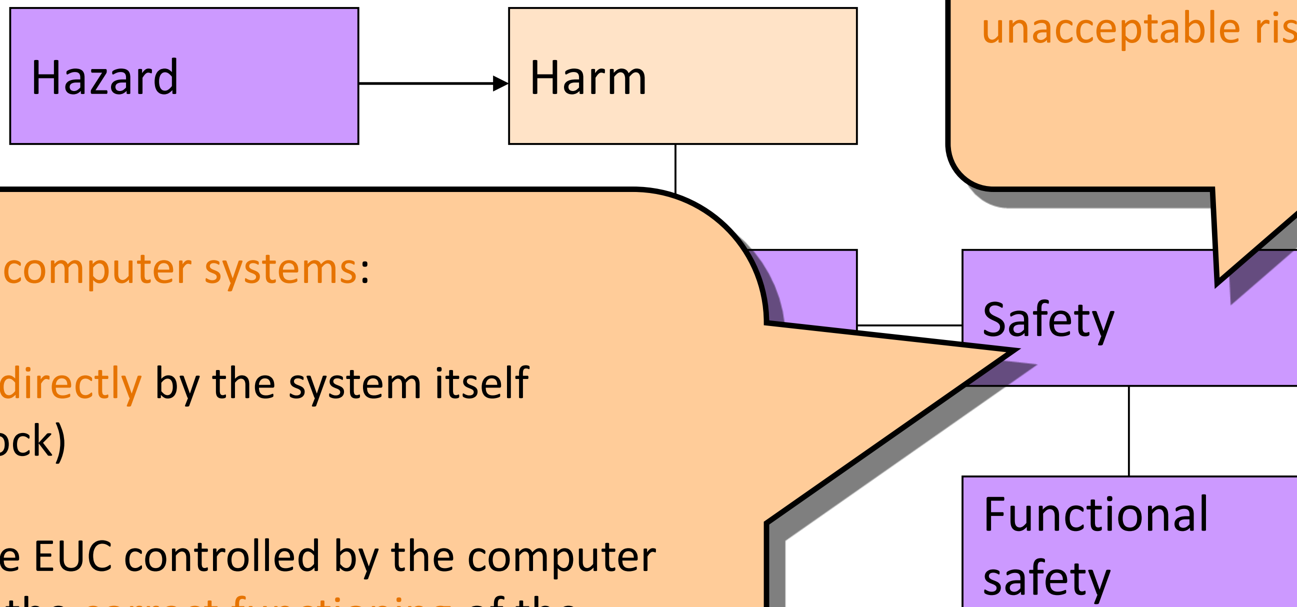


Combination of the probability of occurrence of harm and the severity of that harm

- Tolerable risk: Risk which is accepted in a given context (based on the values of society)
- Residual risk: Risk remaining after protective measures have been taken

Definition of safety

- Central concepts: Hazard, risk and safety



Freedom from unacceptable risk

Forms of safety in computer systems:

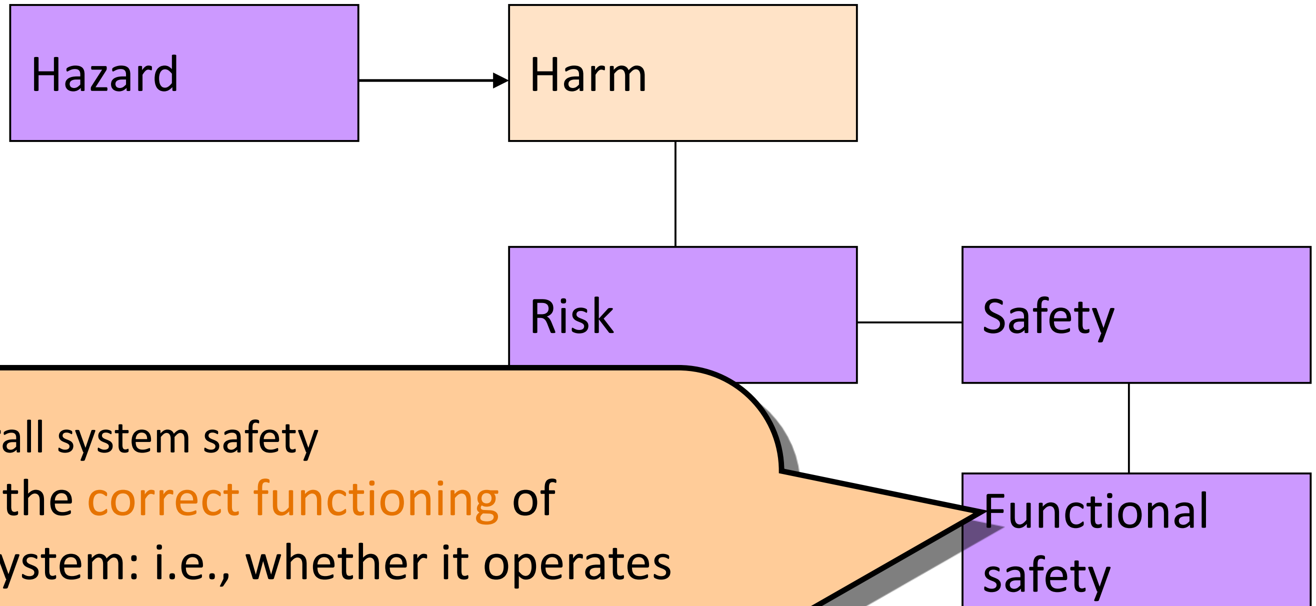
Primary safety:
- Dangers caused directly by the system itself (e.g., electric shock)

Functional safety:
- This concerns the EUC controlled by the computer and is related to the correct functioning of the computer and software.

Indirect safety:
- This relates to the indirect consequences of a computer failure or the production of incorrect information.

Definition of safety

- Central concepts: Hazard, risk and safety

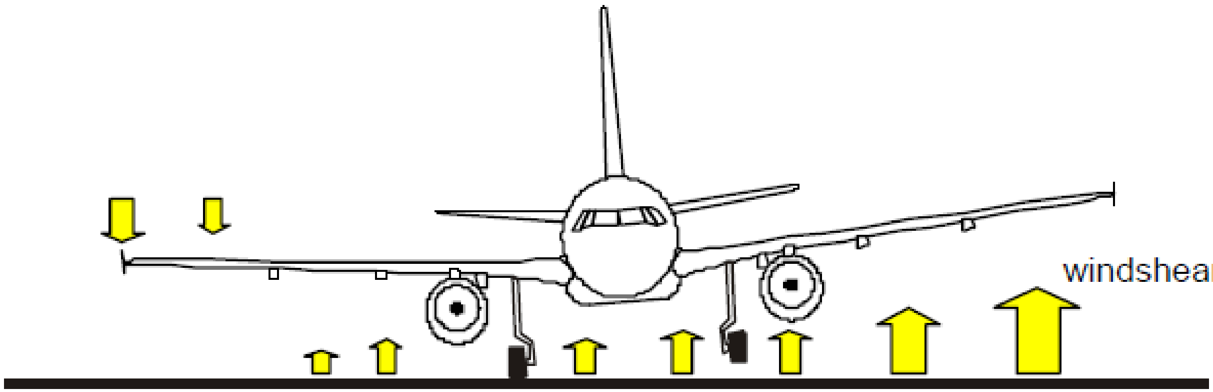


Part of the overall system safety

- depends on the correct functioning of the E/E/PE system: i.e., whether it operates correctly in response to its inputs
- depends on other technology safety-related systems
- depends on external risk reduction facilities

Accident examples

- A320-211 Accident in Warsaw (14 September 1993)
  - Windshear
  - Left gear touched the ground 9 sec later than the right
  - Intelligent braking is controlled by shock absorber + wheel rotation -> delayed braking -> hitting the embankment
- Is the control system ”too intelligent”?
- Correct functioning but not safe behaviour!

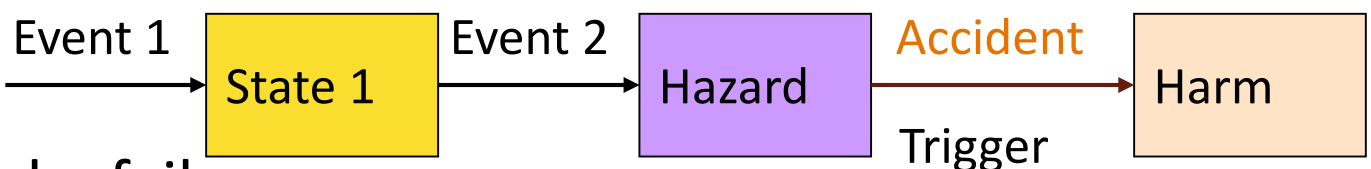


Accident examples

- Toyota car accident in San Diego, August 2009
- Hazard: Stuck accelerator (full power)
  - Floor mat problem
- Hazard control: What about…
  - Braking?
  - Shutting off the engine?
  - Putting the vehicle into neutral? (gearbox: D, P, N)

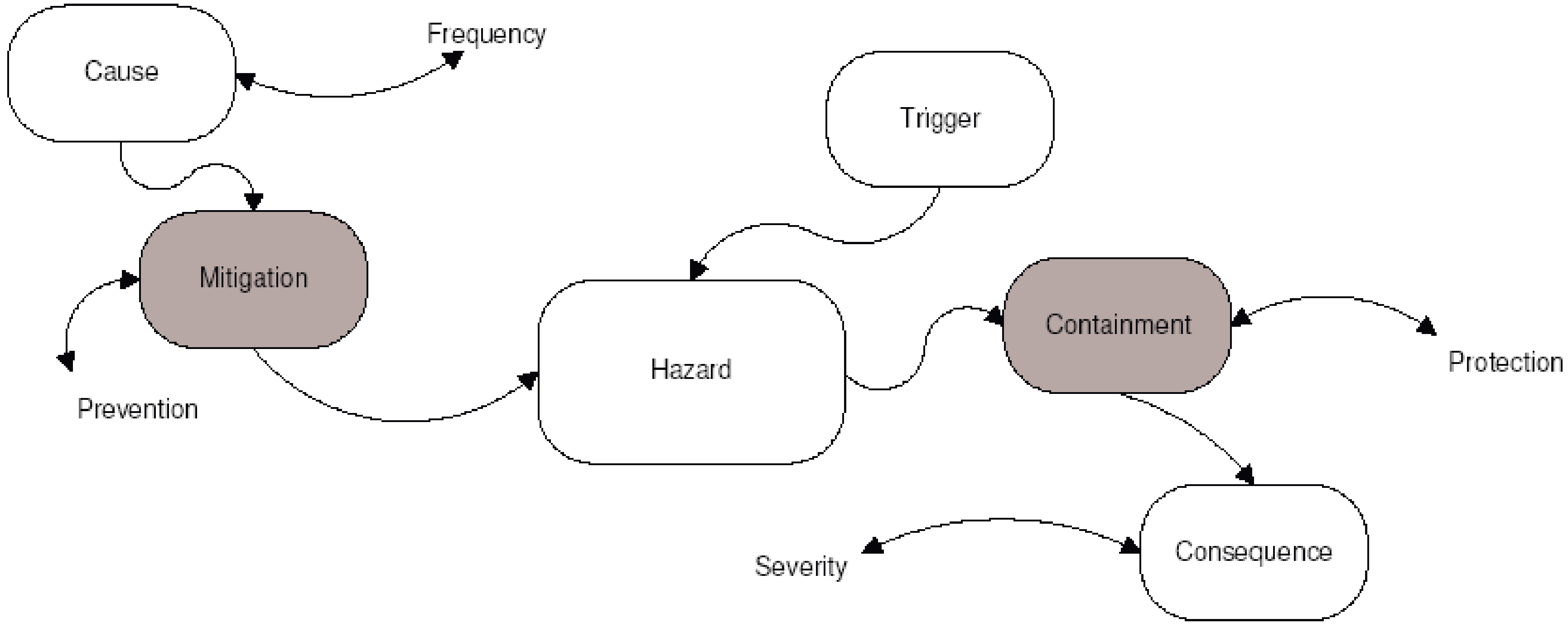
Experiences

- Harm is typically a result of a complex scenario
  - (Temporal) combination of failure(s) and/or normal event(s)
  - Hazards may not result in accidents



- Hazard ≠ failure
  - Undetected (and unhandled) error is a typical cause of hazards
  - Hazard may also be caused by (unexpected) combination of normal events
- Central problems in safety-critical systems:
  - Analysis of hazards
  - Assignment of functions to avoid hazards → accidents → harms

Hazard control



- Risk characteristics:
  - Frequency of occurrence
  - Severity of its consequence
- Mitigation: Eliminate or decrease the chance of a hazard
- Containment: Reduce the consequence of a hazard

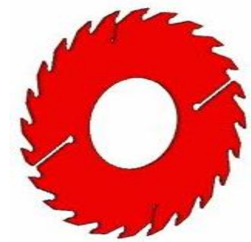
Safety-related system

- Safety function:
  - Function which is intended to achieve or maintain a safe state for the EUC
- Safety-related system:
  - Implements the required safety functions necessary to achieve or maintain a safe state for the EUC,
  - and is intended to achieve the necessary safety integrity for the required safety functions
- Requirements for a safety-related system:
  - What is the safety function: Safety function requirements
  - What is the likelihood of the correct operation of the safety function: Safety integrity requirements

Safety integrity

- Safety integrity:
  - Probability of a safety-related system satisfactorily performing the required safety functions (i.e., without failure)
    - under all stated conditions
    - within a stated period of time
- Types of safety integrity:
  - Random (hardware): Related to random hardware failures
    - Occur at a random time due to degradation mechanisms
  - Systematic: Related to systematic failures
    - Failures related in a deterministic way to faults that can only be eliminated by modification of the design / manufacturing process / operation procedure / documentation / other relevant factors
- Safety integrity level (SIL):
  - Discrete level for specifying safety integrity requirements of the safety functions (i.e., probabilities of failures)

Example: Safety function



- Machine with a rotating blade
  - Blade is protected by a hinged solid cover
- Cleaning of the blade: Lifting of the cover is needed
- Hazard analysis: Avoiding injury of the operator when cleaning the blade
  - If the cover is lifted more than 5 mm then the motor should be stopped
  - The motor should be stopped in less than 1 sec
- Safety function: Interlocking
  - When the cover is lifted to 4 mm, the motor is stopped and braked in 0,8 s
- Safety integrity:
  - The probability of failure of the interlocking (safety function) shall be less than 10^{-4} (one failure in 10.000 operation)
  - Failure of interlocking is not necessarily result in an injury since the operator may be careful

Safety and dependability

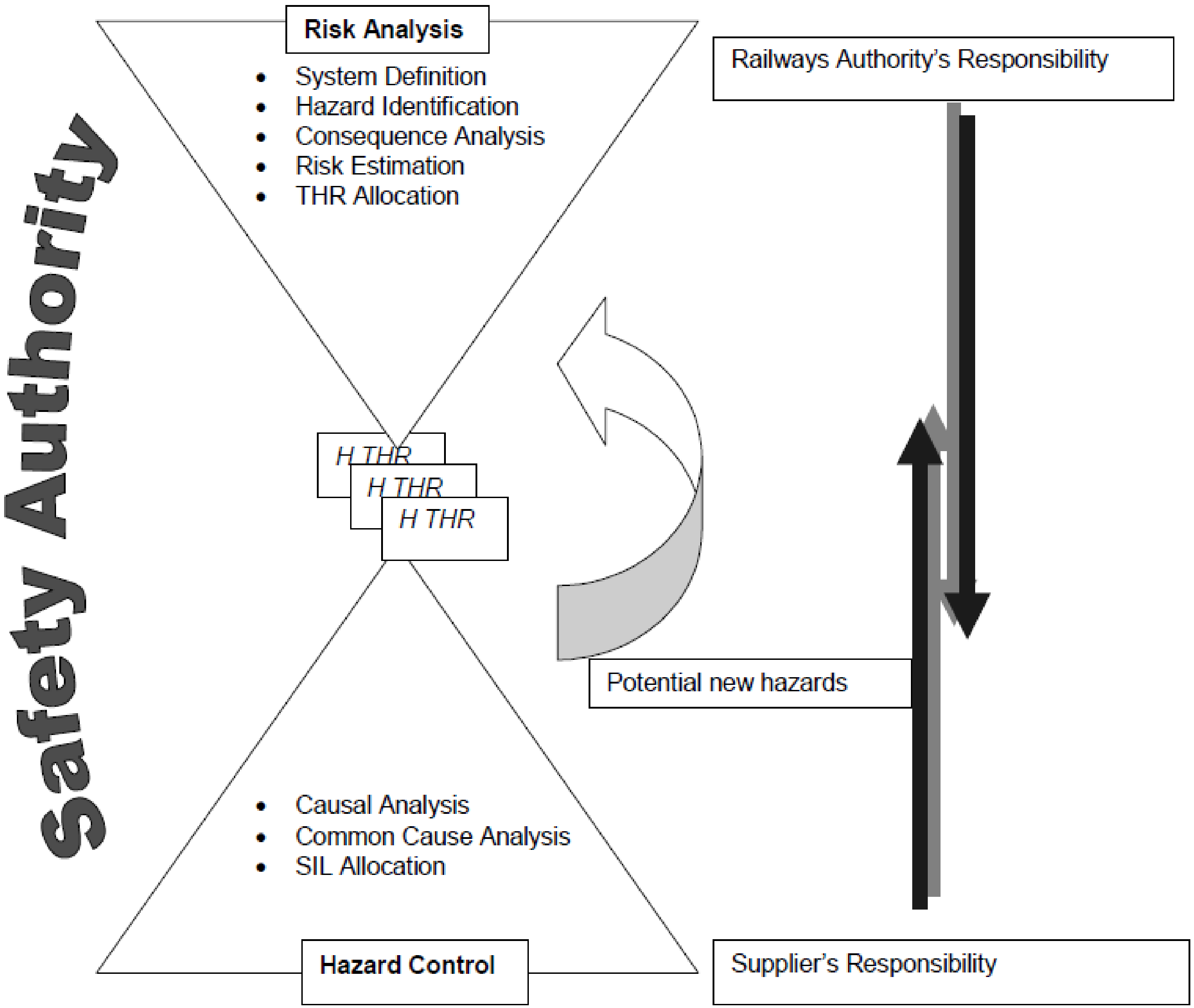
- Safety vs. reliability:
  - Fail-safe state: safe, but 0 reliability
    - Railway signaling, red state: Safety $\neq$ reliability
    - Airplane control: Safety = reliability
- Safety vs. availability:
  - Fail-stop state: safe, but 0 availability (and reliability)
  - High availability may result in (short) unsafe states

Safety requirements

- Requirements for a safety-related system:
  - Safety function requirements:
    - Derived from hazard identification
  - Safety integrity requirements:
    - Related to target failure measure of the safety function
    - Derived from risk estimation: Acceptable risk
- Safety standards: Risk based approach for determining target failure measure
  - Tolerable risk: Risk which is accepted in a given context based on the current values of society
  - It is the result of risk analysis
    - Performed typically by the customer
    - Considering the environment, scenarios, mode of operation, …

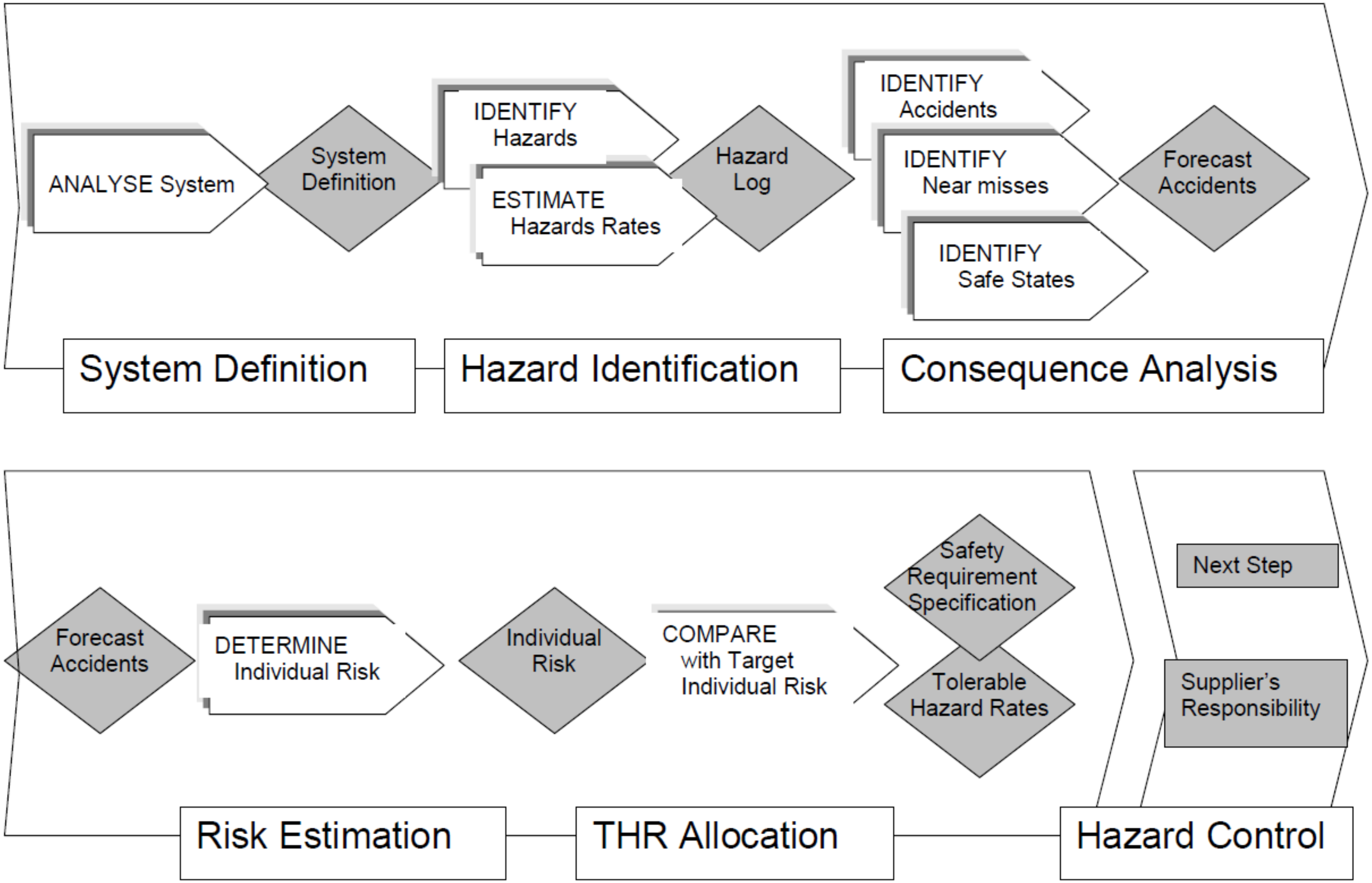
Risk based approach

- EN50129: Railway applications
- THR: Tolerable hazard rate (continuous operation)



Risk analysis

- EN50129 (railway applications)



Mode of operation

- Way in which a safety-related system is to be used:
  - Low demand mode: Frequency of demands for operation is
    - no greater than one per year and
    - no greater than twice the proof-test frequency
  - High demand (or continuous) mode: Frequency of demands for operation is
    - greater than one per year or
    - greater than twice the proof-test frequency
- Target failure measure:
  - Low demand mode: Average probability of failure to perform the desired function on demand
  - High demand mode: Probability of a dangerous failure per hour
    - Acceptable risk -> Tolerable hazard rate (THR)

Safety integrity requirements

- Low demand mode:

SIL	Average probability of failure to perform the function on demand
1	$10^{-2} \leq PFD < 10^{-1}$
2	$10^{-3} \leq PFD < 10^{-2}$
3	$10^{-4} \leq PFD < 10^{-3}$
4	$10^{-5} \leq PFD < 10^{-4}$

- High demand mode:

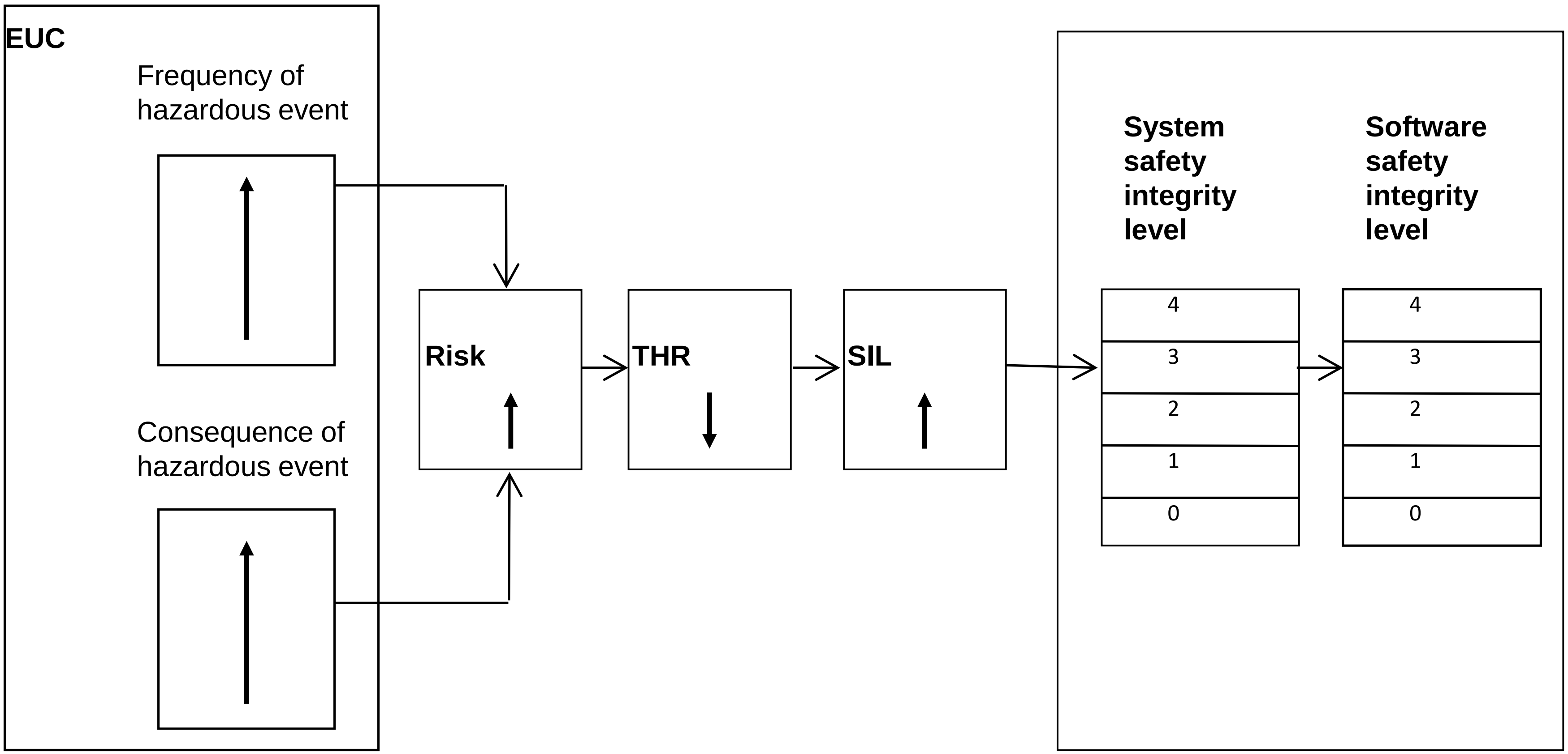
SIL	Probability of dangerous failure per hour per safety function
1	$10^{-6} \leq PFH < 10^{-5}$
2	$10^{-7} \leq PFH < 10^{-6}$
3	$10^{-8} \leq PFH < 10^{-7}$
4	$10^{-9} \leq PFH < 10^{-8}$

(PFH or THR)

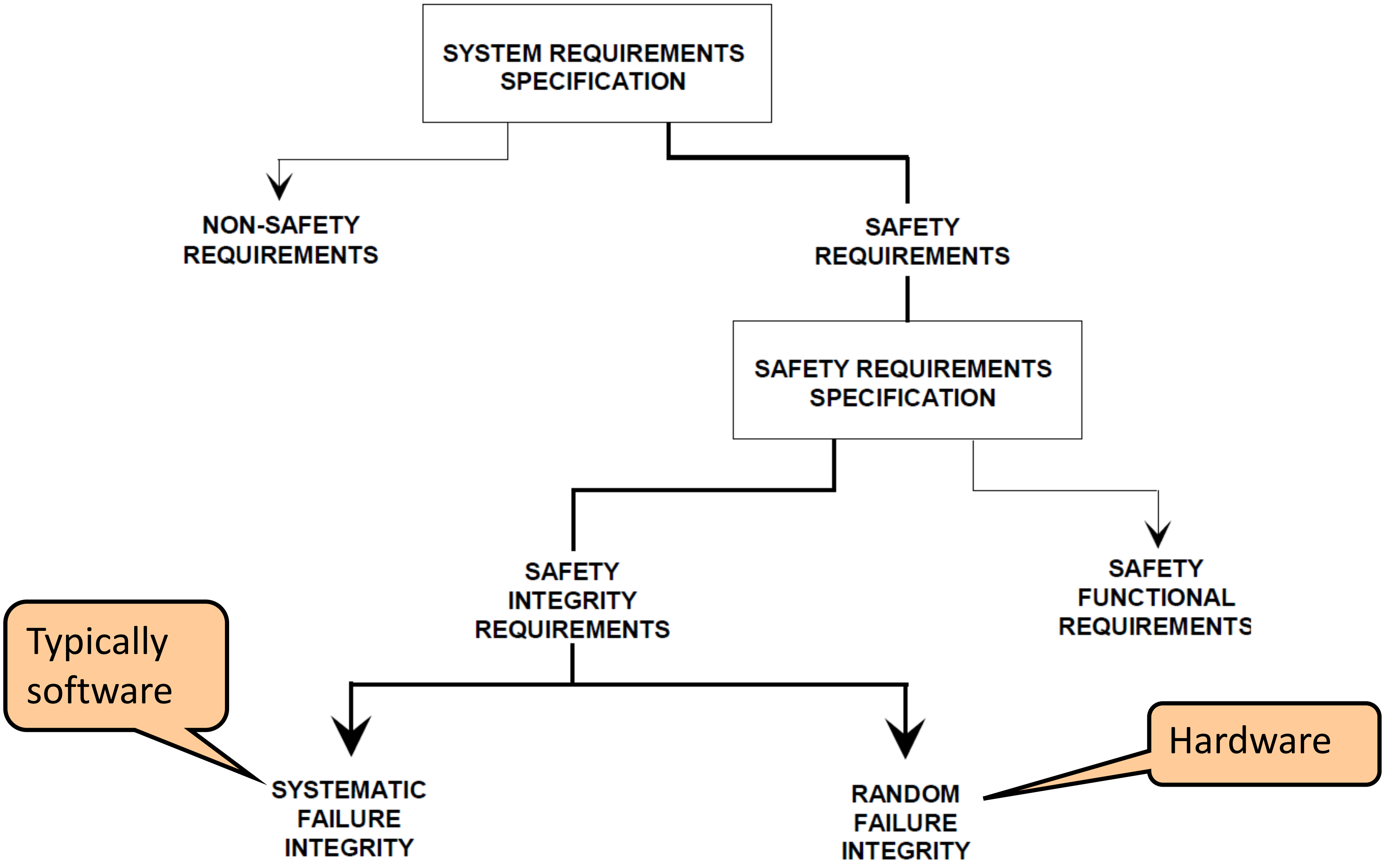
15 years lifetime:
1 failure in case of
750 equipment

Determining SIL: Overview

- Hazard identification and risk analysis -> Target failure measure



Structure of requirements



Challenges in achieving functional safety

- E/E/PE systems: Complexity
  - Impossible to determine every failure mode
  - Difficult to predict safety performance
- Preventing/controlling dangerous failures resulting from
  - Incorrect specification (system, HW, SW)
  - Omissions in safety requirement specification
  - Hardware failure mechanisms: Random or systematic
  - Software failure mechanisms: Systematic
  - Common cause failures
  - Human (operator) errors
  - Environmental influences (e.g., temperature, EM, mechanical)
  - Supply system disturbances (e.g., power supply)
  - …

Demonstrating SIL requirements

- Approaches:
  - Random failure integrity:
    - Quantitative approach: Based on statistics, experiments
  - Systematic failure integrity:
    - Qualitative approach: Rigor in the engineering
      - Development life cycle
      - Techniques and measures
      - Documentation
      - Independence of persons
- Safety case:
  - Documented demonstration that the product complies with the specified safety requirements
  - Systematic demonstration

Summary of the basic concepts

System safety

- emphasizes building in safety, not adding it to a completed design
- deals with systems as a whole rather than with subsystems or components
- takes a larger view of hazards than just failures
- emphasizes analysis rather than past experience and standards
- emphasizes qualitative rather than quantitative approaches

Dependability related requirements

(Safety is not enough)

Characterizing the system services

- Typical characteristics of services:
  - Reliability, availability, integrity, ...
  - These depend on the failures during the use of the services (the good quality of the production process is not enough)
- Composite characteristic: Dependability
  - Definition: Ability to provide service in which reliance can justifiably be placed
    - Justifiably: based on analysis, evaluation, measurements
    - Reliance: the service satisfies the needs
  - Basic question: How to avoid or handle the faults affecting the services?

Fault effects

Development process → **Product in operation**

- Design faults
- Implementation faults

- Hardware faults
- Configuration faults
- Operator faults

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- Design faults
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Development process:

- Better quality management, better methodology
- But: Increasing complexity, difficulty in verification

Typical estimations for 1000 lines of code:

- Good development “by hand” : <10 faults
- Tool-supported development: ~1-2 faults
- Application of formal methods: <1 faults

Fault effects

Development process → **Product in operation**

- Design faults
- Implementation faults

- Hardware faults
- Configuration faults
- Operator faults

Limits of the technology:

- Better quality control, better materials
- But: increasing sensitivity to environment effects

Typical estimations:

- CPU: 10^{-5}…10^{-6} faults/hour
- RAM: 10^{-4}…10^{-5} faults/hour
- LCD: ~ 2…3 years lifetime

Fault effects

Development process → **Product in operation**

- Design faults
- Implementation faults

- Hardware faults
- Configuration faults
- Operator faults

Verification during the development

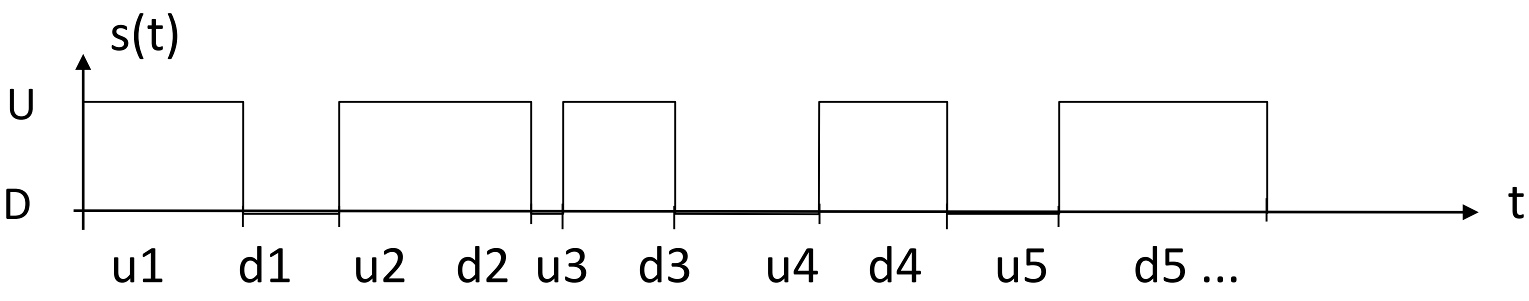
Fault tolerance during operation

Dependability and security

- Basic attributes of dependability:
  - Availability: Probability of correct service (considering repairs and maintenance)
  - Reliability: Probability of continuous correct service (until the first failure)
  - Safety: Freedom from unacceptable risk of harm
  - Integrity: Avoidance of erroneous changes or alterations
  - Maintainability: Possibility of repairs and improvements
- (Attributes of security:)
  - Availability
  - Integrity
  - Confidentiality: absence of unauthorized disclosure of information

Dependability metrics: Mean values

- Partitioning the state of the system: s(t)
  - Correct (U, up) and incorrect (D, down) state partitions



- Mean values:
  - **Mean Time to First Failure**: MTFF = E{u1}
  - **Mean Up Time**: MUT = MTTF = E{ui}

    (Mean Time To Failure)
  - **Mean Down Time**: MDT = MTTR = E{di}

    (Mean Time To Repair)
  - **Mean Time Between Failures**: MTBF = MUT + MDT

Dependability metrics: Probability functions

- **Availability**:

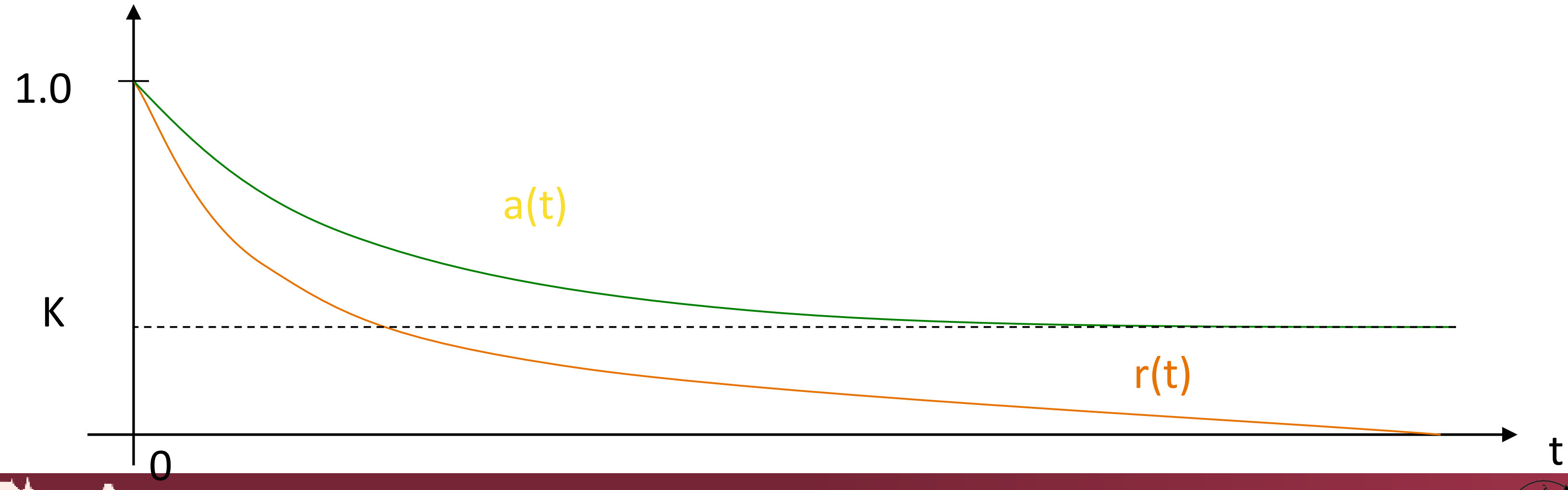
  $$a(t) = P\{s(t) \in U\}$$ (failures may occur)

- **Reliability**:

  $$r(t) = P\{s(t') \in U, \forall t' < t\}$$ (no failure until t)

- **Asymptotic availability**: $K = \lim_{t \to \infty} a(t)$ (regular repairs)

  In other way: $K = A = \mathrm{MTTF}/(\mathrm{MTTF} + \mathrm{MTTR})$



Availability related requirements

Availability	Failure period per year
99%	~ 3,5 days
99,9%	~ 9 hours
99,99% („4 nines”)	~ 1 hour
99,999% („5 nines”)	~ 5 minutes
99,9999% („6 nines”)	~ 32 sec
99,99999%	~ 3 sec

Availability of a system built up from components, where the availability of a component is 95%:

- Availability of a system built from 2 components: 90%
- Availability of a system built from 5 components : 77%
- Availability of a system built from 10 components : 60%

Attributes of components

- Fault rate: $\lambda(t)$
  - Probability density that the component will fail at time point t given that it has been correct until t

$$\lambda(t)\Delta t = P\left\{ s(t+\Delta t) \in D \mid s(t) \in U \right\} \text{ while } \Delta t \to 0$$

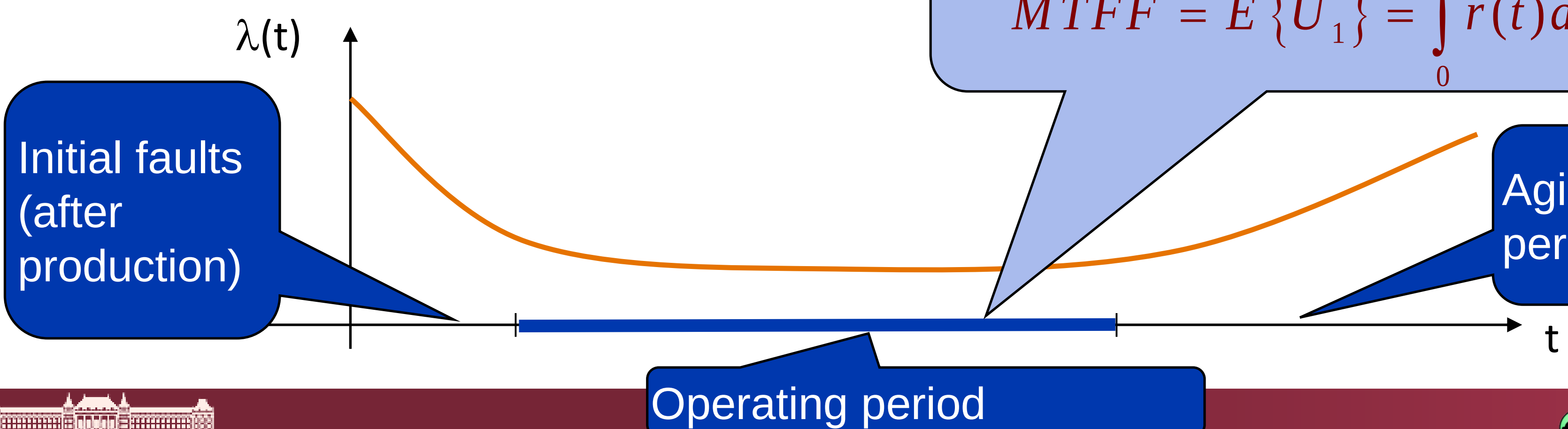
  - In other way (on the basis of the definition of reliability):

$$\lambda(t) = -\frac{1}{r(t)} \frac{dr(t)}{dt}, \quad \text{thus } r(t) = e^{-\int_0^t \lambda(t)dt}$$

  - For electronic components:

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

$$MTFF = E\{U_1\} = \int_0^\infty r(t)dt = \frac{1}{\lambda}$$



Case study: development of a DMI

Driver

DMI

EVC

EVC: European Vital Computer (on board)

Maintenance centre

Characteristic:

- Safety-critical functions
  - Information visualization
  - Processing driver commands
  - Data transfer to EVC
- Safe wireless communication
  - System configuration
  - Diagnostics
  - Software update

Case study: DMI requirements

- Safety:
  - Safety Integrity Level: SIL 2
  - Tolerable Hazard Rate: $10^{-7} <= THR < 10^{-6}$ hazardous failures per hours
  - CENELEC standards: EN 50129 and EN 50128
- Reliability:
  - Mean Time To Failure: MTTF > 5000 hours
    (5000 hours: ~ 7 months)
- Availability:
  - A = MTTF / (MTTF+MTTR), A > 0.9952
    Faulty state: shall be less than 42 hours per year
    MTTR < 24 hours if MTTF=5000 hours

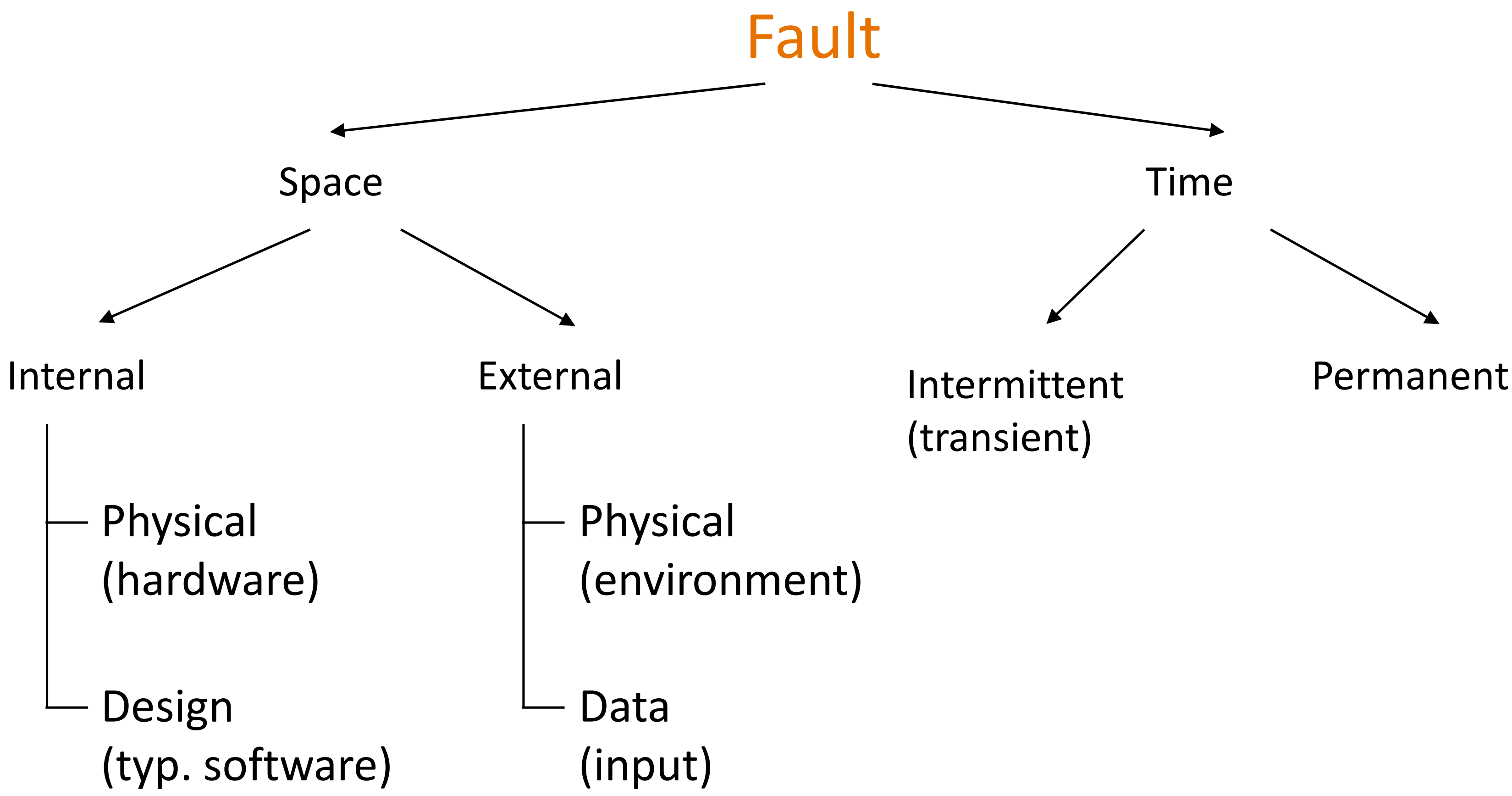
Threats to dependability

Fault: adjudged or hypothesized cause of an error → **Component or system** — **Error:** State leading to the failure → **Failure**: the delivered service deviates from correct service

Fault → Error → Failure examples:

Fault		Error		Failure
Bit flip in the memory due to a cosmic particle	→	Reading the faulty memory cell will result in incorrect value	→	The robot arm collides with the wall
The programmer increases a variable instead of decreasing	→	The faulty statement is executed and the value of the variable will be incorrect	→	The final result of the computation will be incorrect

The characteristics of faults



Software fault:

- Permanent design fault (systematic)
- Activation of the fault depends on the operational profile (inputs)

Means to improve dependability

- Fault prevention:
  - Physical faults: Good components, shielding, ...
  - Design faults: Good design methodology
- Fault removal:
  - Design phase: Verification and corrections
  - Prototype phase: Testing, diagnostics, repair
- Fault tolerance: avoiding service failures
  - Operational phase: Fault handling, reconfiguration
- Fault forecasting: estimating faults and their effects
  - Measurements and prediction

    E.g., Self-Monitoring, Analysis and Reporting Technology (SMART)