Dependable Systems

Definitions and Metrics

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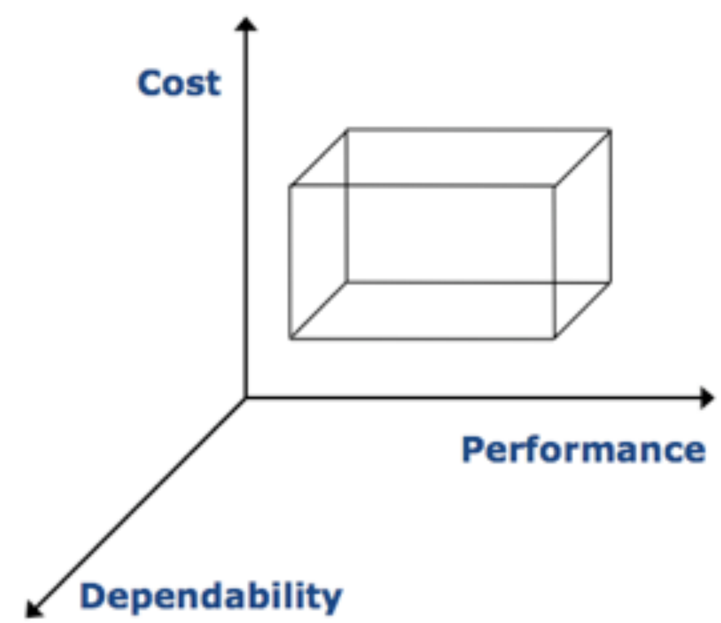
Sources:

J.C. Laprie. Dependability: Basic Concepts and Terminology
Eusgeld, Irene et al.: Dependability Metrics. 4909. Springer Publishing, 2008
Echtle, Klaus: Fehlertoleranzverfahren. Heidelberg, Germany : Springer Verlag, 1990.
Pfister, Gregory F.: High Availability. In: In Search of Clusters. , S. 379-452

Dependability

- **Umbrella term** for **operational** requirements on a system
  - IFIP WG 10.4: "*[..] the trustworthiness of a computing system which allows reliance to be justifiably placed on the service it delivers [..]*"
  - IEC IEV: "*dependability (is) the collective term used to describe the availability performance and its influencing factors : reliability performance, maintainability performance and maintenance support performance*"
  - Laprie: „ *Trustworthiness of a computer system such that reliance can be placed on the service it delivers to the user* “
- Adds a third dimension to system quality
- General question: How to deal with unexpected events ?
- In German: ‚Verlässlichkeit‘ vs. ‚Zuverlässigkeit‘

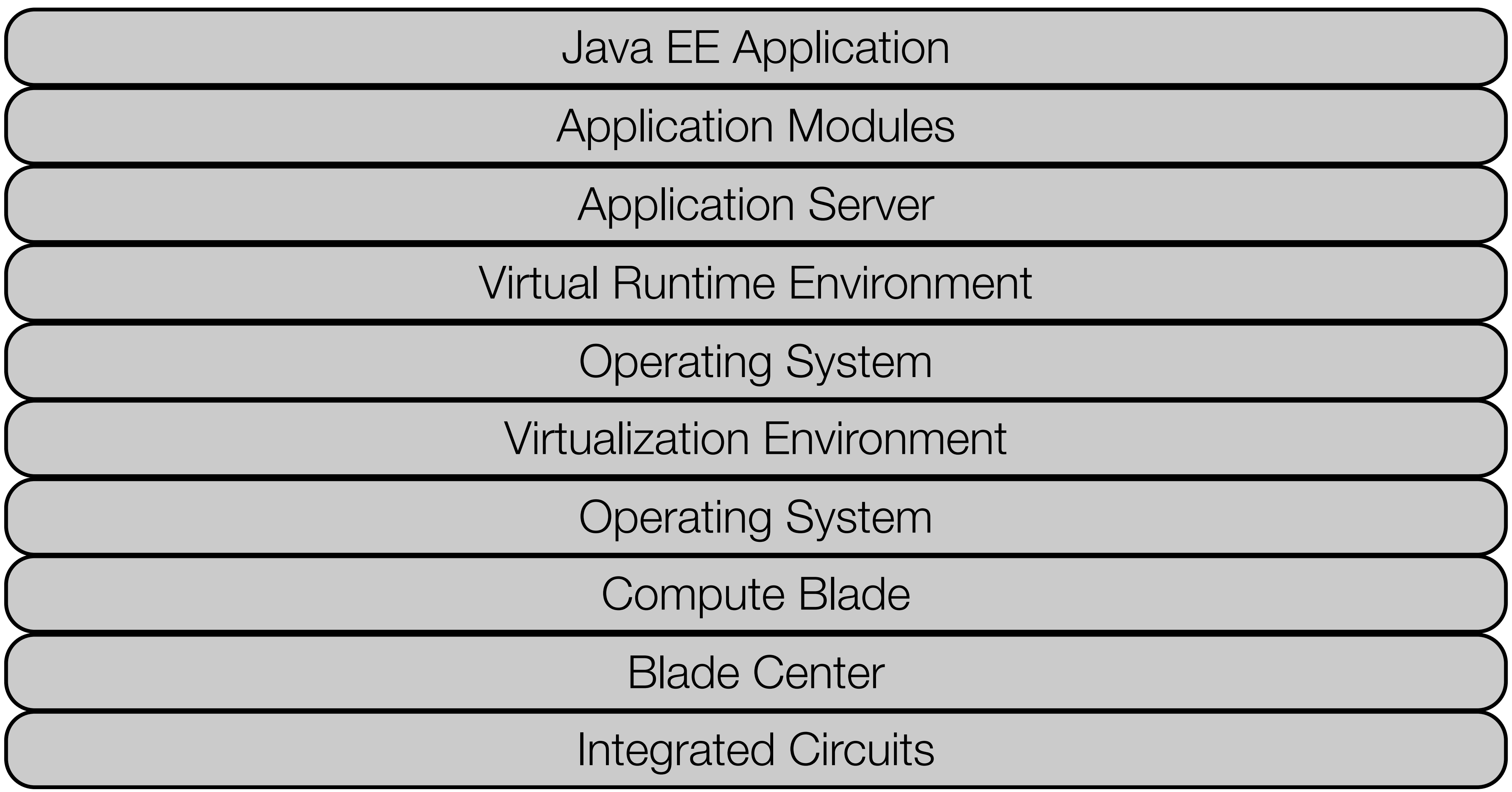


System Type Examples

- **Dependable (reliable) system**
  - Delivers a required service during its lifetime
- **Fault-tolerant computer system**
  - Continues correct service provisioning in the presence of faults
- **Real-time computer system**
  - Deliver a service within given time constraints (physical time, duration, ...)
- **Responsive computer system**
  - Fault-tolerant real-time system

System Integration Levels

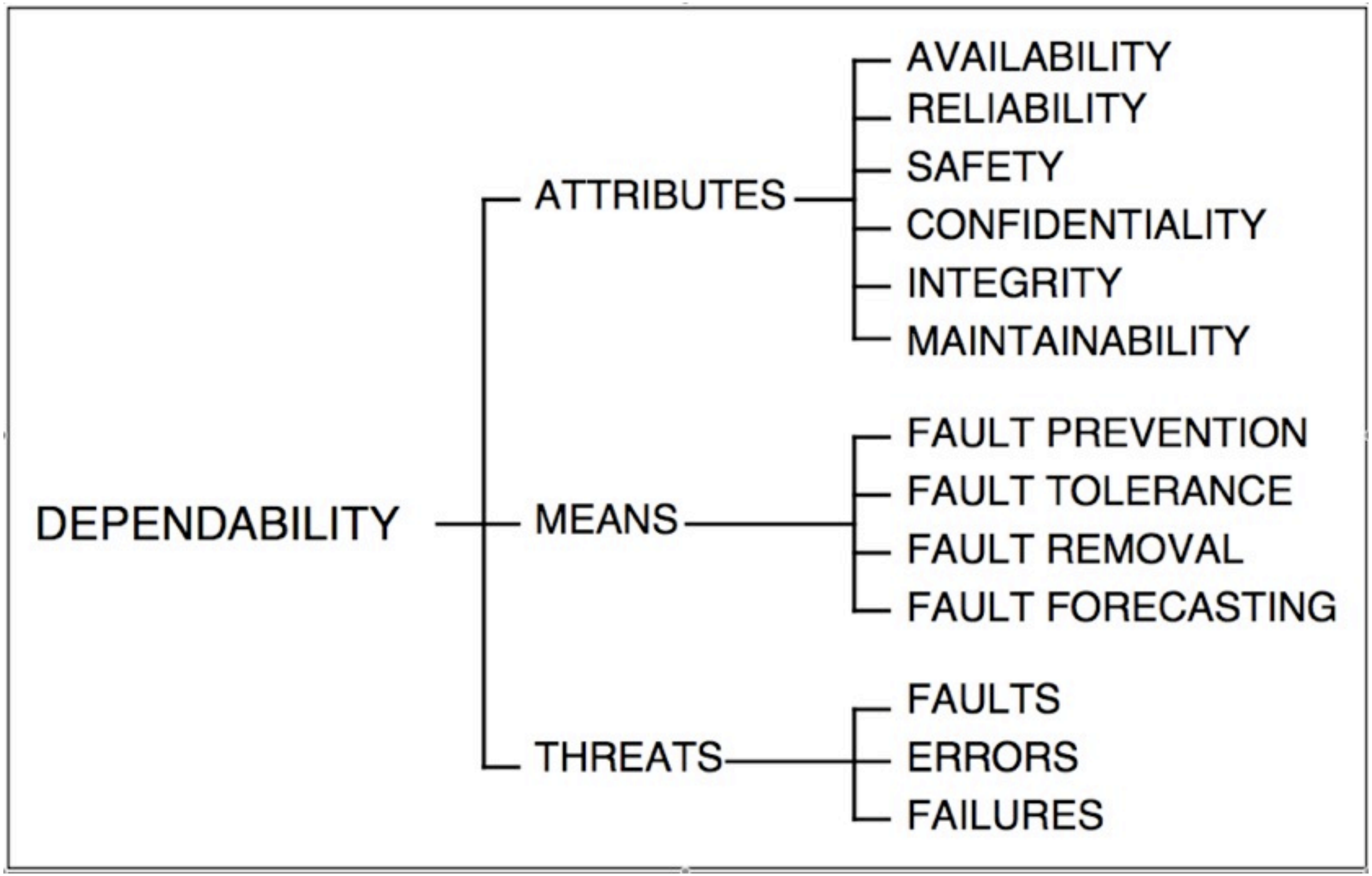
- Dependability has to be considered at every level
- Decomposition approach influences dependability success

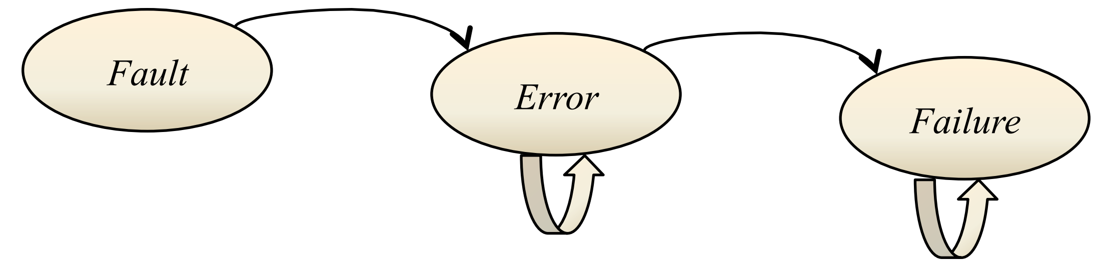


Dependability Stakeholders

- **System** - Entity with function, behavior, and structure
  - A number of components or subsystems, which interact under the control of a design [Robinson]
- **Service** - System behavior abstraction, as perceived by the user
- **User** - Human or physical system that interacts with the systems service
- **Specification** - Definition of expected service and delivery conditions
  - On different levels, can lead to specification fault
- Reliance demands assessment of **non-functional dependability attributes**
- Provide ability for trustworthy service delivery by **dependability means**
- Undesired (maybe expected) circumstances form **dependability threats**

Dependability Tree (Laprie)

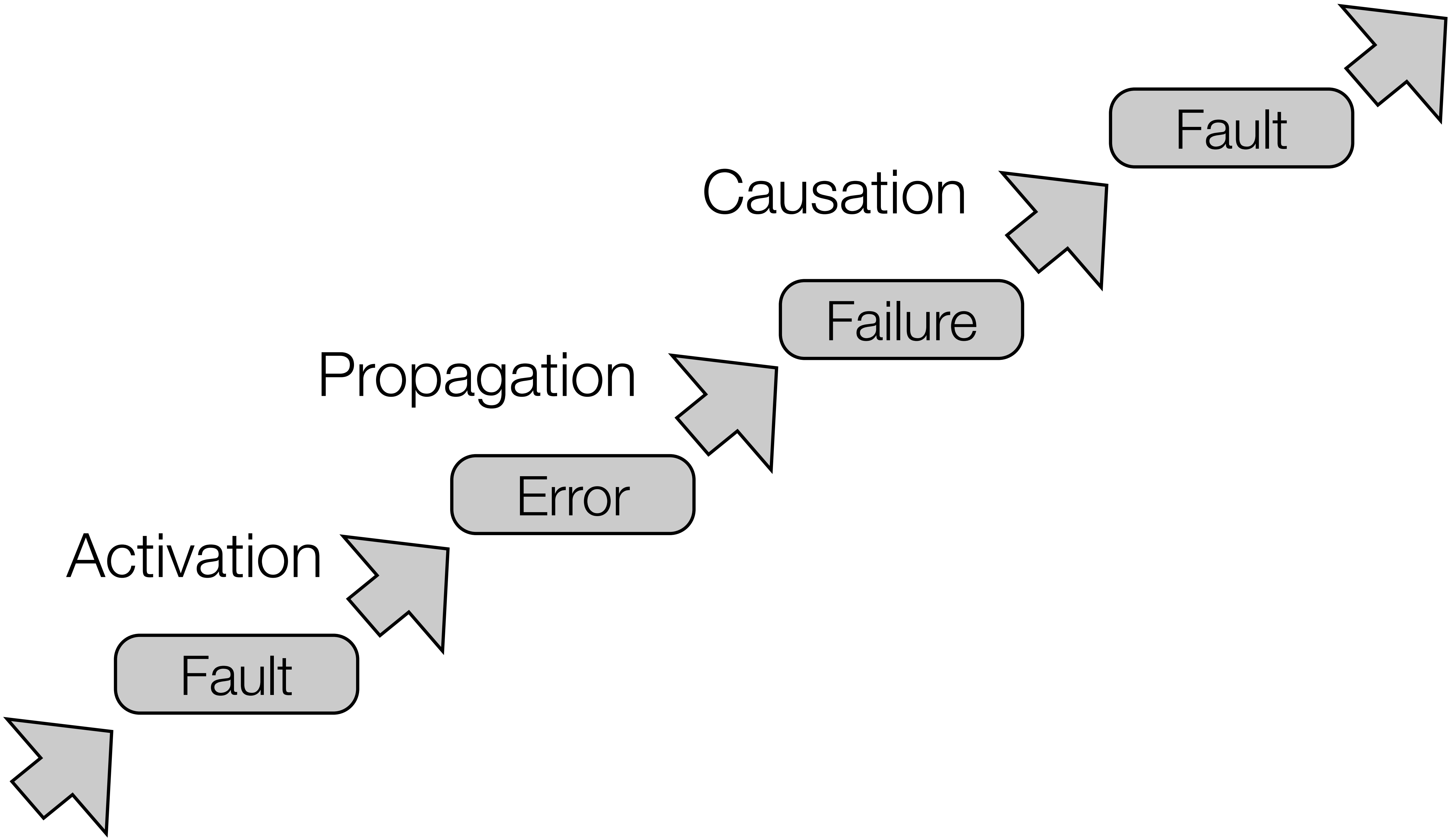




Dependability Threats

- System **failure - ‚Ausfall‘**
  - Event that occurs when the service no longer complies with the specification / deviates from the correct service.
- System **error - ‚Fehler(zustand)‘**
  - Part of system state that can lead to subsequent failure
  - Some sources define errors as active faults - not in this course ...
- System **fault - ‚Fehler(ursache)‘**
  - Adjudged or hypothesized cause of an error
- Failure occurs when error state alters the provided service
- Systems are build from connected components, which are again systems
- Fault is the consequence of a failure of some other system to deliver its service

Chain of Dependability Threats (Avizienis)



Faults

- High diversity in possible sources and types
  - Fault nature
    - **Accidental** faults (‚Zufallsfehler‘) vs. **intentional** faults (‚Absichtsfehler‘)
    - Intentional faults are created deliberately, presumably malevolently
  - Fault origin viewpoints (not exclusive)
    - Phenomenological causes: **Physical / natural** faults vs. **human-made** faults
    - System boundaries: **Internal** faults (part of system state that produces an error) vs. **external** faults (interference with the environment)
    - Phase of creation: **Design** faults vs. **operational** faults
  - Temporal persistence
    - **Permanent** faults vs. **temporary** faults

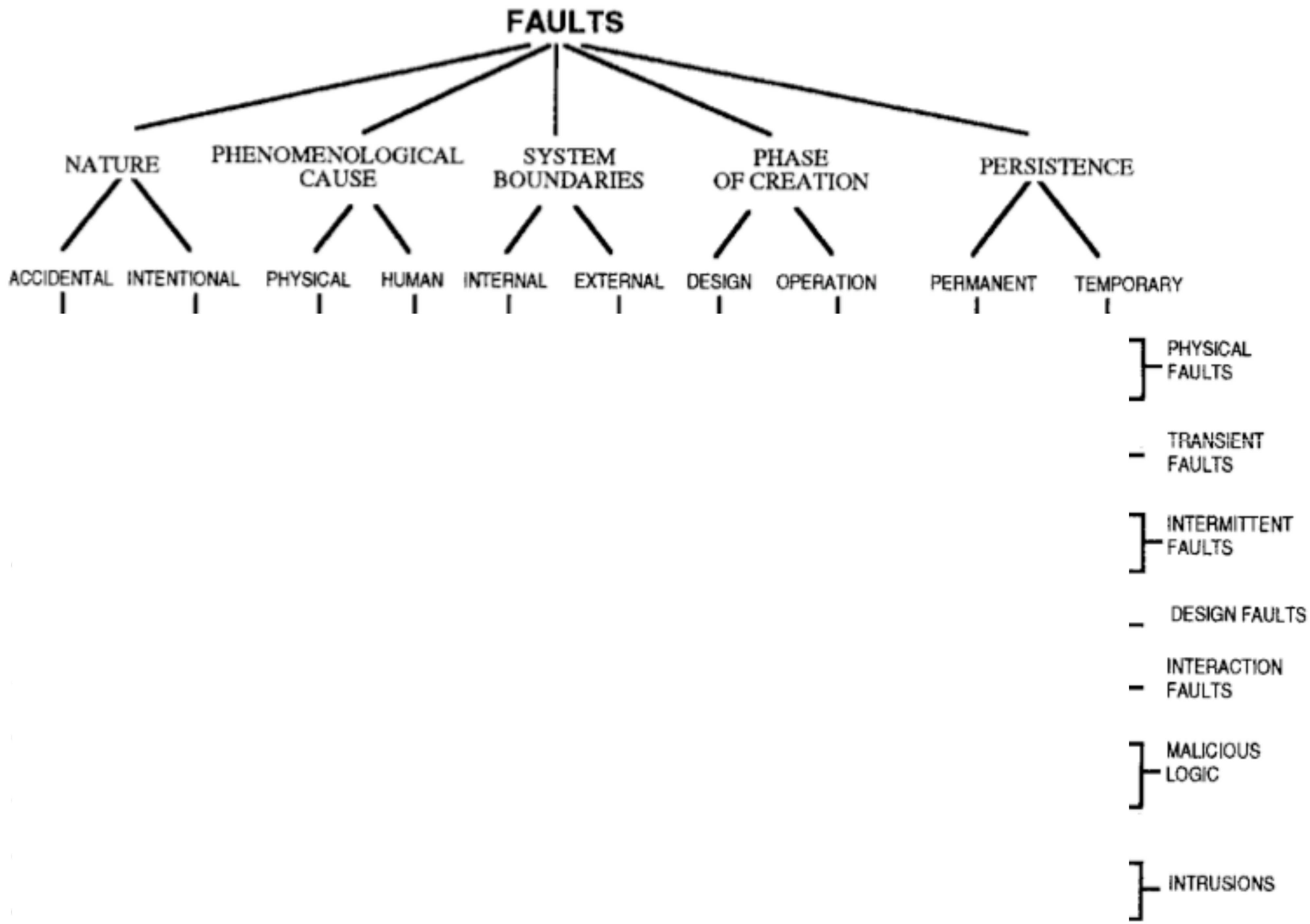
Observations on Faults

- An external fault is a design fault - inability or refusal to foresee all situations
- Design faults are created during system development, system modification, or operational procedure creation and establishment
- Just replacing broken version of the same component leads to **recurrent faults**
- Physical faults are **accidental faults**
- Temporary external accidental physical faults are also called **transient faults**
- Temporary internal accidental faults are also called **intermittent faults**
  - Examples: Pattern-sensitive memory hardware, system overload
  - Arbitrary concept - Permanent faults with unknown activation condition
- Intentional and design faults are human-made faults, might be **malicious faults**
- Hardware production defects are typically **physical faults**

Observations on Faults

- A fault is **active** when it produces an error
- A non-active internal fault is a **dormant / passive fault** (‚inaktive Fehlerursache‘)
  - Origin in hardware fault analysis - often cycling between dormant and active
- Many specialized versions of the term ‚fault‘, e.g. **bug**
  - **Heisenbug** - Intermittent software fault, **Bohrbug** - Permanent software fault
  - **Mandelbugs** - Appear chaotic due to many dependencies
- **Fault-tolerant system design** is a contradiction
  - Design demands specification, faults are non-specified cases
  - Solution: Specification for fault-free case + additional fault specification
- Fault can mean performance or timing faults (derivation from expected load / timing)

Fault Characterization (Laprie & Kanoun)



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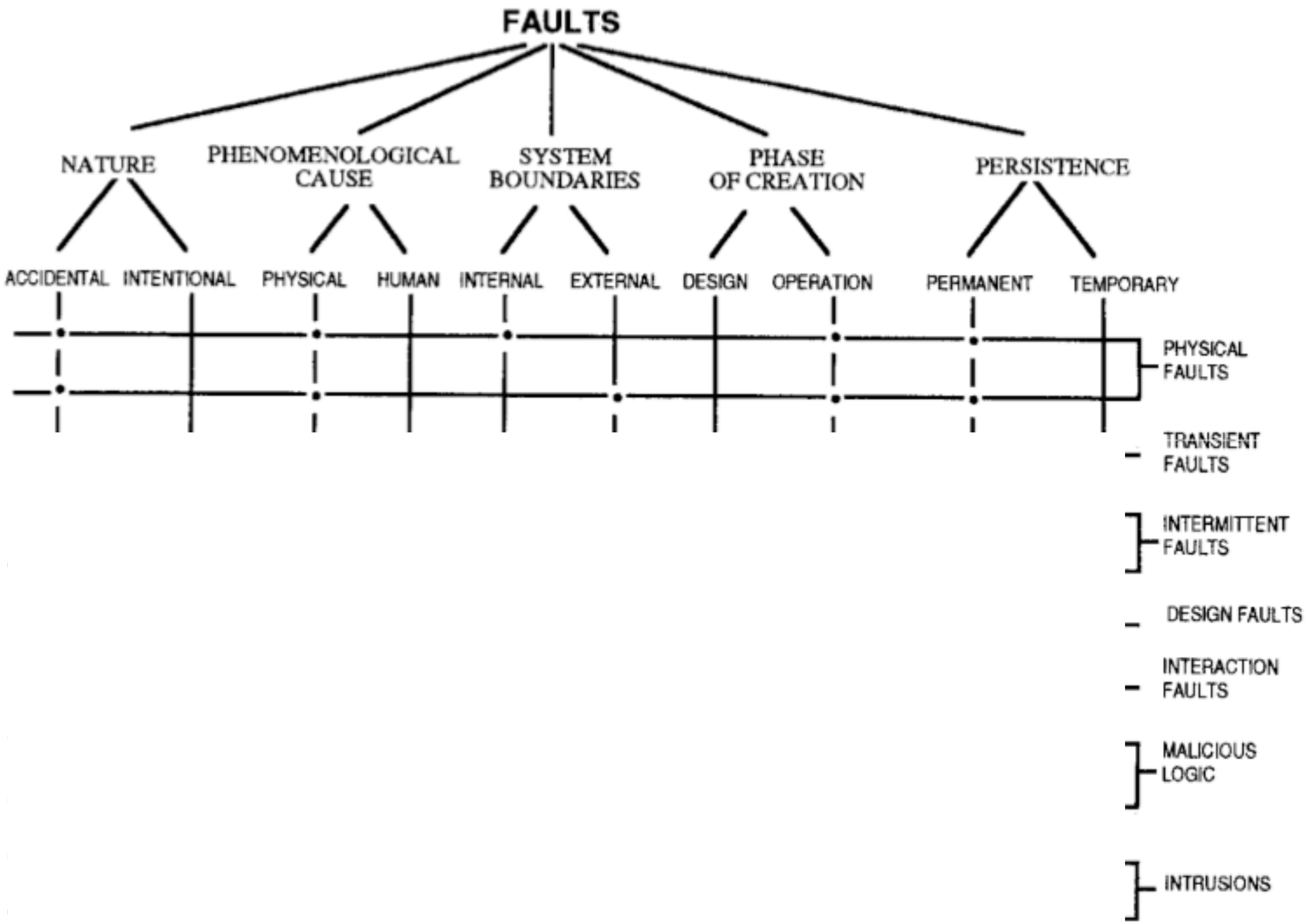

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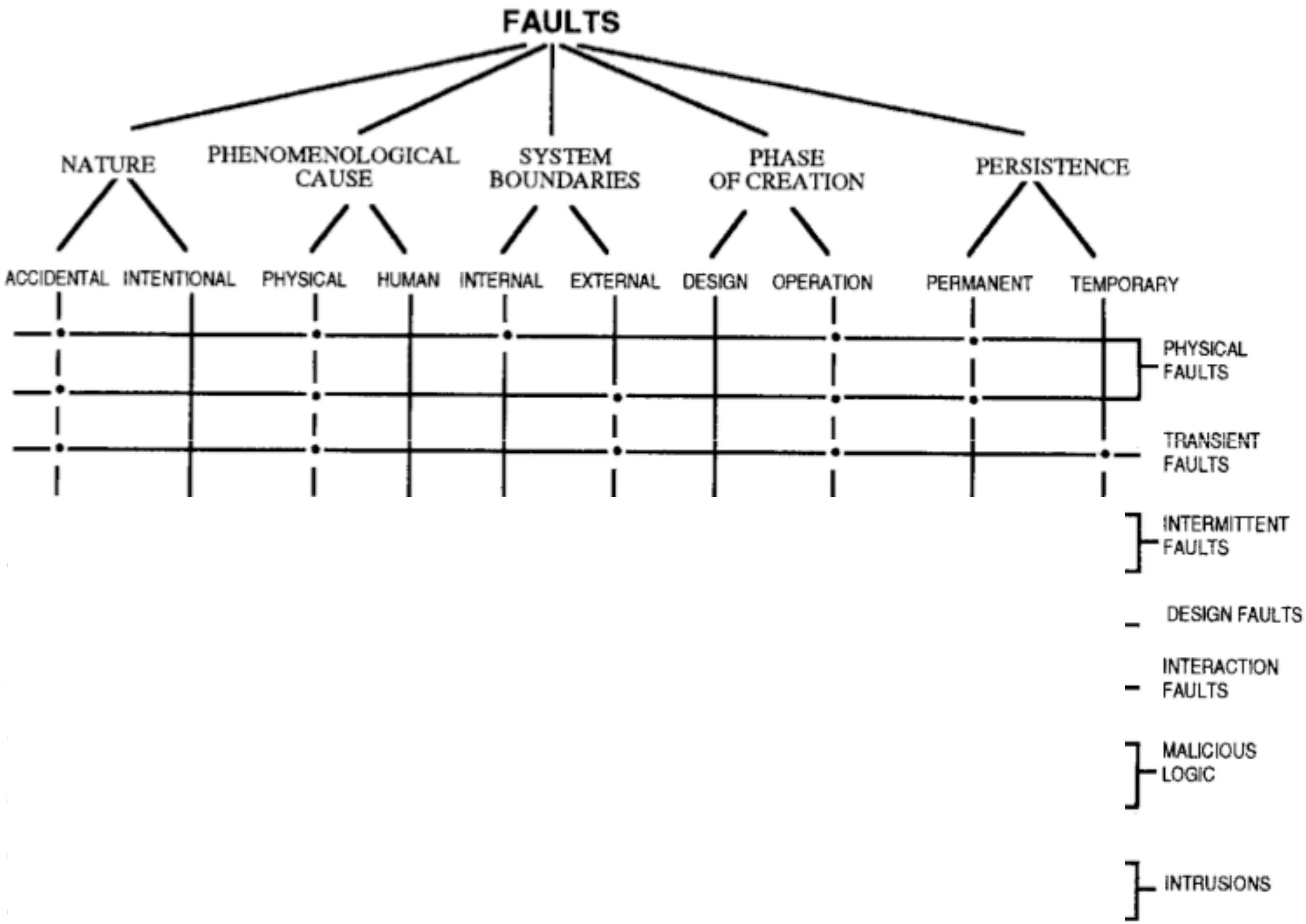

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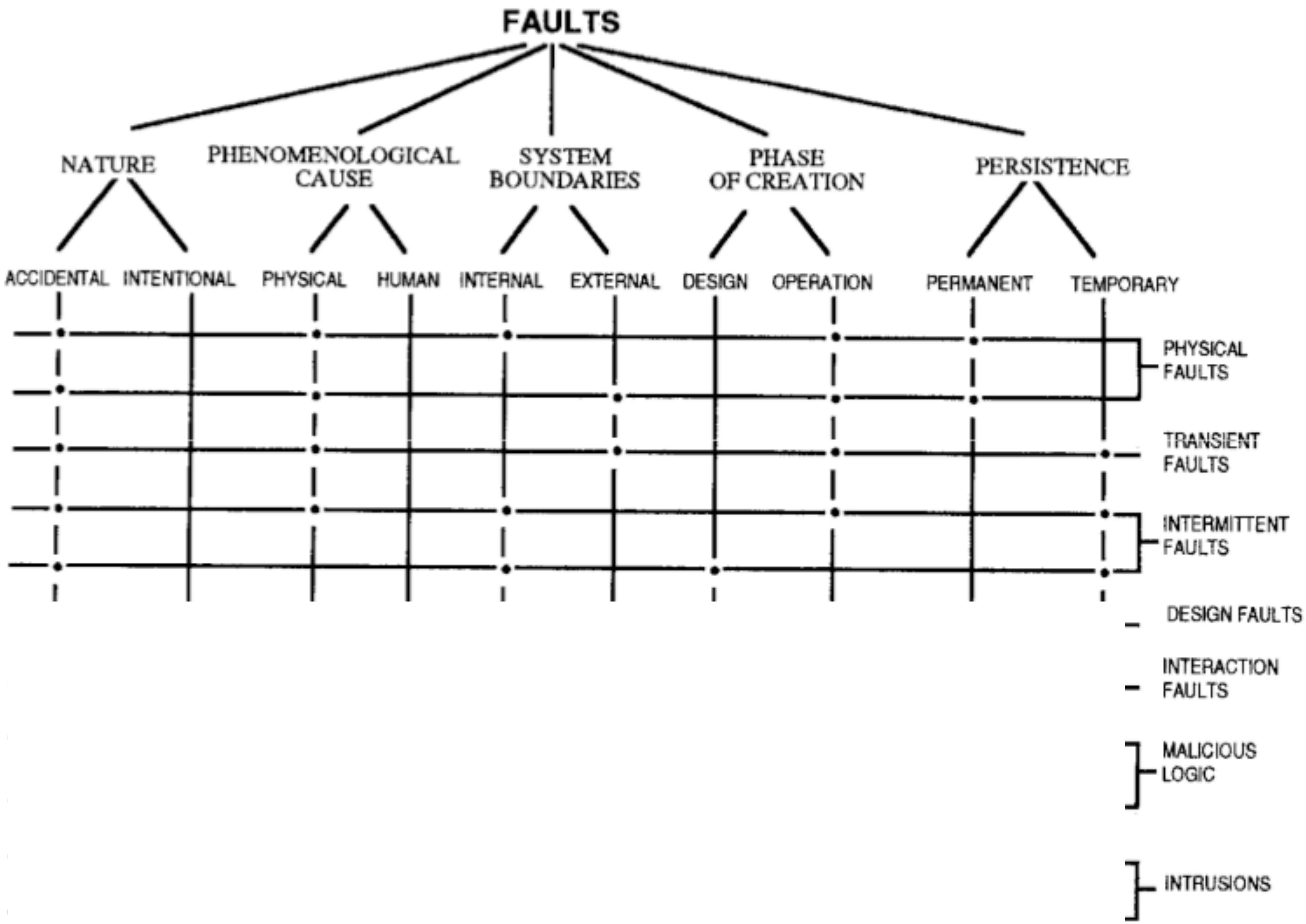

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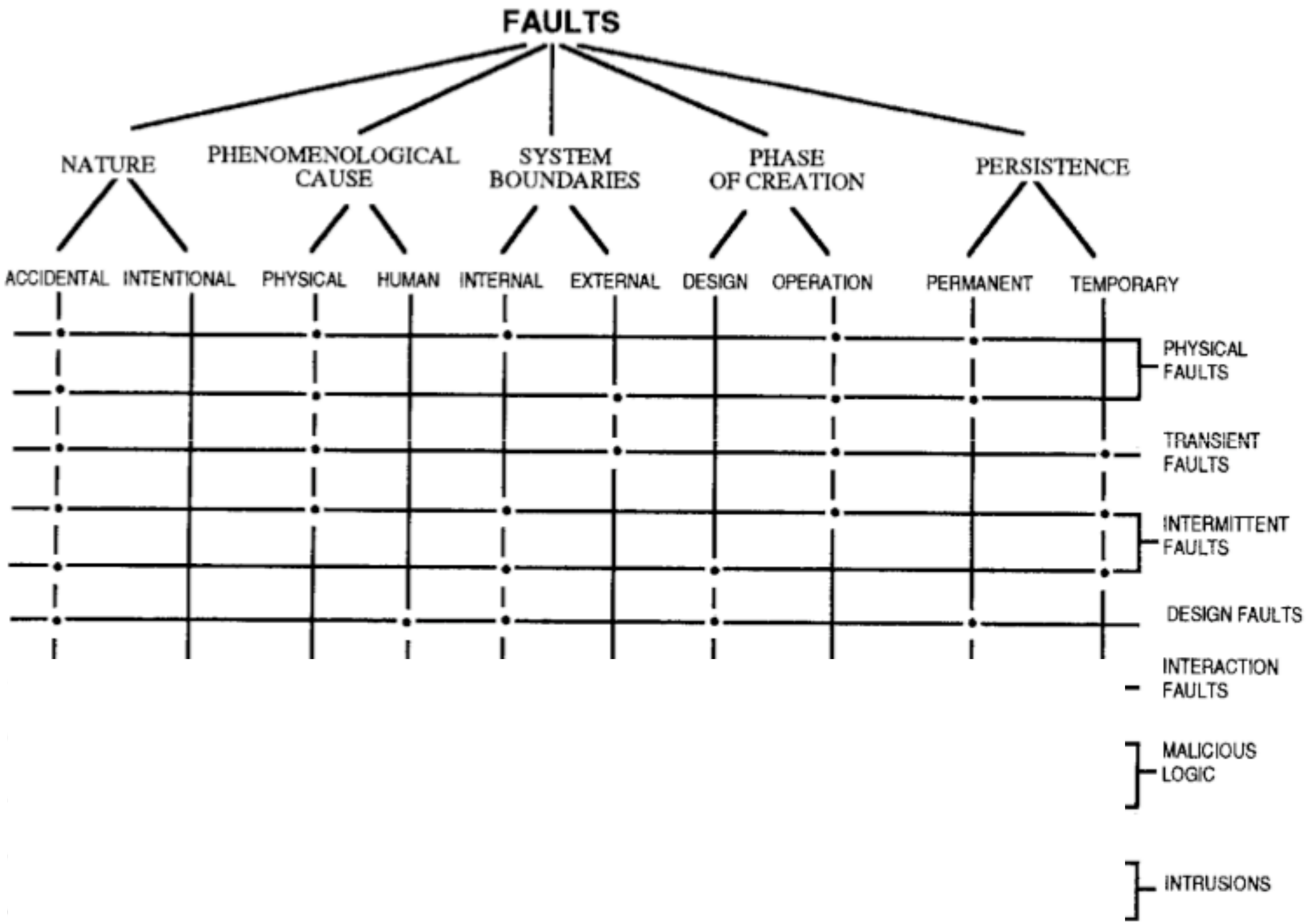

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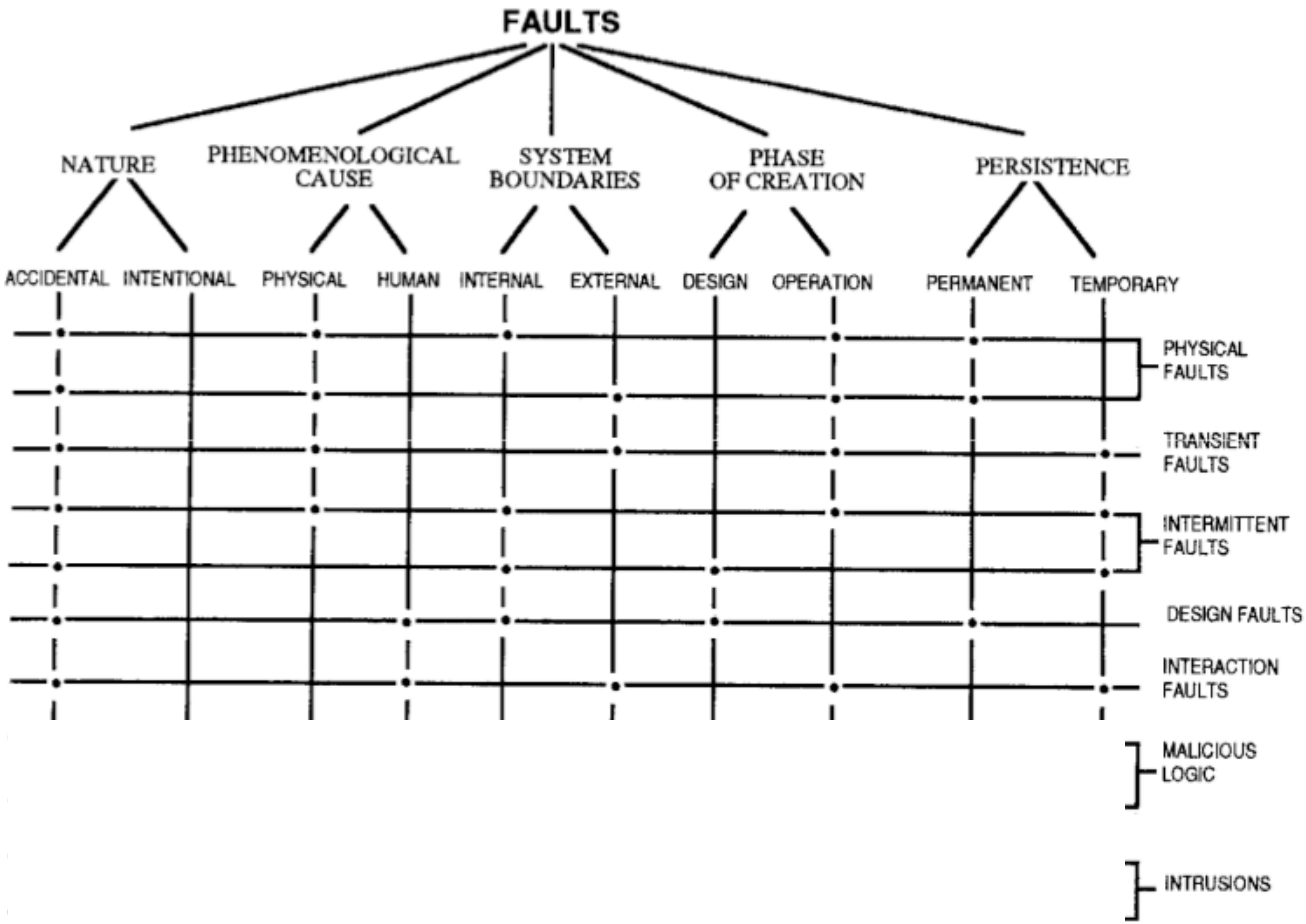

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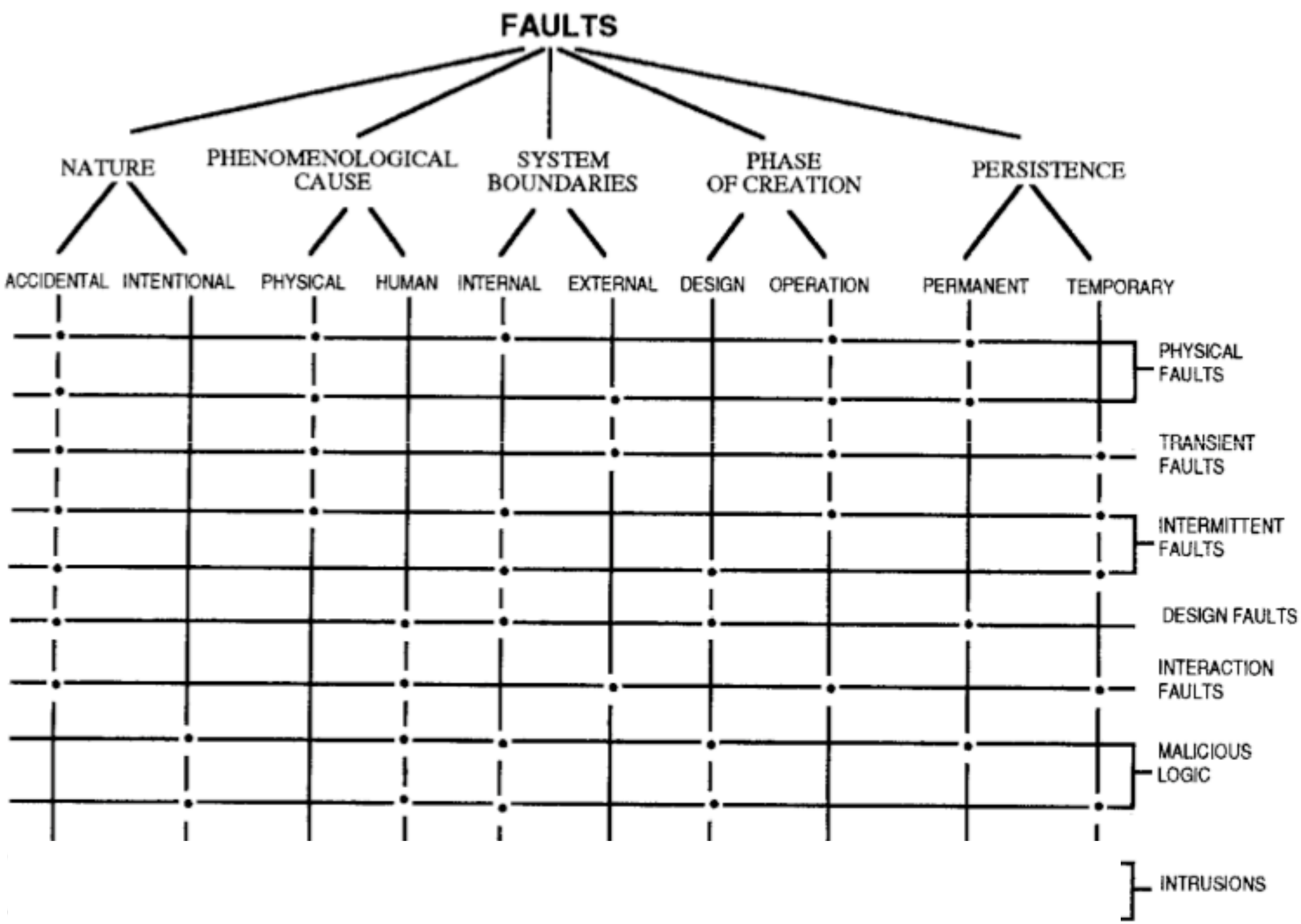

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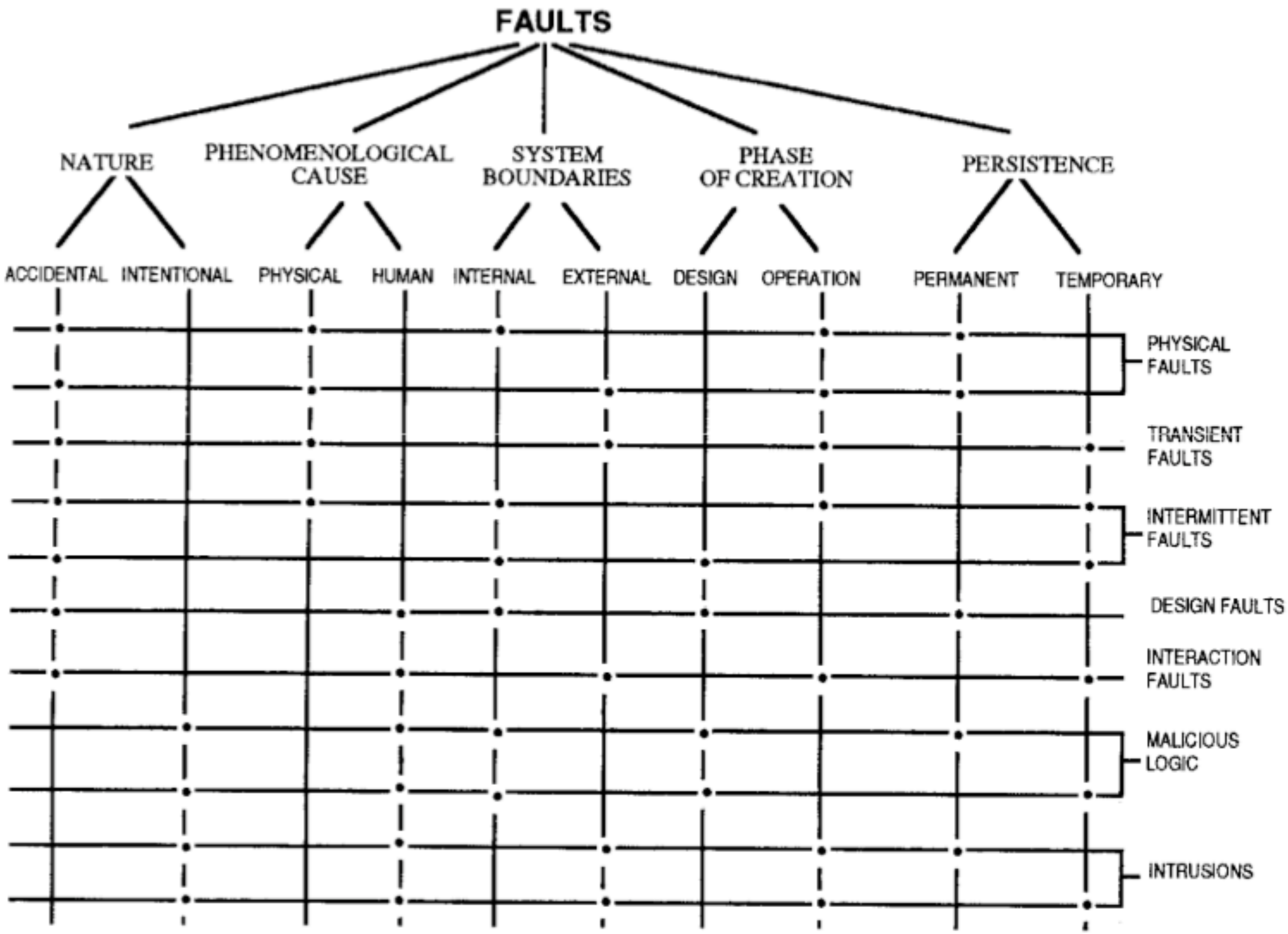


Fault Model

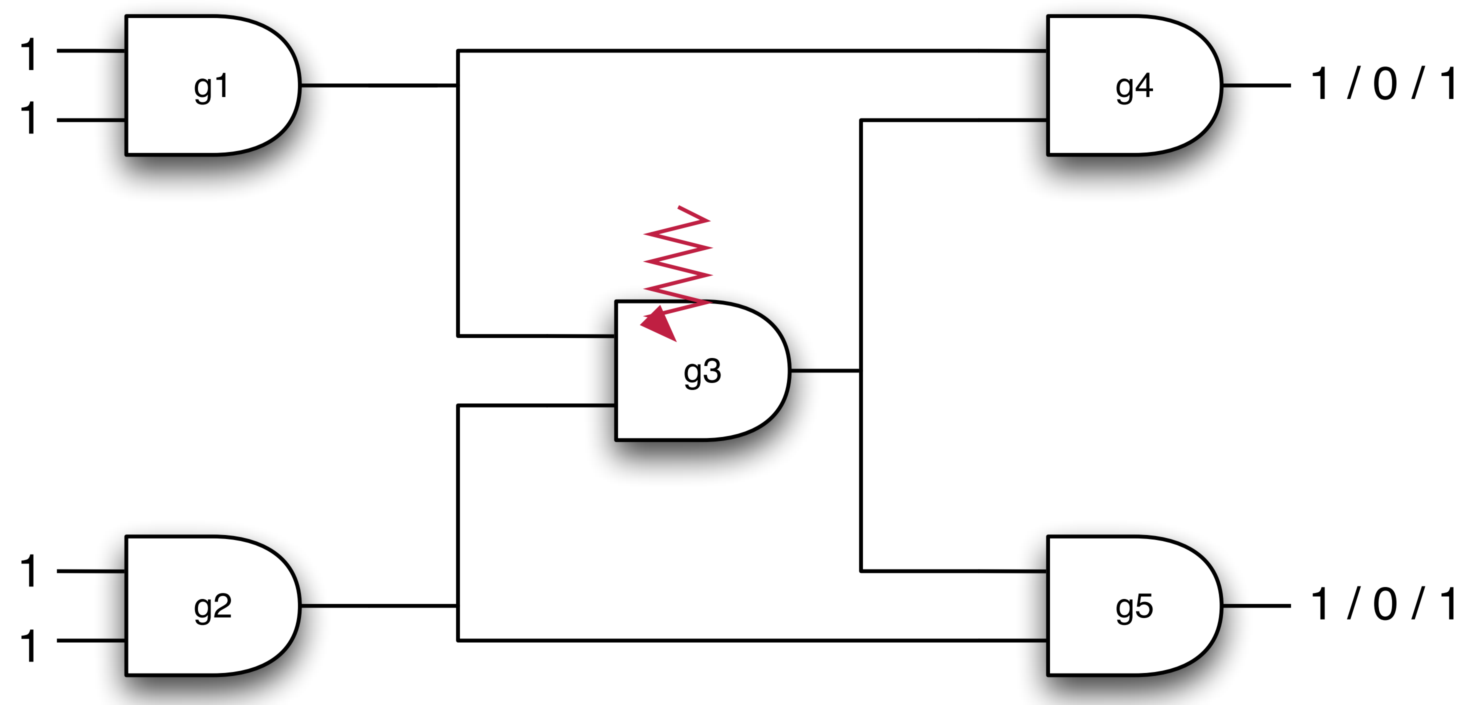
- Faults can be classified into different categories on different abstraction levels
  - Physics
  - Circuit level / switching circuit level
    - Interesting for hardware design research (not this course)
    - Investigate logical signals on connections
      - stuck-at-zero, stuck-at-one, bridging faults, stuck-open
  - Register transfer level
  - Processor-memory-switch (PMS) level
  - Hardware system level
  - ... (Software) ...

Physical Faults [Goloubeva]

- Highly energized particles originate from space, atmospheric, or ground radiation
  - Cosmic radiation, solar heavy ions, solar protons, ...
- Interaction of particle that strikes a circuit - atomic displacement, direct ionization, indirect ionization created by nuclear reactions
- Smaller structures are sensitive to ionization effects from all kinds of particles
- **Single Event Upset (SEU)** - injected charge changes content of a memory bit
- Dynamic random access memory (DRAM) - typical building blocks for main memory
  - No inherent refreshing, influence on storage capacitor changes value
- Static random access memory (SRAM), for caches, registers, pipeline, ...
  - Impact on restoring transistor leads to invalid refresh operation

Physical Faults [Goloubeva]

- Logic circuits: Shrinking size, reduction of power supply, increase of frequency
  - Noise margin is extremely reduced, single-event strike impacts circuit lines
- **Single Event Transient (SET):** Particles modify voltage in a combinational circuit
  - Can be modeled at gate level as erroneous transition on the gate output



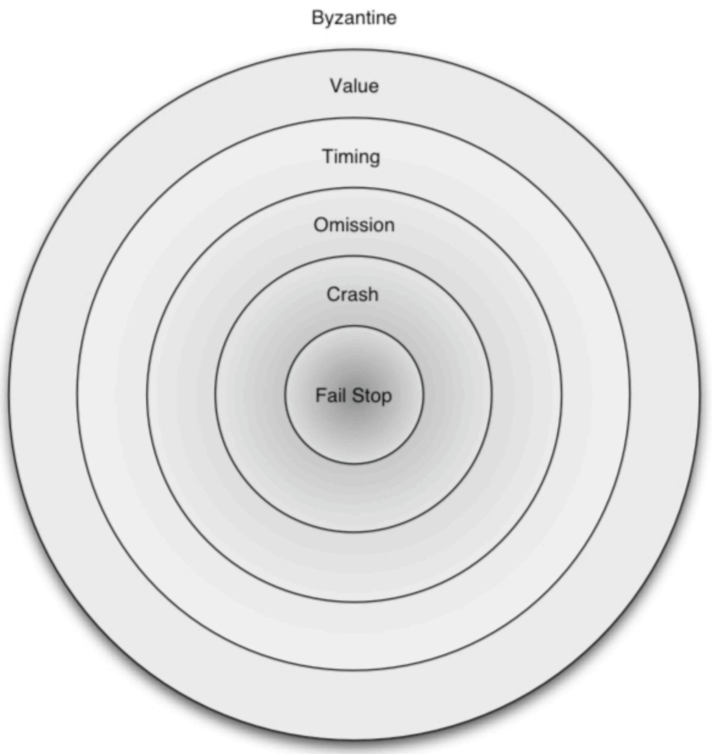
Fault Model for Semiconductor Memories

- **Stuck-at**-1 or stuck-at-0 (hard) faults, **transition / bit-flip faults** (0->1, 1->0)
- **Open and short circuits** - Too much or too little metallization; Also open bonds
- **Input and output leakage** - Leakage current in excess of the specified limit
- **Multiple writing** - Data written into more than one cell when writing into one cell
- **Pattern sensitivity** - Device does not perform reliably with certain test pattern(s)
- **Refresh dysfunction** - Data are lost during the specified minimum refresh time
- **Write recovery** - Write followed by reading/writing at different location resulting in reading/writing at same location
- **Sense amplifier recovery** - Data accessed for a number of cycles are the same and then suddenly changed, sense amplifier tends to stay in the same state
- **Sleeping sickness** - Memory loses information in less than the stated hold time (typically tens of milliseconds)

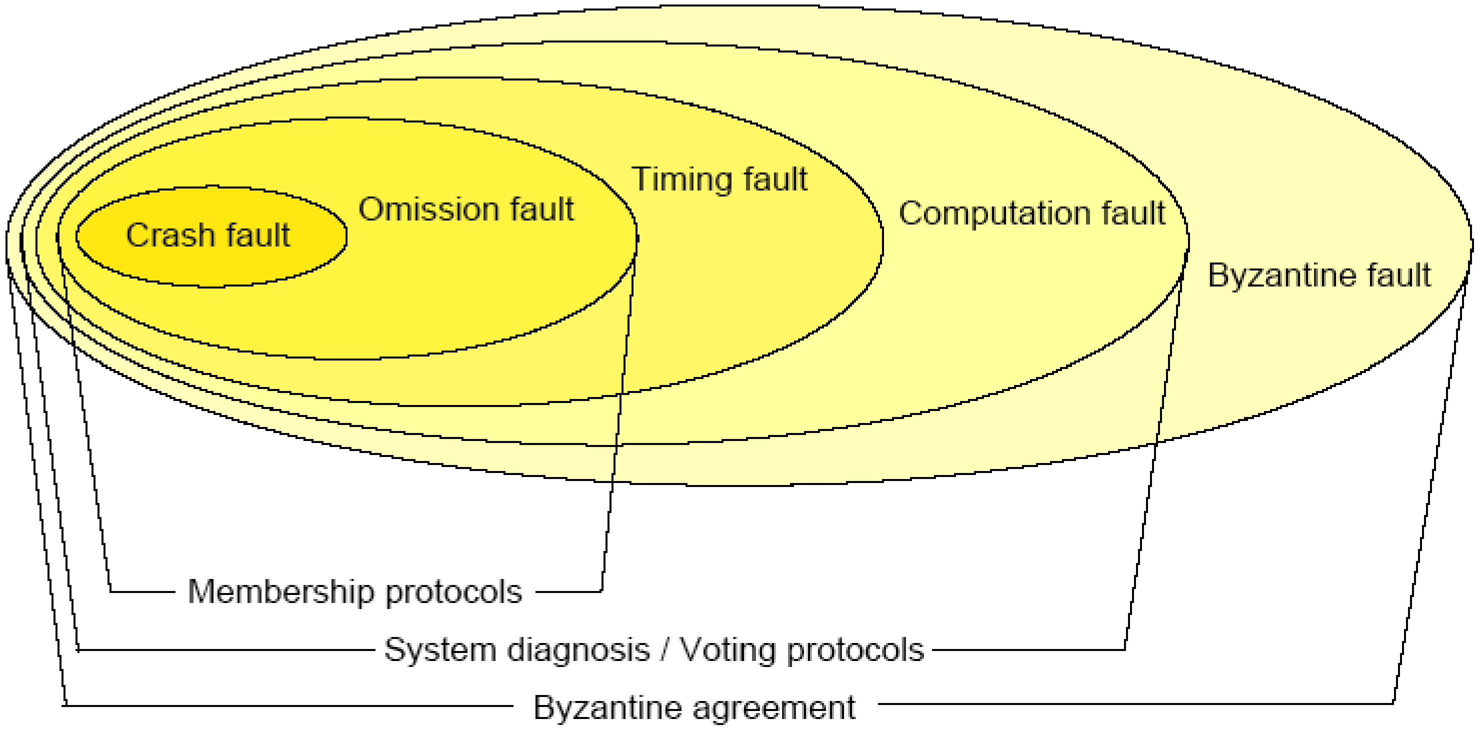
Fault Model for Semiconductor Memories

- **Decoder malfunction** - Inability to address same portions of the array
  - No cell accessed by certain address, multiple cells accessed by certain address
  - Certain cell not accessed by any address
  - Certain cell accessed by multiple addresses
- **Bridging fault** - Short between cells, AND type or OR type
- **State coupling fault** - Coupled (victim) cell is forced to 0 or 1 if coupling (aggressor) cell is in given state
- **Inversion coupling fault** - Transition in coupling cell inverts coupled cell
- **Idempotent coupling fault** - Coupled cell is forced to 0 or 1 if coupling cell transits from 0 to 1 or 1 to 0
- **Disturb fault** - Victim cell forced to 0 or 1 if we read or write aggressor cell (may be the same cell)

System-Level Fault Model



- Idea from hardware background, meanwhile also in software
    - Usage: How many faults of different classes can occur ? What do I tolerate ?
- Process as black box, only look on input and output messages
- Link faults are mapped to the participating components
- Timing of faults: Fault delay, repeat time, recovery time, reboot time, ...
- Every participating component would need a fault model - pick the most urgent ones



System-Level Fault Model [Cristian]

- **Fail-Stop** Fault : Processor stops all operations, notifies the other ones
- **Crash** Fault : Processor looses internal state or stops without notification
- **Omission** Fault : Processor will break a deadline or does not react to some task at all
    - Send / Receiver Omission Fault: Necessary message was not not sent / not received in time
- **Timing** Fault / **Performance** Fault : Processor stops / reacts to a task before its time window, after its time window, or never
- **Incorrect Computation** Fault : No correct output on correct input
- **Byzantine** Fault / **Arbitrary** Fault : Every possible fault
    - Authenticated Byzantine Fault : Every possible fault, but authenticated messages cannot be tampered

Errors

- State of the system, not an event !
- Escalates to failure depending on
  - Intentional / unintentional redundancy
  - System activity
  - User‘s definition of a failure
    - Examples: Maximum outage time, acceptable delay, retransmission rate
- System activity can overwrite the error state before damage is happening
- **Latent** (not recognized) vs. **detected** error coming from an active fault
- Hardware often contains unintentional redundancy, makes it difficult to test

Hardware Error Models [Goloubeva]

- Hardware faults effect state information, e.g. register values
  - Stuck-at and other hardware faults therefore can also be denoted as error
- More interesting to investigate resulting effects on system-level
  - **Single data error** - Program data is corrupted (in cache, memory, or register)
  - **Single code error** - Effect on one instruction of the code
    - **Type 1/2** - Instruction modification without / with change of control flow
- Nature of error state can confirm to the nature of the originating fault
  - Transient vs. permanent, static vs. dynamic, single vs. multiple
  - Influence from utilized dependability means

Hardware Error Models [Goloubeva]

- Mapping of hardware-level single bit-flip error to other layers
  - **Memory data segment, processor data cache**: System-level single data error
  - **Memory code segment, processor code cache:** System-level single code error of type 1 (modification of target register) or type 2 (modification of branch target)
  - **Memory stack segment:** System-level data error or type 2 code error
  - **Processor register:** Depending on processor architecture and register type
    - Single data error if register holds data interpreted by the application
    - Single type 1 code error, if register holds address used by load/store operation
    - Single type 2 code error, if register holds address of a branch target
  - Processor control register: Everything could happen ...

Hardware Error Models - Code Errors [Goloubeva]

```
       MOV R0, 10                   MOV R0, 10
       MOV R1,  1                   MOV R1,  1
LOOP:  ADD R1, R1      ──►   LOOP:  SUB R1, R1
       SUB R0,  1                   SUB R0,  1
       BNZ LOOP                     BNZ LOOP
```

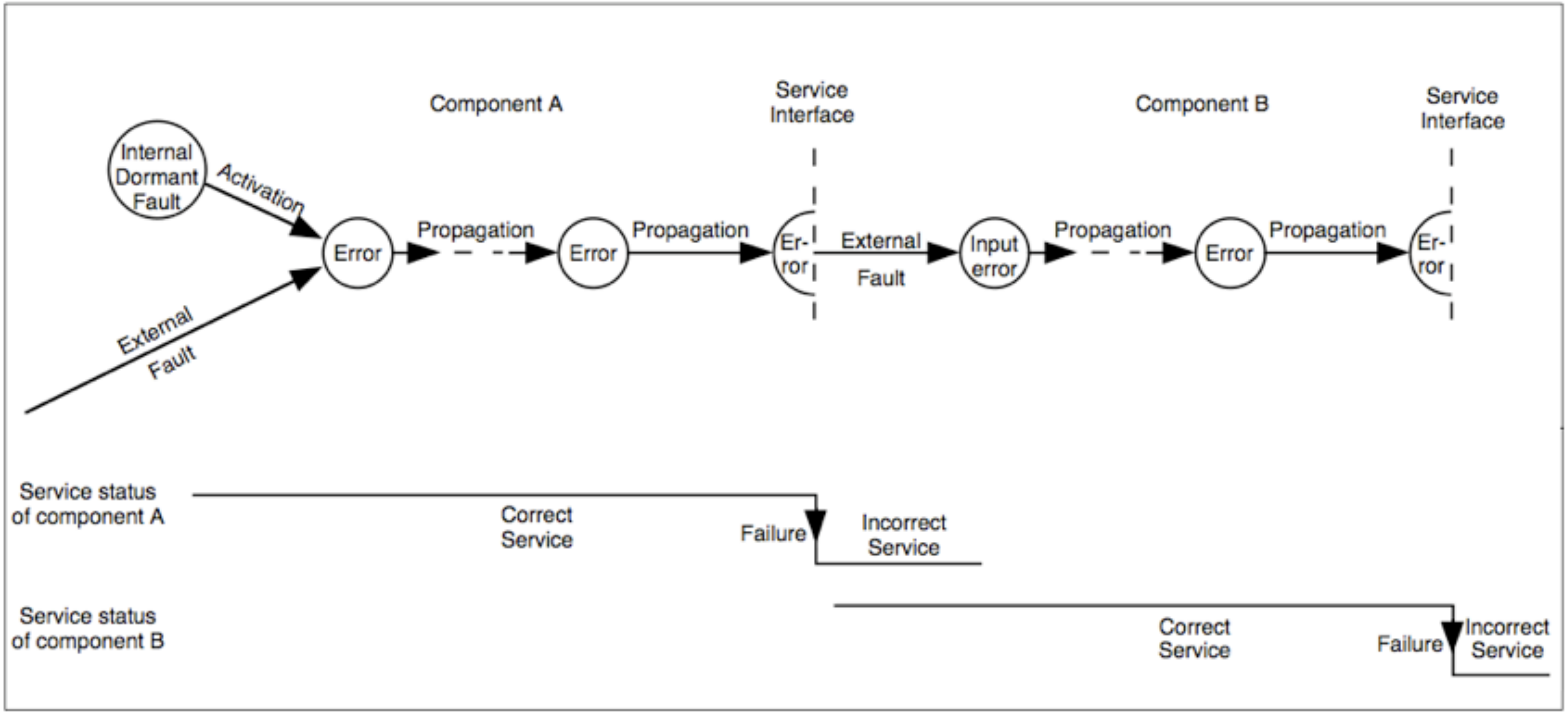
```
       MOV R0, 10                   MOV R0, 10
       MOV R1,  1                   MOV R1,  1
LOOP:  ADD R1, R1      ──►   LOOP:  ADD R1, R1
       SUB R0,  1                   SUB R0,  1
       BNZ LOOP                     BNZ FOOBAR
```

```
       MOV R0, 10                   MOV R0, 10
       MOV R1,  1                   MOV R1,  1
LOOP:  ADD R1, R1      ──►   LOOP:  ADD R1, R1
       SUB R0,  1                   SUB R0,  1
       BNZ LOOP                     BZ LOOP
```

Software Error Models [Goloubeva]

- Similar terminology, but completely different semantics
- Syntactical errors are handled by compiler, semantical errors occur at runtime
  - Static vs. dynamic, permanent vs. temporary errors
- Example for C programming language
  - Errors affecting assignments (missing / wrong local variable values)
  - Errors affecting conditional instructions (wrong boolean or iteration condition)
  - Errors affecting function call / return (wrong parameters, return statement)
  - Errors affecting algorithms (missing statements or function calls, wrong operators)
- Under research in the software engineering field - field studies, automated code analysis, developer interviews

Error Propagation



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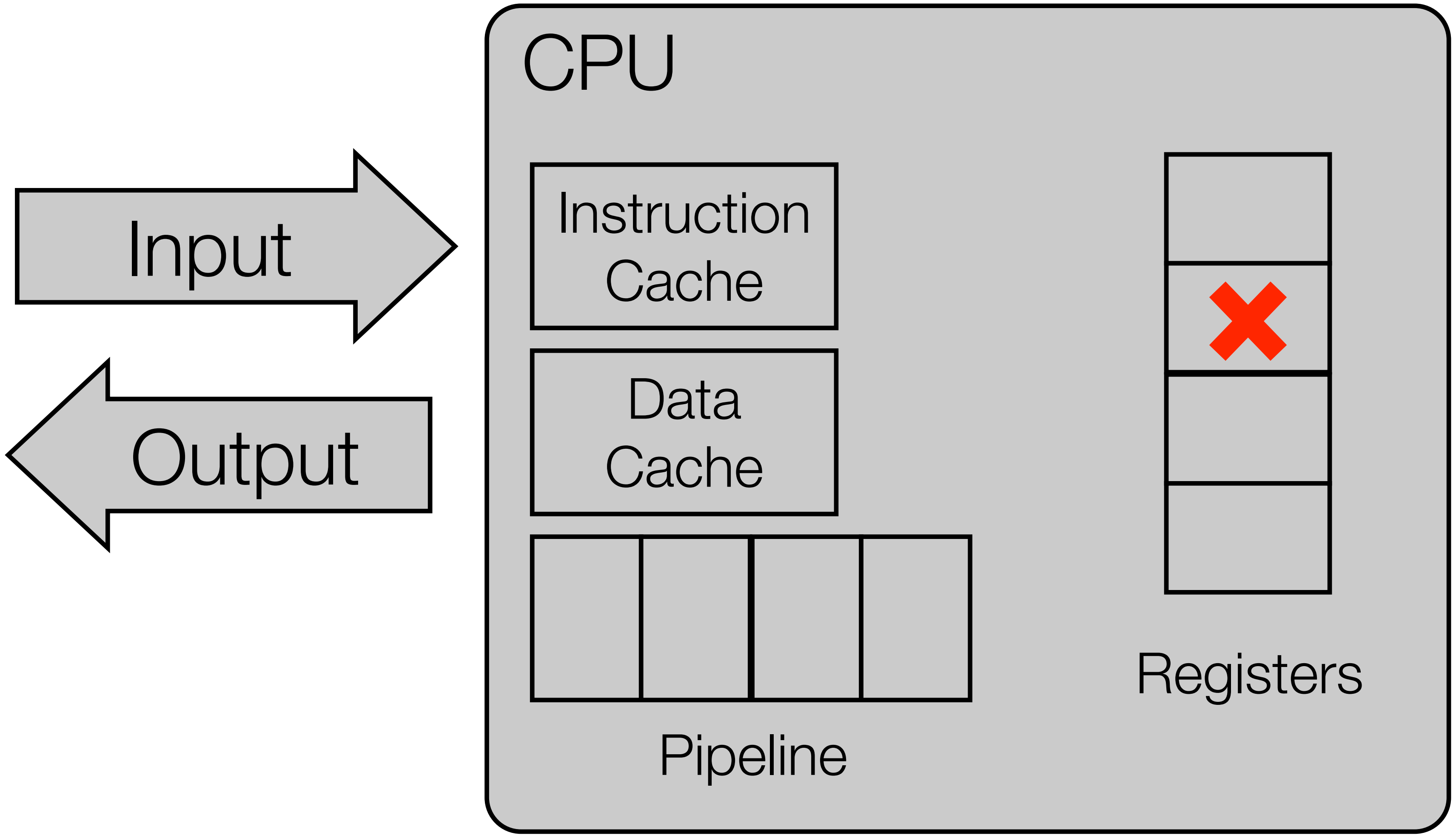
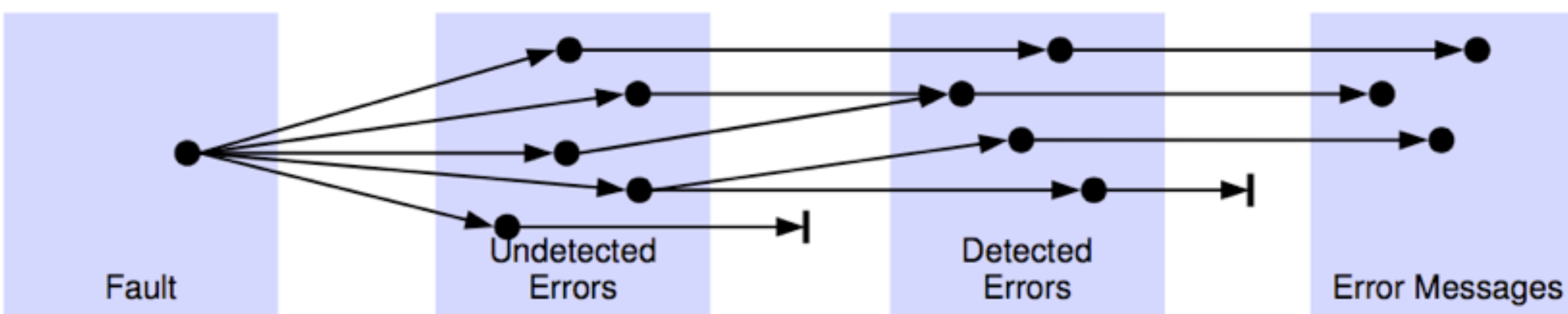
Error Propagation [Goloubeva]



Error Message Occurrence (Hansen & Siewiorek)

- Same fault can lead to different (detected or undetected) errors
- Errors become detected by error detection mechanisms
  - Some undetected errors are detected by several detectors
  - Some detectors report several undetected errors together
  - Some undetected errors are not detected at all
- Detected errors might not be logged, if the system stops too fast



Failures

- Non-compliance with the specification - **arbitrary failure** (‘willkürlicher Ausfall‘)
- System failures can be further categorized in **failure modes**
  - **Fail-silent** / **crash failure** mode - incorrect results are not delivered
  - **Fail-stop** mode - constant value is delivered
- Failure mode view points
  - Failure mode **domain** - what is influenced
    - Service result - **value failures,** service timeliness - **timing failures**
    - Service availability - **stopping failures**
  - **User perception** in this mode - consistent / inconsistent for all users
  - Failure **consequences** in this mode - allow ordering of failure modes

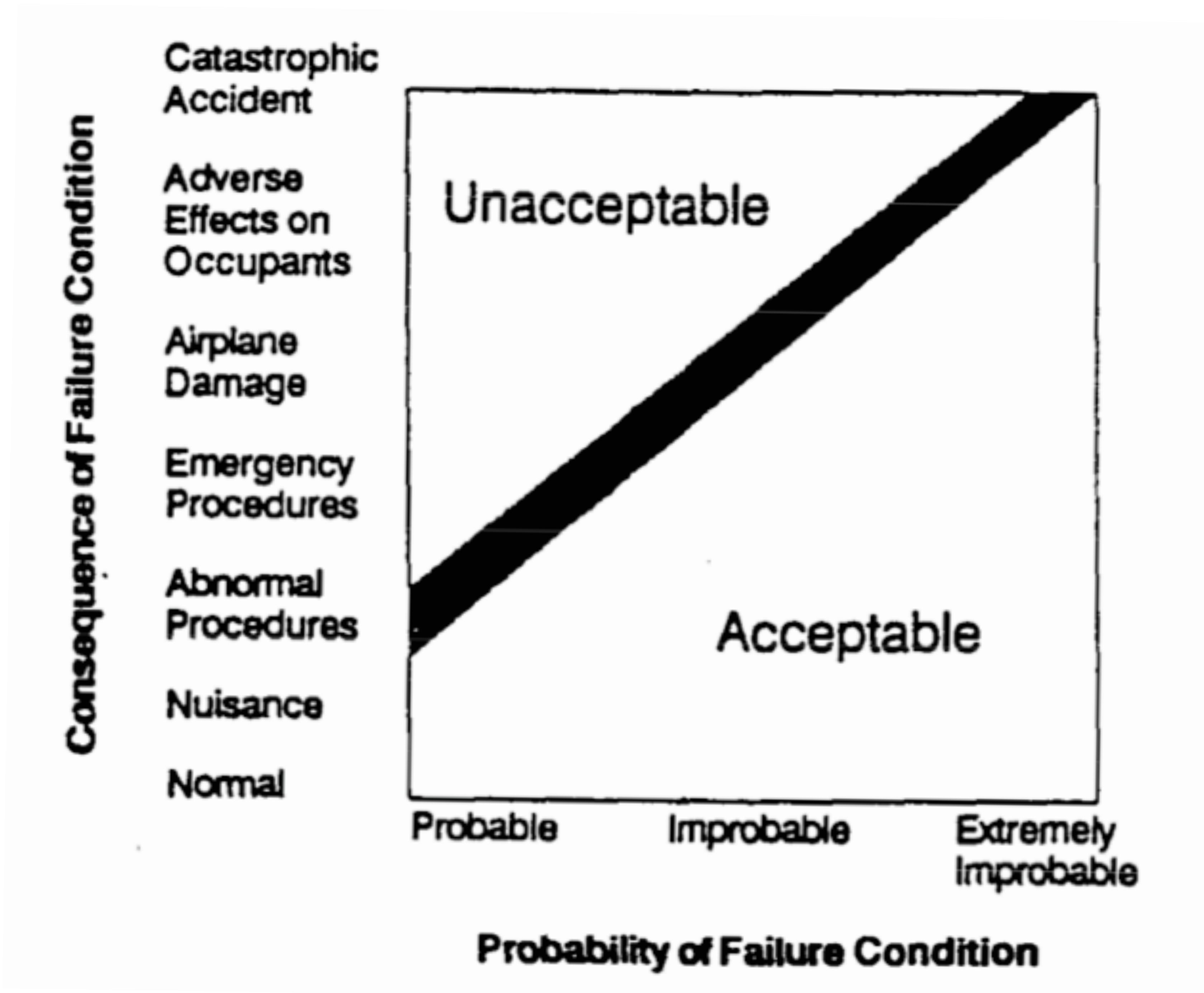
Failure Severity (‚Schweregrad des Ausfalls‘)

- Denotes consequences of failure
- **Benign failures** (‚unkritische Ausfälle‘)
  - Failure costs and operational benefits are similar
  - Sometimes also umbrella term for failures only detected by inspection
  - A system with only such failures is **fail-safe**
- **Catastrophic failures** (‚kritische Ausfälle‘)
  - Costs of failure consequences are much larger than service benefit
- **Significant / serious failures -** Intermediate steps expressing reduced service
- Grading of failure consequences on overall system depends on application
  - Flying airplane - Catastrophic stopping failure, Train - Benign stopping failure
- **Criticality** - Highest severity of possible failure modes in the system

Criticality Levels Example: DO-178B Standard

- *Software Considerations in Airborne Systems and Equipment Certification*
  - Mature document, developed for more than 20 years
- Definition of **severity of failure conditions** for airplane, crew, and passengers
  - *Catastrophic* - Loss of ability to continue safe flight and landing
  - *Major* - Reduced airplane or crew capability to cope with operating conditions
    - Reduction in safety margins and functional capabilities
    - Higher workload or physical distress for the crew
  - *Minor* - Not significantly reduced airplane safety, slight increase in workload
  - *No effect* - Failure results in no loss of operational capabilities and no increase in crew workload

Example: DO-178B Standard

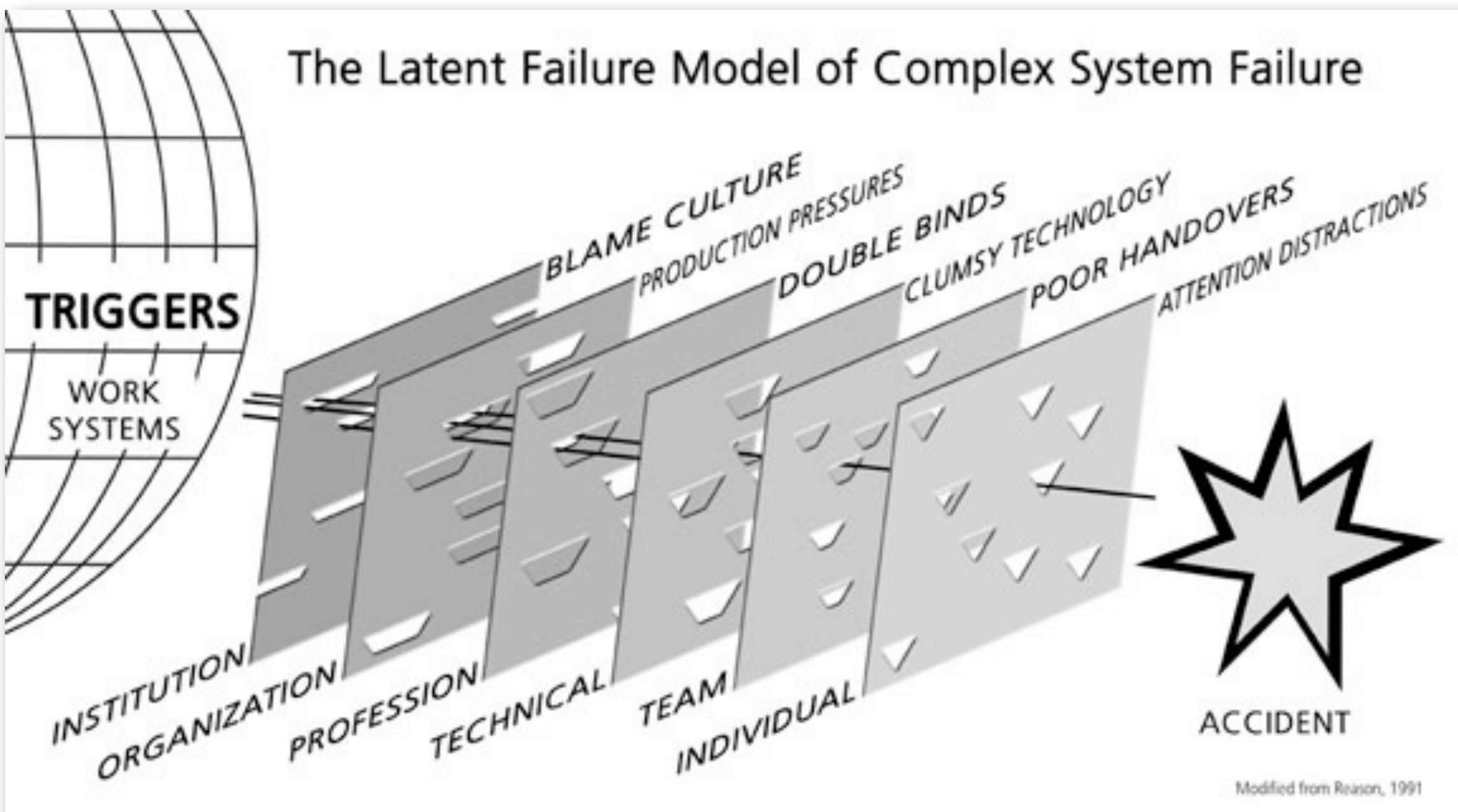


Failure Types

- Duration of the failure
  - **Permanent** failures - no possibility for repairing or replacement
  - **Recoverable** failures - back in operation after a fault is recovered
  - **Transient** failures - short duration, no major recovery action
- Effect of the failure
  - **Functional** failures - system does not operate according to its specification
  - **Performance** failures - performance or SLA specifications not met
- Scope of the failure
  - **Partial** failure - only parts of the system become unavailable
  - **Total** failure - all services go down

Swiss Cheese Model (Prof. Reason)

- Origins in medical research
- Defenses, barriers, and safeguards might be penetrated by fault trajectory



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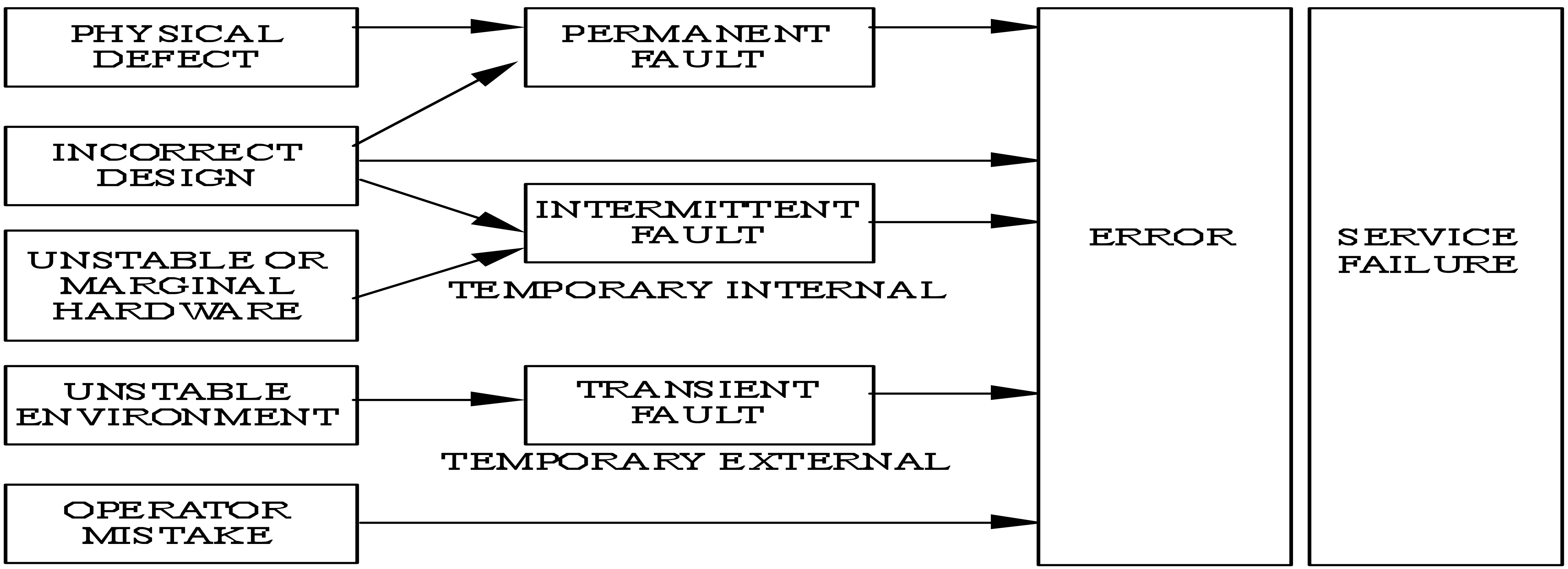
Observations on Failures

- Failures vs. Load
  - Typically positive correlation
    - Increasing load can lead to wear-out - increasing failure rate
    - Higher load can show up failure causes
    - Detected faults lead to recovery activities - load increases
  - Feedback effects possible
- Related faults (attributed to a common cause) can lead to **common-mode failures**

Chain of Dependability Threats



SOURCES OF ERRORS

[from Siewiorek and Swarz]

Security - Vulnerability Assessment [Johnston]

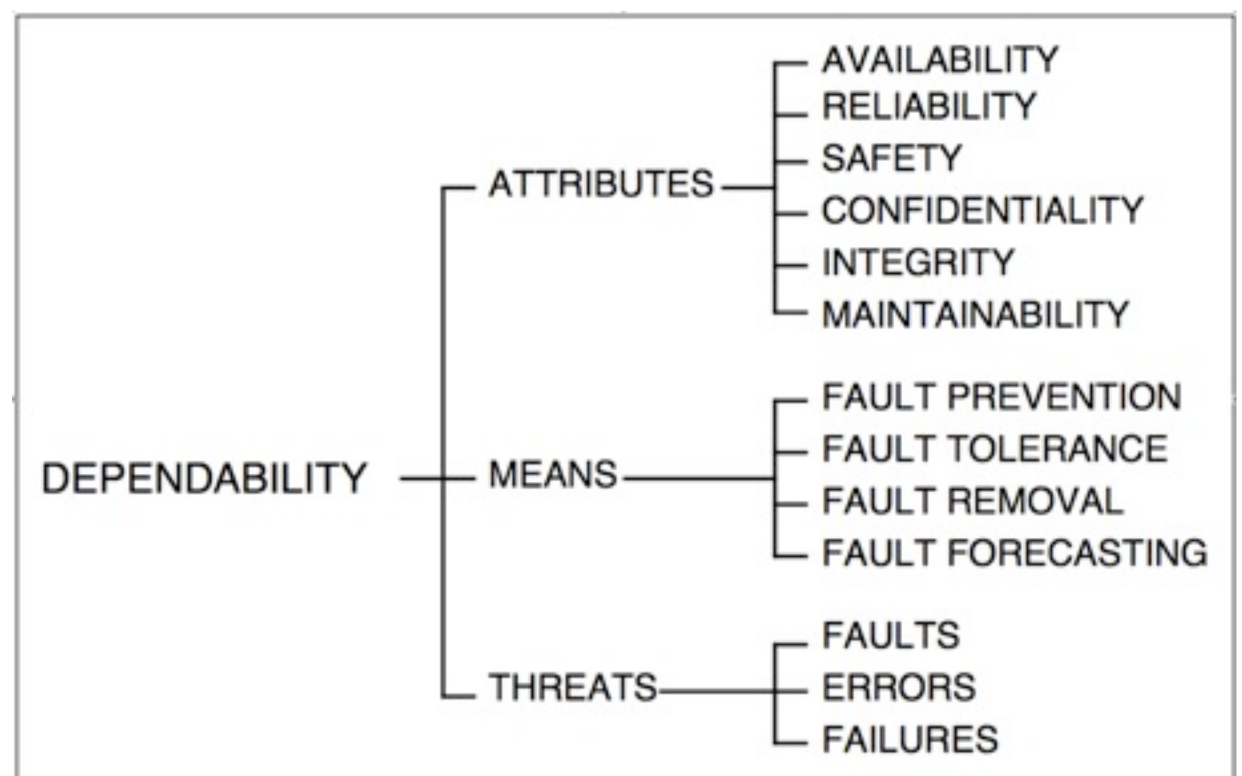
- Different dependability attribute targets might lead to different terminology
- Example: Vulnerability assessment for nuclear *security*
  - **Threat**: Who might attack against what asset, using what resources, with what goal in mind, when / where / why, with what probability
  - **Threat assessment (TA)**: Attempting to predict the threats - proactive security
  - **Vulnerability**: Specific weakness in security that could be exploited
  - **Vulnerability assessment (VA)**: Attempting to discover / demonstrate them
  - **Risk management**: Deploy, modify, and re-assign security resources, based on TA results, VA results, assets, security breach consequences, and costs (time, money, human resources)
  - **Attack**: Attempt to harm valuable asset by exploiting one or more vulnerabilities

Security - Vulnerability Assessment [Johnston]

- Threats and vulnerabilities are different concepts, and must be treated separately
    - Vulnerabilities without threats are not interesting
    - Vulnerabilities do not define threats (bad locks do not imply thieves to show up)
- No one-to-one mapping, different attacks can exploit the same vulnerability
- TA involves mostly speculation about unknown people, so VA is more important
- Correct VA should identify large amount of issues with cheap countermeasures
- System features can become a vulnerability only in combination with an attack
- TA and VA are not pass / fail certifications

Means for Dependability

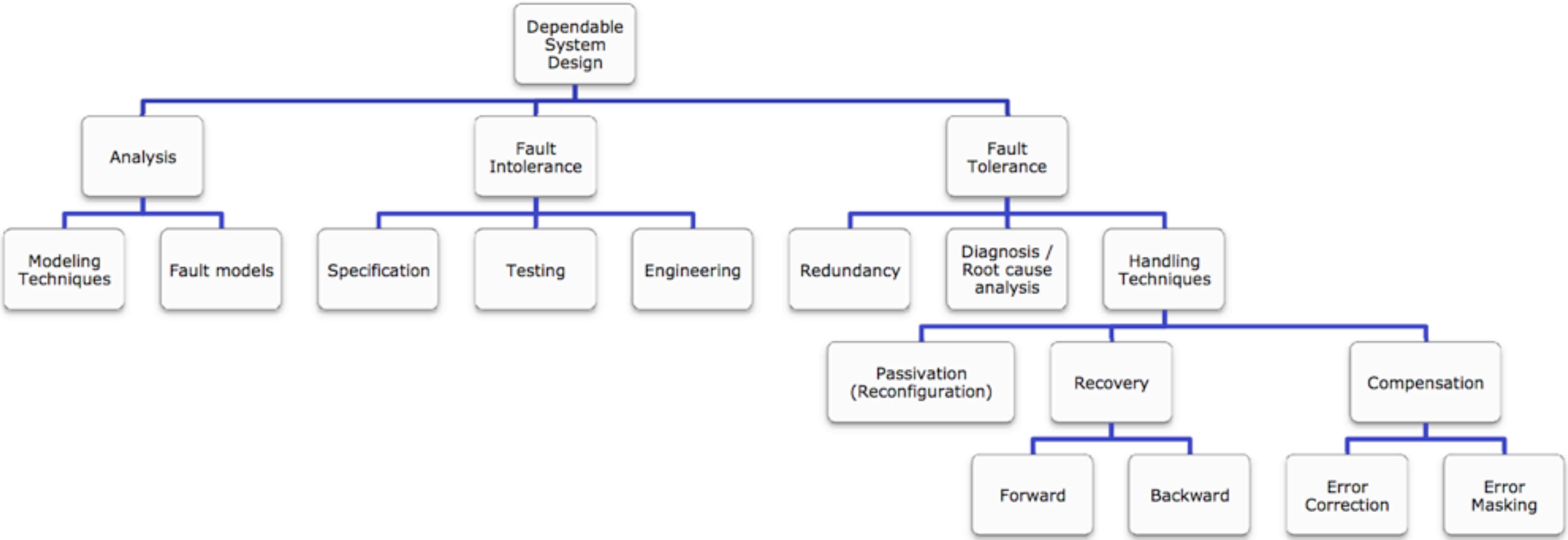
- **Fault prevention** - Prevent fault occurrence or introduction
- **Fault tolerance** - Provide service matching the specification under faults
- **Fault removal** - How to reduce the presence of faults
- **Fault forecasting**- Estimate the present number, future incidence, and the consequences of faults
- Combined utilization



Dependability Means (Laprie)

- Offline / online techniques
  - Fault intolerance techniques
    - **Fault prevention** - Prevent fault occurrence or introduction
    - **Fault removal** - Reduce the presence of faults
    - 100% fault-free servicing for the whole life time is not possible
  - Fault tolerance techniques
    - **Fault forecasting** - Estimate the present number, future incidence, and the consequences of faults
    - **Fault tolerance** - Provide service complying with specification in spite of faults
- Problems with **coverage** and **validation of the validator**

Dependable System Design (Echtle)



Fault Prevention

- Specific approaches for avoiding faults
    - Specialized specification formalisms and techniques
    - Specialized development / manufacturing process to prevent design faults
    - Shielding
    - Only use ultra-reliable components
- General engineering approaches
    - Software engineering procedures
    - Quality management regulations and enforcement
    - Training and organization of maintenance departments

Fault Removal

- Make faults disappear before fault tolerance becomes relevant
- Step 1: Verification
  - Check if the system adheres to **verification conditions**; if not, take next steps
  - **Static verification**: Static analysis, data flow analysis, compiler checks
  - **Dynamic verification**: Symbolic execution or verification testing
- Step 2: Diagnosis
  - Find the faults that influenced the verification conditions
- Step 3: Correction
  - Fix the problem, repeat the steps (**regression**)
- Fault removal during operation: **Corrective maintenance (curative / preventive)**

Testing

- Selecting test inputs is driven from different view points
  - Testing purpose: **conformance testing**, **fault-finding testing**
  - System model: **functional testing** (with functional model) or **structural testing**
  - Fault model: enables **fault-based testing**
- Deterministic testing vs. random testing
- Structural testing of hardware is fault-finding, fault-based, structural testing
- Structural testing of software is fault-finding, non-fault-based, structural testing
- **Golden unit**: Reference system for comparison of output for a given input

Fault Tolerance

- Fault tolerance is the ability of a system to operate correctly in presence of faults.

  or

- A system S is called **k-fault-tolerant** with respect to a set of algorithms $\{A_1, A_2, \ldots, A_p\}$ and a set of faults $\{F_1, F_2, \ldots, F_p\}$ if for every k-fault F in S, A_i is executable by a subsystem of system S with k faults. (Hayes, 9/76)

  or

- Fault tolerance is the use of **redundancy** (time or space) to achieve the desired level of system dependability - costs !

- Accepts that an implemented system will not be fault-free

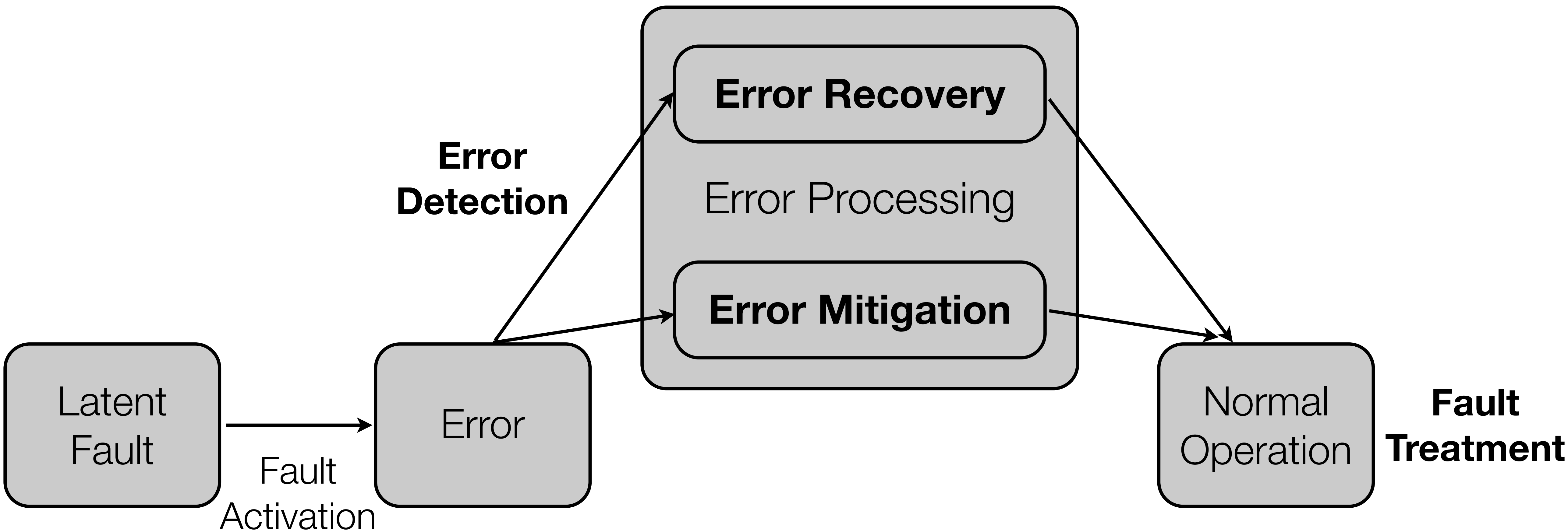
- Implements automatic recovery from errors

- Is a recursive concept (voter replication, self-checking checkers, stable memory)

Fault Tolerance

- Typical design methodology in many technical and biological systems
  - Spare wheel in cars, redundant organs, ...
- Fault tolerance mechanisms need to be evaluated by dependability attributes
  - Minimum, maximum, average reliability and availability
  - Easy to formulate and understand, hard to prove - failure rate remains unknown
  - Quantitative limits based on fault model (which faults in which components)
- Typically ‚one-fault-at-a-time‘ assumption
- Different attributes of fault tolerance implementation to be checked
  - Functional verification, sensitivity analysis, minimum amount of resource resp. computational overhead, implementation performance, transparency, portability

Phases of Fault Tolerance (Hanmer)



Decomposition of Fault Tolerance (Lee & Anderson)

- **Error detection**
  - Presence of fault is deducted by detecting an error in some subsystem
  - Implies failure of the according component
- **Damage confinement**
  - Delimit damage caused due to the component failure
- **Error processing - recovery / compensation**
  - System recovers from the effect of an error
- **Fault treatment**
  - Ensure that fault does not cause again failures

Fault Tolerance - Error Detection

- **Replication check**
  - Output of replicated components is compared / voted
  - Independent failures, physical causes -> many replicas possible (e.g. HW)
  - Finds also design faults, if replicated components are from different vendors
- **Timing checks** (‚watchdog timers‘)
  - Timing violation often implies that component output is also incorrect
  - Typical solution for node failure detection in a distributed system
- **Reasonableness checks** - Run-time range checks, assertions
- Structural and coding checks, diagnostics checks, algorithmic checks
- Ideal: **Self-checking component** with clear **error confinement areas**

Fault Tolerance - Error Detection

- Replication checks are powerful and expensive, examples:
    - Execute identical copies on different hardware (component failures)
    - Execute separate and different versions (assumes independent design faults)
    - Execute same copies different times (transient faults)
    - Replicate only portion of the system
    - Works for both hardware and software
- Signaling aspect in the error detection task
    - Typical software model are exceptions, a way for implementing forward recovery
- Combination fault detection and fault location

Fault Tolerance - Damage Confinement (Taylor)

- **System decomposition**
  - Every communication link might enable damage spreading
  - Introduce mutual suspicion
  - Hardware-based separation of software components
  - OS-based separation (processes, runtime monitors, special shells)
- **Law-governed architecture**
  - Externalize contrains on interaction by runtime rules
- **Strongly-typed language**
  - Language guarantees the absence of unintended control flows

Preventing Error Propagation

- Especially relevant when single components communicate their data
  - **Single-source information** - local clock, sensor data, transaction status ...
  - Non-failed component must find an **agreement** how to treat received information
    - Special topic in distributed systems
    - Atomic broadcast, clock synchronization, membership protocols

Fault Tolerance - Error Processing Through Recovery

- **Forward error recovery**
  - Error is masked to reach again a consistent state (**fault compensation**)
  - Corrective actions need detailled knowledge (**damage assessment**)
  - New state is typically computed in another way
    - Examples: error correcting codes, non-journaling file system check, advanced exception handlers, (voters)
- **Backward error recovery**
  - Roll back to previous consistent state (**recovery point** / **checkpoint**)
  - Very suitable for transient faults
  - Computation can be re-done with same components (**retry**), with alternate components (**reconfigure**), or can be ignored (**skip frame**)

Fault Tolerance - Fault Treatment

- **Fault diagnosis** - determine error cause‘s location and nature
- **Fault passivation** - (remove faulty component &) reconfigure system
  - Error processing might already remove the fault - ‚**soft fault**‘
  - Typical example are temporary faults
- Fault tolerance manager
  - Careful diagnosis with hardware support
  - Damage assessment by disabling faulty components automatically
  - Example: IBM mainframe architecture
- Software rejuvenation
  - Gracefully terminating an application and immediately restarting it at a clean internal state

Fault Tolerant Mindset (Hanmer)

- What can go wrong in any given situation ?
  - Mindset to be applied in all development stages
- „Every problem in computer science boils down to tradeoffs“ [Henschen]
  - Fault prevention vs. fault tolerance vs. failure severity
- KISS principles, leave out „bells and whistles“
- Incremental additions of reliability - long-term products
- Defensive Programming
  - Simple error handling; fix root cause, not symptoms; make data auditble; make code maintainable;

Fault Tolerant Design Methodology (Hanmer)

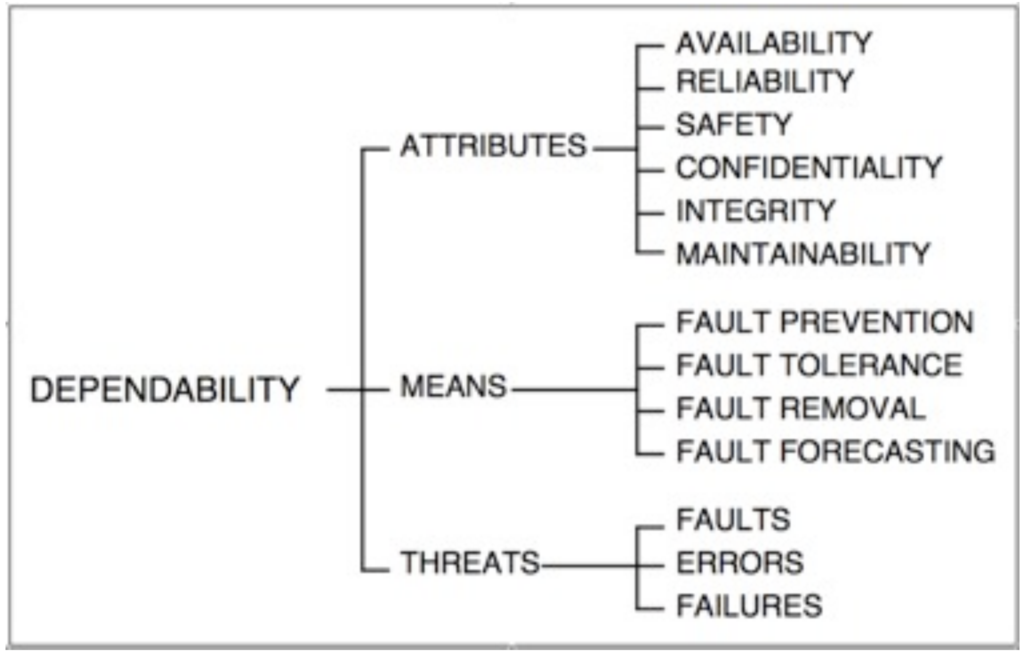
- Assess things that can go wrong with the system (e.g. fault trees).
  - Find potential risks and according system failures.
- Define strategies to mitigate the identified risks.
  - Failure avoidance options, prevent faults from activation
- Create a mental model of the system design with redundancy.
- Design error detection and error processing capabilities.
- Design in the failure mitigation capabilities.
- Design human-computer interactions and modes of management.

Dependable Design Strategies (Malek)

- Decompose the system
  - Identify fault classes, fault latency and fault impact for the components
  - Identify “weak spots” and assess potential damage
  - Integrate partial recovery / reintegration / restart
- Determine qualitative and quantitative specs for fault tolerance and evaluate your design in specific environment
- Develop / utilize fault and error detection techniques and algorithms
- Develop / utilize fault isolation techniques and algorithms
- Refine fault tolerance, iterate for improvement
- Re-use proven components, but be aware of integration issues

Attributes of Dependability

- **Non-functional attributes** such as reliability and maintainability
- **Complementary nature of viewpoints** in the area of dependability
- In comparison to functional properties
  - ... hard to define
  - ... hard to abstract
  - ... ‚Divide and conquer‘ does not work as good
  - ... difficult interrelationships
  - ... often probabilistic dependencies



Attributes of Dependability

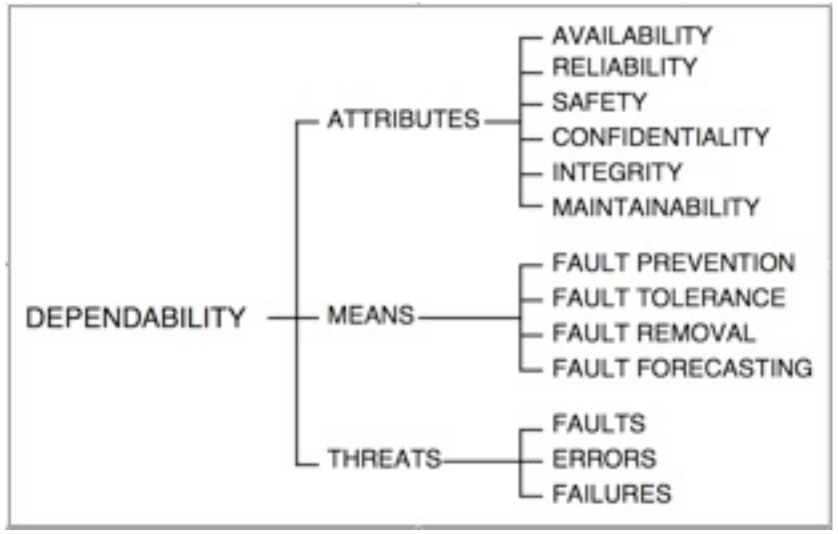
- **Reliability (‚Funktionsfähigkeit‘)** - Continuity of service
  - Initial goal for computer system trustworthiness; other disciplines have different understanding
  - *„Reliability is not doing the wrong thing.“* [Gray85]
  - *„Reliability: Ability of a system or component to perform its required functions under stated conditions for a specified period of time*“ [IEEE]
  - *„Reliability is the probability that an item will not fail.“* [Misra]
- **Availability (‚Verfügbarkeit‘)** - Readiness for usage
  - *„Probability that a system is able to deliver correctly its service at any given time.“* [Goloubeva]
  - *„Maintainability is the probability that the item can be successfully restored to operation after failure; and availability ... is a function of reliability and maintainability .“* [Misra]

Observations on Dependability Attributes

- Availability is always required
- Reliability, safety, and security may be optional
- Reliability might be analyzed for hardware / software components
- Availability is always from the system view point

Attributes of Dependability

- **Safety** - Avoidance of catastrophic consequences on the environment
  - Critical applications
  - Specification needs to describe things that should not happen
- **Security** - Prevention of unauthorized access and / or information handling
  - Became especially relevant with distributed systems
- **Confidentiality** - Absence of unauthorized disclosure of information
- **Integrity** - Absence of improper system alteration
  - With respect to either accidental or intentional faults
- **Maintainability** - Ability to undergo modifications and repairs



In Detail

- **Reliability** - Function *R(t)*
  - Probability that a system is functioning properly and constantly over time period t
    - Assumes that system was fully operational at t=0
    - Denotes failure-free interval of operation
- **Availability** - Fraction of / points in time were a system is operational
  - Describe system behavior in presence of error treatment mechanisms (fault tolerance, repairing)
  - **Instantaneous availability (at t)** - Probability that a system is performing correctly at time t; equal to reliability for non-repairable systems: $A_i(t) = R(t)$
  - **Steady-state availability** - Probability that a system will be operational at any random point of time, expressed as the fraction of time a system is operational during its expected lifetime: $A_s(t) = Uptime / Lifetime$

Reliability Definition: PDF & CDF

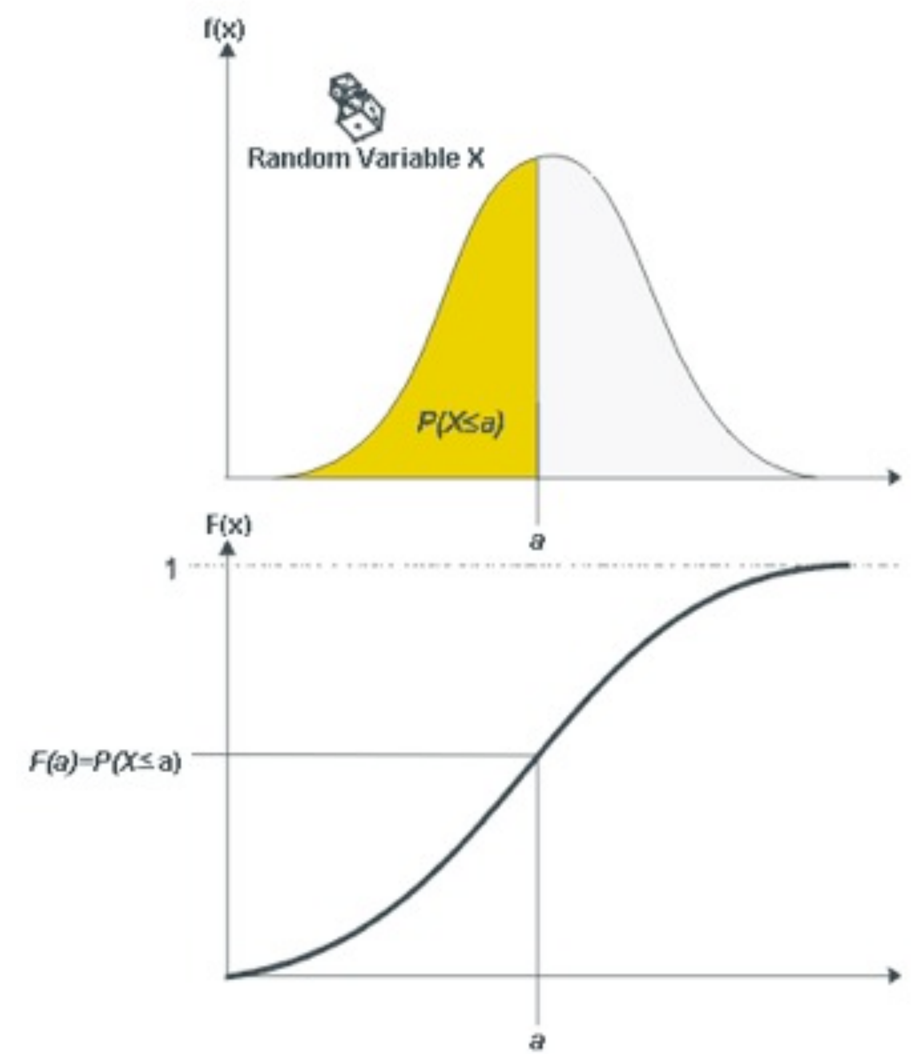
- Probability density function *pdf* for random variable *X*
  - Discrete variable: Probability that *X* will be *x*
  - Continuous variable: Probability that *X* is in *[a, b]*
    - Computed as area under the density function in this range

$$P(a \le X \le b) = \int_a^b f(x)dx \text{ and } f(x) \ge 0 \text{ for all } x$$

- Cumulative distribution function *cdf(x)*: Probability that the value of X is at most x

$$F(x) = P(X \le x) = \int_{0,-\infty}^{x} f(s)ds$$

  - Limits of integration depend on the nature of the distribution function



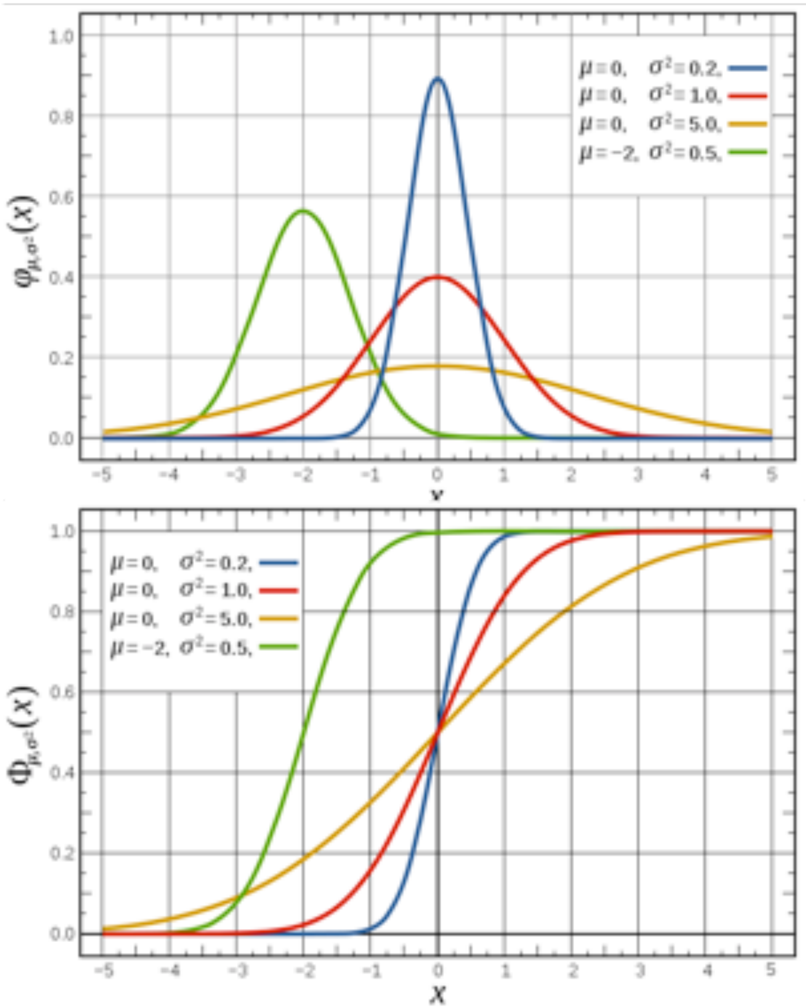
(C) weibull.com

- Value of *cdf* at *x* is always area under *pdf* up to *x*

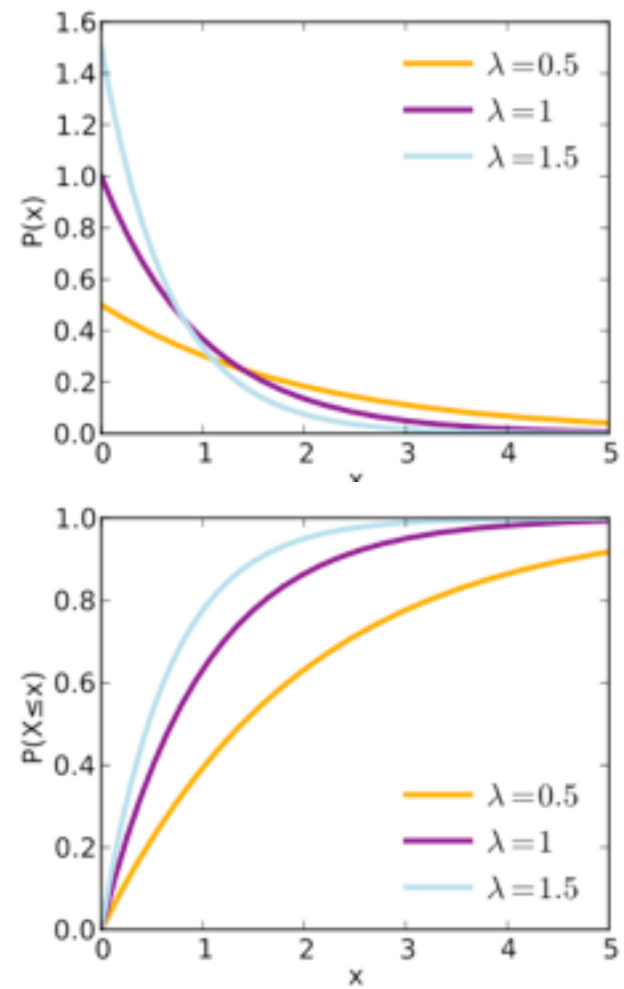
PDF Examples

- Well-known statistical distributions, each describing a random variable behavior
- Parameters of the distribution derived from data, complete description then by *pdf*

Normal distribution
(mean, variance)



Exponential distribution
(rate parameter)

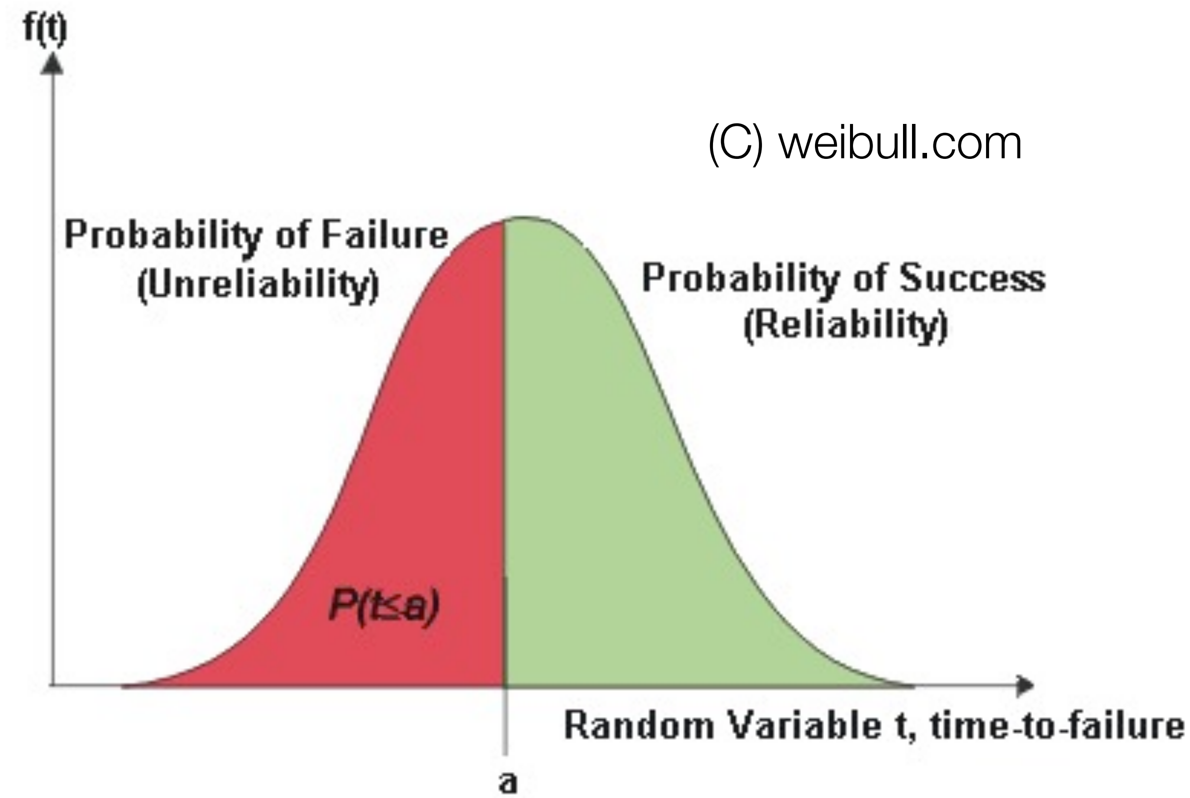


Probability density function

Cumulative distribution function

The Reliability Function R(t)

- Reliability: Probability *R(t)* that a component works for time period [0,*t*]
- Idea: Express time period of correct operation as **continuos random variable *X***
  -> **time to failure**
    - *cdf(t) of this variable:* Describes probability of failure before t -> **Unreliability Function F(t)**
    - *1-cdf(t):* Describes probability of a failure after t -> time to failure -> **Reliability Function R(t)**
        - This works because working / non-working is a binary decision



- Typically, failures are modeled as Poisson process
    - Poisson properties lead to exponential distribution for the time between events
    - This time therefore only depends on failure rate parameter

Failure Rate

- Treat pdf for time-to-failure random variable X as **failure density function**
  - Can be computed as derivative of the unreliability function

$$f(t) = dF(t)/dt$$

- **Failure rate** / hazard rate function - mean frequency of failures at time t
  - Conditional probability of a failure between a and b, given the survival until t

$$\lambda(t) = \frac{f(t)}{R(t)} = \lambda \text{ for constant failure rate}$$

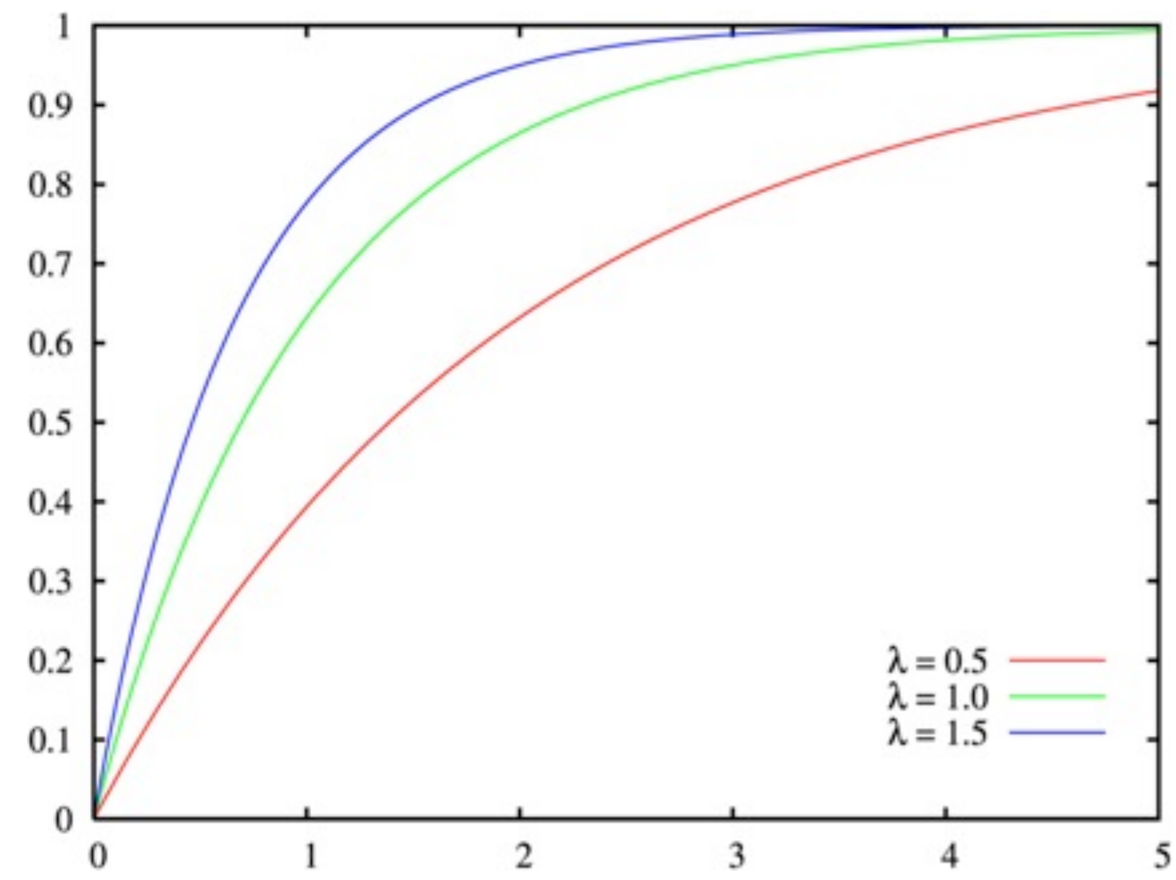
Why Exponential ?

- Distribution function that models (beside others) the **memoryless property** of the Poisson process
  - $P(T > t + s | T > t) = P(T > s)$, e.g. $P_{Failure}(5 \text{ years} | T > 2 \text{ years}) = P_{Failure}(3 \text{ years})$
  - Failure is not the result of wear-out
  - Models ‚intrinsic failure' part of the bath-tube curve, were most components spend the majority of their life time
  - Weibull distribution can also model tear-in and wear-out
- Some natural phenomena have constant failure rate (e.g. cosmic ray particles)
- Example: Product support determines an outage rate of 0.5% per day, independent from age
  - Failure rate is 0.005, so mean time to failure = 200 days
  - Numerical formulation for „law of small numbers"

The Reliability Function R(t)

- Failures occur continuously and independently at a constant average rate (Poisson process)
- Increasing probability of failure with increasing t - cdt function
- Failure rate λ from experience or complexity measures
- Cumulative distribution function:

$$F(x;\lambda) = \begin{cases} 1 - e^{-\lambda x}, & x \ge 0, \\ 0, & x < 0. \end{cases}$$

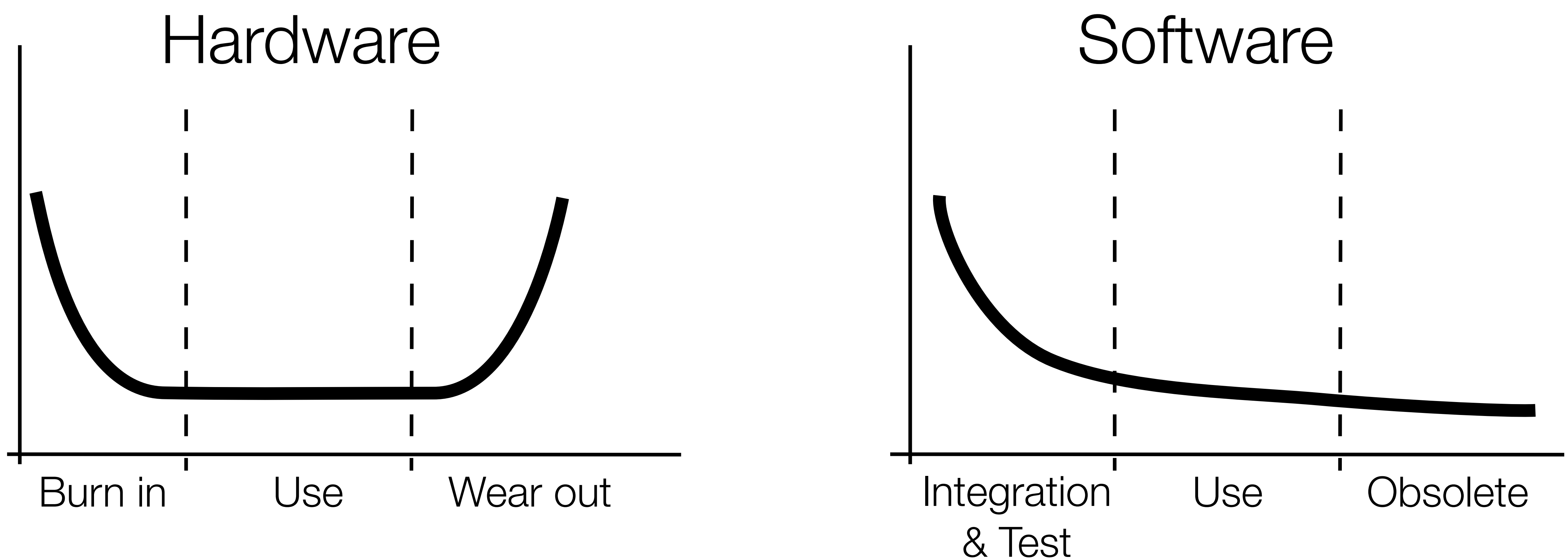


CDF: Probability of a failure before t

- Reliability function (survival probability) for exponential failure distribution:

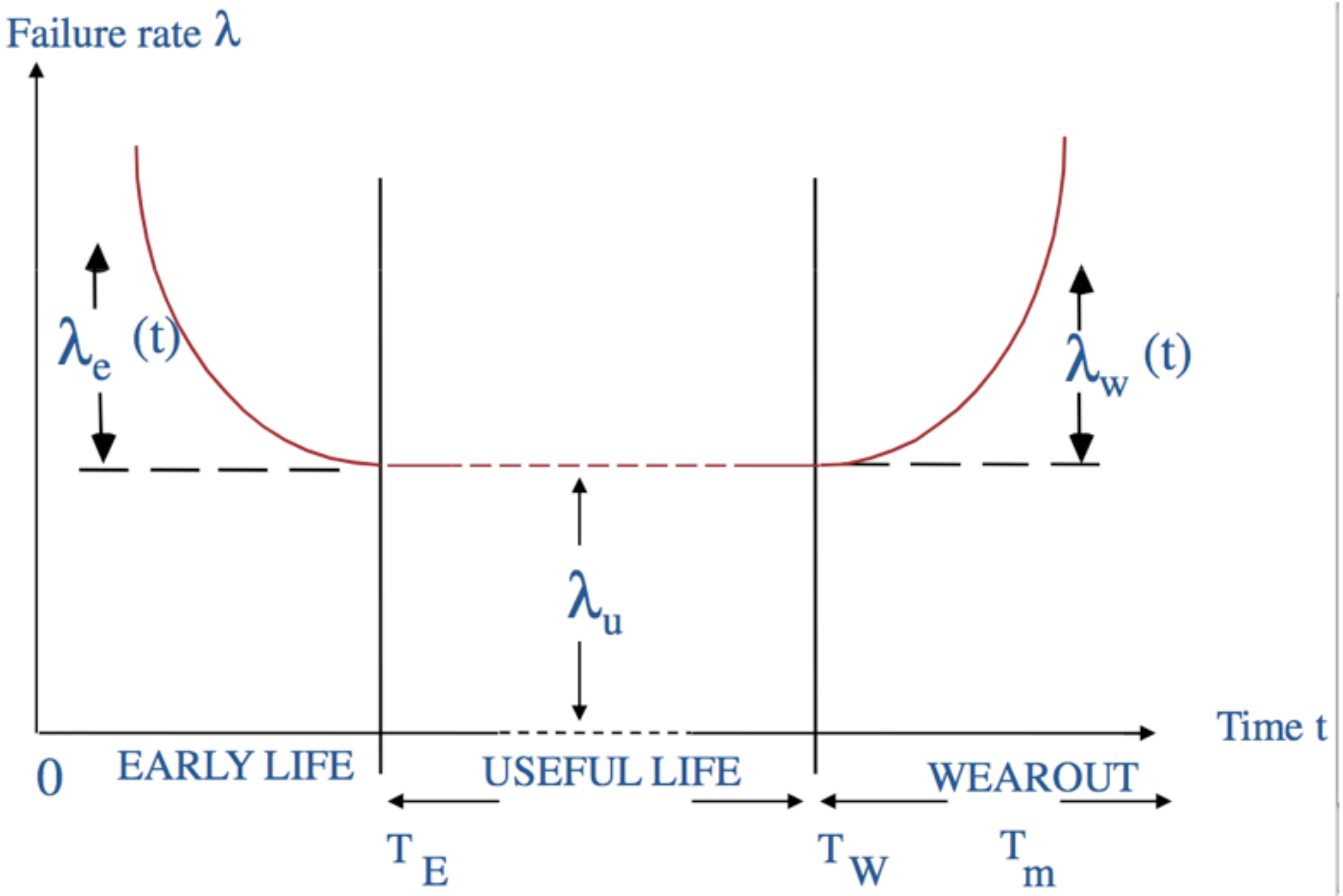
$$R(t) = P(X > t) = 1 - F(t) = e^{-\lambda x} \text{ with } F(x) = 1 - e^{-\lambda x}$$

Variable Failure Rate in Real World



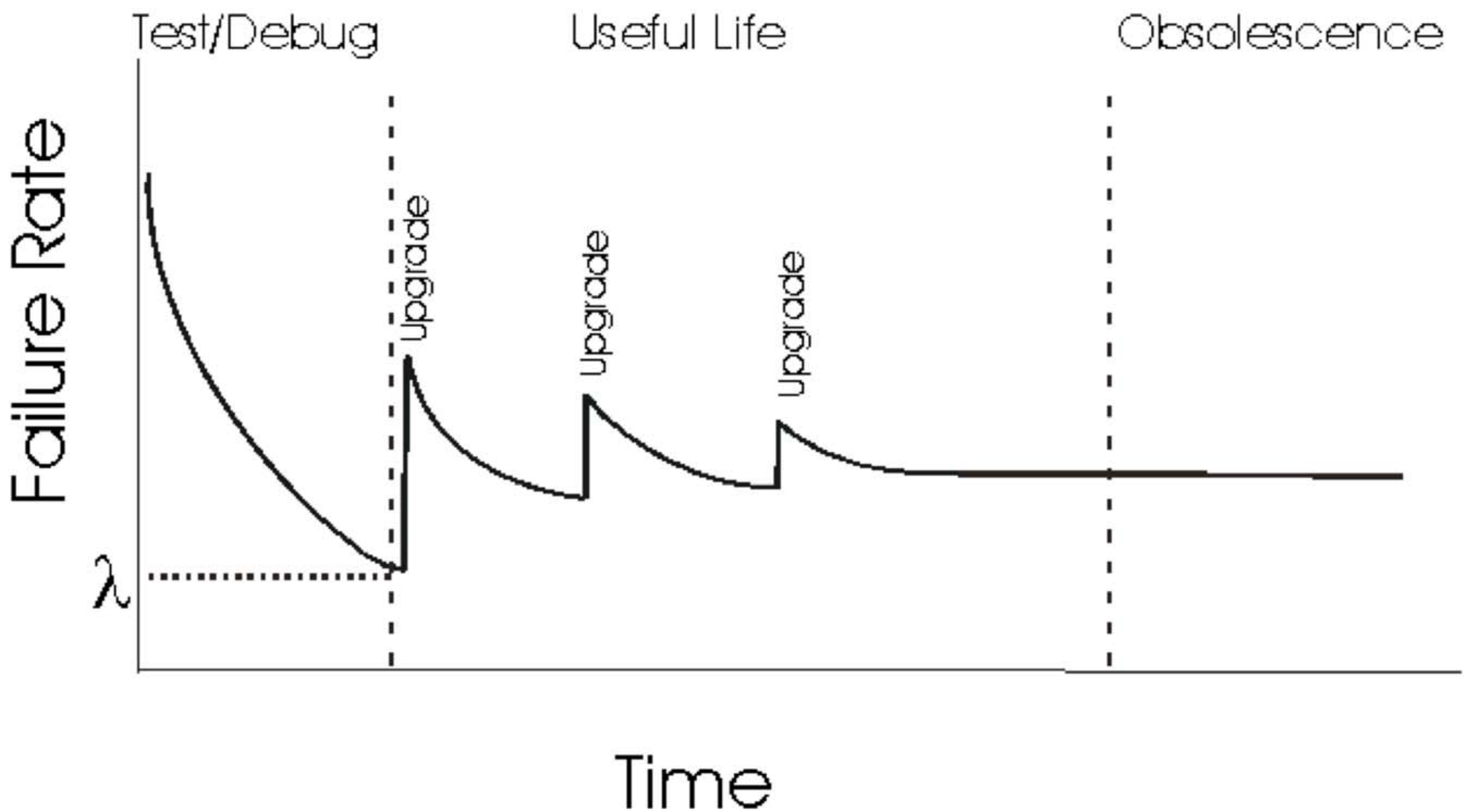
- Failure rate is treated as constant parameter of the exponential distribution
- (maybe invalid) simplification, mostly combined solution in practice:
  - Exponential distribution when failure rate is constant
  - Weibull distribution when failure rate is monotonic decreasing / increasing

Hardware Failure Rate



Software Failure Rate

- Industrial practice
- When do you stop testing ? - No more time, or no more money ...



(C) Malek

Failure Rate Examples

- Standards from experience provide base data for component reliability
- Society of Automotive Engineers (SAE) reliability model

$$\lambda_p = \lambda_b \Pi_{i=1}^{b} \pi_i$$

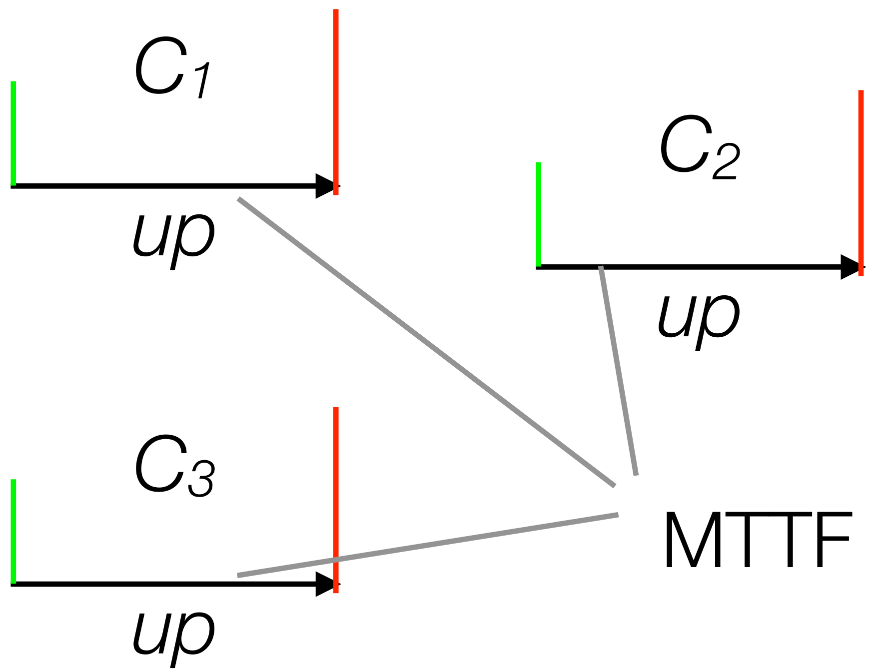
- Predicted failure rate λ_p
- Base failure rate for the component λ_b
- Various modification factors π_i
  - Component composition
  - Ambient temperature
  - Location in the vehicle

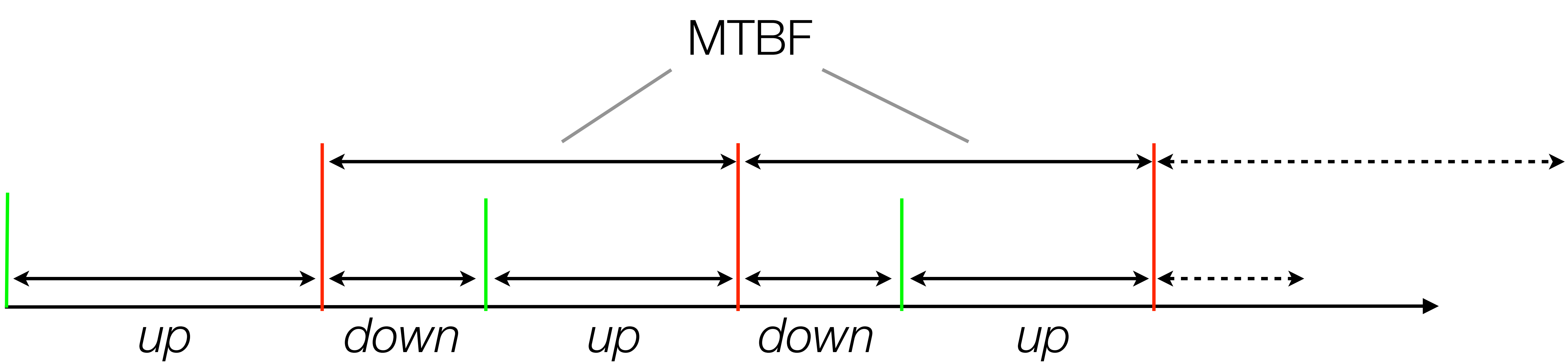
Example: Item-Level Sparing Analysis [Misra]

- Sparing analysis challenges
  - How many spares do you need to keep the system available at the desired rate ?
  - When are you going to need to spares (manufacturing time) ?
  - Where the spares should be kept ?
  - What system level you want to spare at ?

Steady-State Availability

- **Mean time to failure (MTTF)** - Average time it takes to fail
- **Mean time to recover / repair (MTTR)** - Average time it takes to recover
- **Mean time between failures (MTBF)** - Average time between two successive failures





Steady-State Availability and MTBF

- Expressing reliability with MTBF ‚should' imply a repairable system
  - If all failures can be repaired, the MTBF estimate can become constant as time tends to infinity
  - In reliable systems, the downtime is short in comparison to uptime, so the steady-state condition holds earlier
  - MTBF = MTTF + MTTR
  - **Availability** = MTTF (accumulated up time) / MTBF (accumulated life time) = MTTF / (MTTF + MTTR)
- Expressing reliability with MTTF ‚should' imply a non-repairable system
  - **MTBF (mean time BEFORE failure)** = MTTF -> typical source of confusion
- If time to failure is exponentially distributed, then the reciprocal of the rate parameter is equivalent to the distribution mean

$$\lambda = \frac{1}{MTTF}$$

Example

- Test population with 50 HDDs and 100 hours of testing, 2 drives fail during the test
  - As usual, we assume exponential distribution of the time to failure
  - Reliability at t=100 is known to be 98%
  - Reciprocal of the according failure rate is the MTTF

$$R(t) = P(X > t) = 1 - F(t) = e^{-\lambda x} \text{ with } F(x) = 1 - e^{-\lambda x}$$

$$R(100hours) = e^{-\lambda 100} = 0.98$$

$$\lambda = -\frac{ln 0.98}{100} = 0,000202$$

$$MTTF = \frac{1}{\lambda} = 4949,831hours$$

MTBF / MTTF in Practice

- Often express average failure behavior (statistics) for a component population
- Good for relative comparison, not for expected life time expectation of one unit
- Example: Hard disk with MTTF of 500.000 hours and 5 years of expected operation (‚service life')
    - Drive of this type is expected to run 5 years without problems
    - Large group of such drives will (on average) have one failed drive after 500.000 hours of **accumulated** life time
    - What to buy: Model with longer MTBF or longer warranty time ?

Operational Availability Calculation [Misra]

- **Uptime** elements: Standby time, operating time
- **Downtime** elements
  - *Logistic*: Spares availability, spares location, transportation of spares
  - *Preventive maintenance*: Inspection, servicing
  - *Administrative delay*
    - Finding personnel, reviewing manuals, complying with supply procedures, locating tools, setting up test equipment
  - *Corrective maintenance*
    - Preparation time, fault location diagnosis, getting parts, correcting faults, testing

MTTR Examples

- Hardware MTTR with spares onsite
  - Operator available - 30min
  - Operator on call - 2 hours
  - Operator available during working hours - 14h
  - Without spares - at least 24h
- SW MTTR with watchdog
  - Reboot from ROM - 30s
  - Reboot from disk - 3 min
  - Reboot from network - 10 min

Steady-State Availability

$$A = \frac{Uptime}{Uptime + Downtime} = \frac{MTTF}{MTTF + MTTR}$$

Availability	Downtime per year	Downtime per week
90.0 % (1 nine)	36.5 days	16.8 hours
99.0 % (2 nines)	3.65 days	1.68 hours
99.9 % (3 nines)	8.76 hours	10.1 min
99.99 % (4 nines)	52.6 min	1.01 min
99.999 % (5 nines)	5.26 min	6.05 s
99.9999 % (6 nines)	31.5 s	0.605 s
99.99999 % (7 nines)	0.3 s	6 ms

MTTR >> MTTF [Fox]

- Armando Fox on ‚Recovery-Oriented Computing'
  - A = MTTF / (MTTF + MTTR)
    - 10x decrease of MTTR as good as 10x increase of MTTF ?
    - MTTF's are not claimable, but MTTR claims are verifiable
    - Proving MTTF numbers demands system-years of observation and experience
    - Lowering MTTR directly improves user experience of one specific outage, since MTTF is typically longer than one user session
  - HCI factor of failed system
    - Miller, 1968: >1sec "sluggish", >10sec "distracted" (user moves away)
    - 2001 Web user study: ~5sec „acceptable", ~10sec „excessively slow"

MTTR >> MTTF [Fox]

- Proposal: Utility curve for recovery time
  - Factors: Length of recovery time, level of service availability during error state
  - Key distinction between interactive (session-based) and non-interactive systems
- If error state leads to some steady-state latency
  - For how long will users tolerate temporary degradation ?
  - How much degradation is acceptable ?
  - Do they show a preference for increased latency vs. worse QOS vs. being turned away and incentivized to return?
- Long recovery times are often reasoned by stateful components
  - Utilize alternative architecture concepts

Availability