Dependable Systems

Summary

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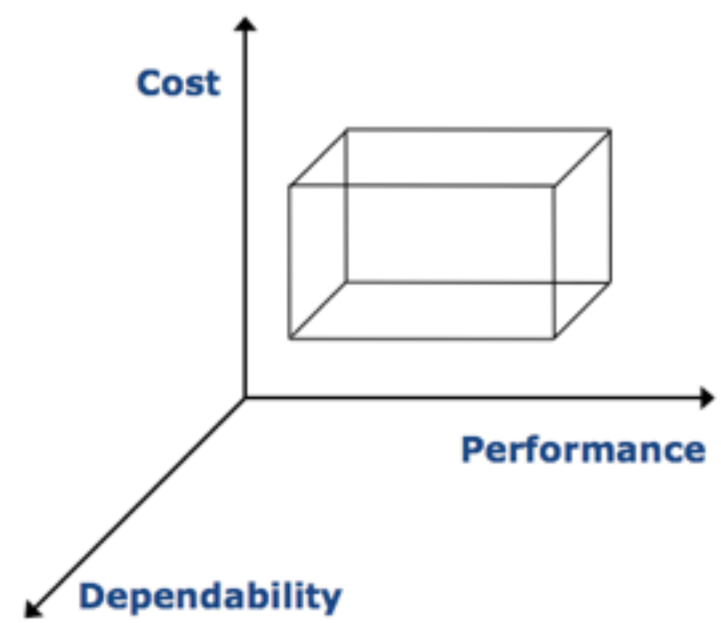
Dependability

- **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‘



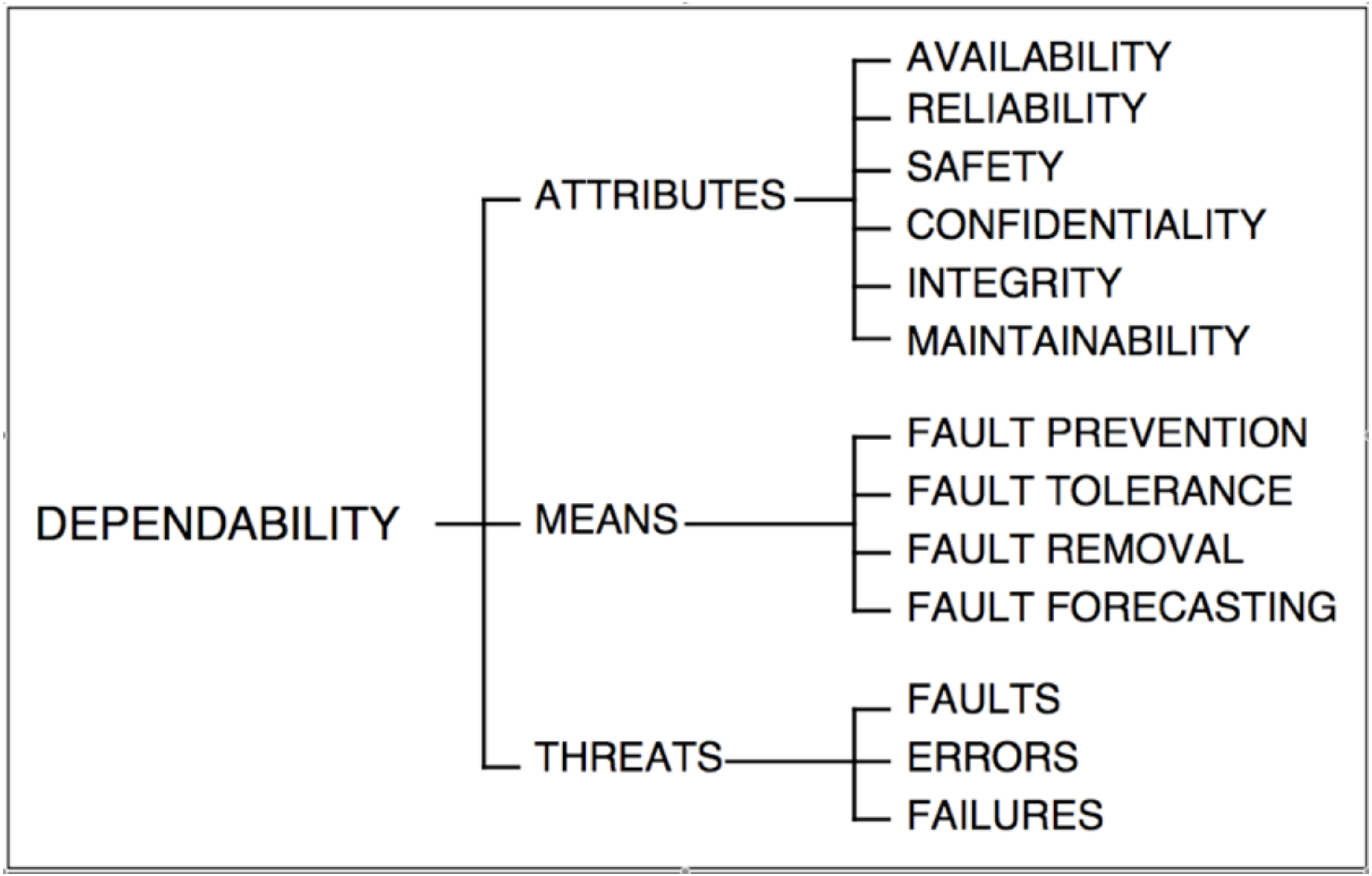
Course Topics

- Definitions and metrics
  - Fault, error, failure, fault models, fault tolerance, fault forecasting, ...
  - Reliability, availability, maintainability, error mitigation, damage confinement, ...
  - Reliability engineering, reliability testing, MTTF, MTBF, failure rate, ...
- Fault tolerance patterns
  - N-out-of-M, voting, heartbeat, ...
- Analytical evaluation
  - Reliability block diagrams, fault tree analysis, ...
  - Petri nets, Markov chains
  - Root cause analysis, risk analysis and assessment

Course Topics

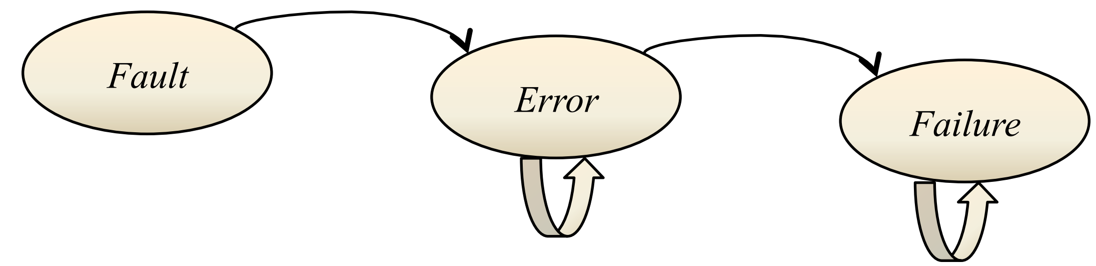
- Hardware-Implemented Dependability
  - Failure rates, testing, hardware redundancy approaches
- Software-Implemented Dependability
  - Fault-tolerant programming: simplex, recovery blocks, checkpointing, roll-back, ...
  - Testing, software metrics
  - Fault-tolerant distributed systems: Transactions, consensus, clocks, ...
- Advanced approaches
  - Autonomic computing, rejuvenation, online failure prediction, performability
- Case studies from practice

Dependability Tree (Laprie)



Dependability Stakeholders

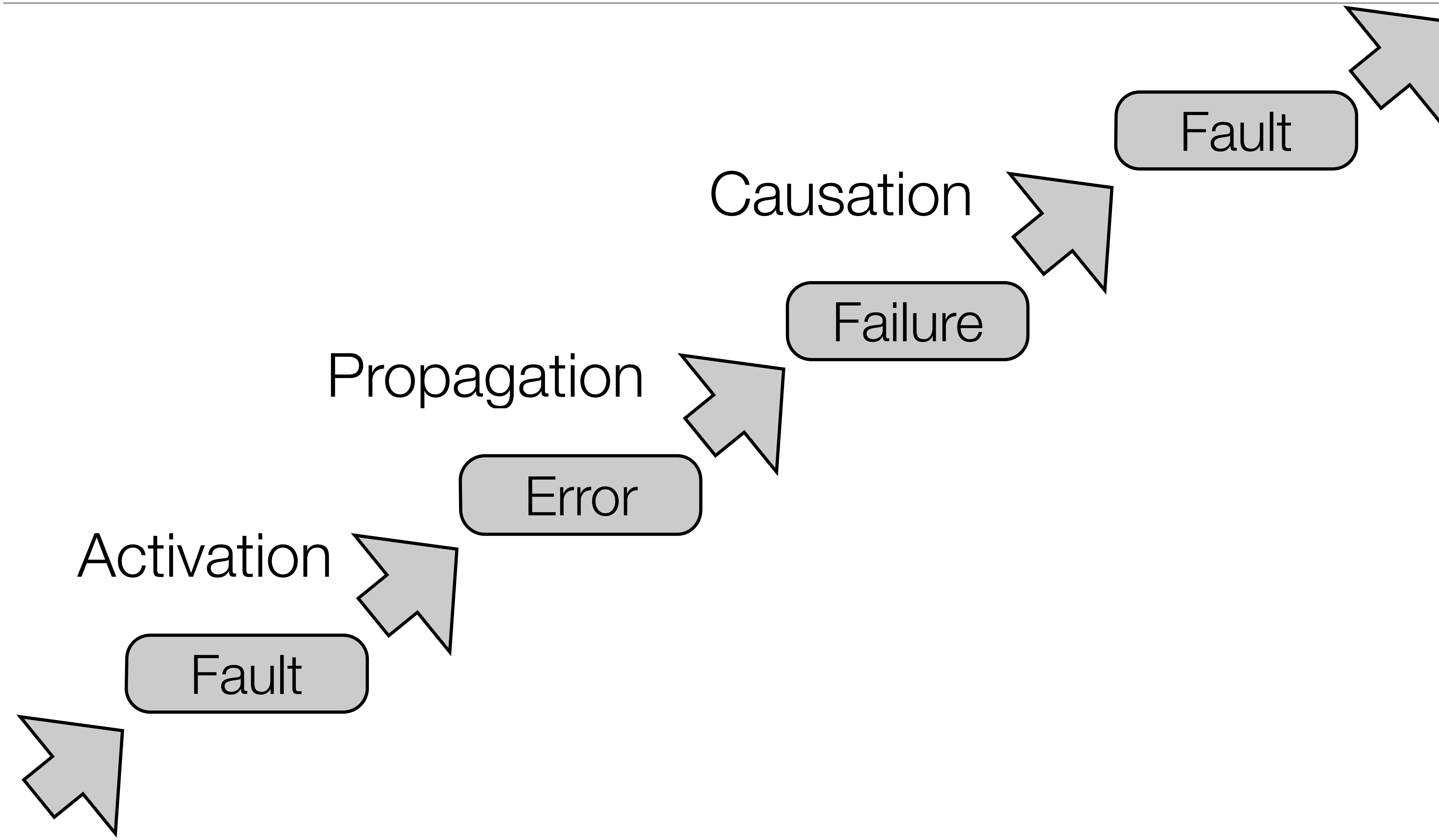
- **System** - Entity with function, behavior, and structure
  - A number of components or subsystems, which interact under the control of a design [Robinson]
- **Service** - System behavior abstraction, as perceived by the user
- **User** - Human or physical system that interacts with the systems service
- **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**



2 - 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

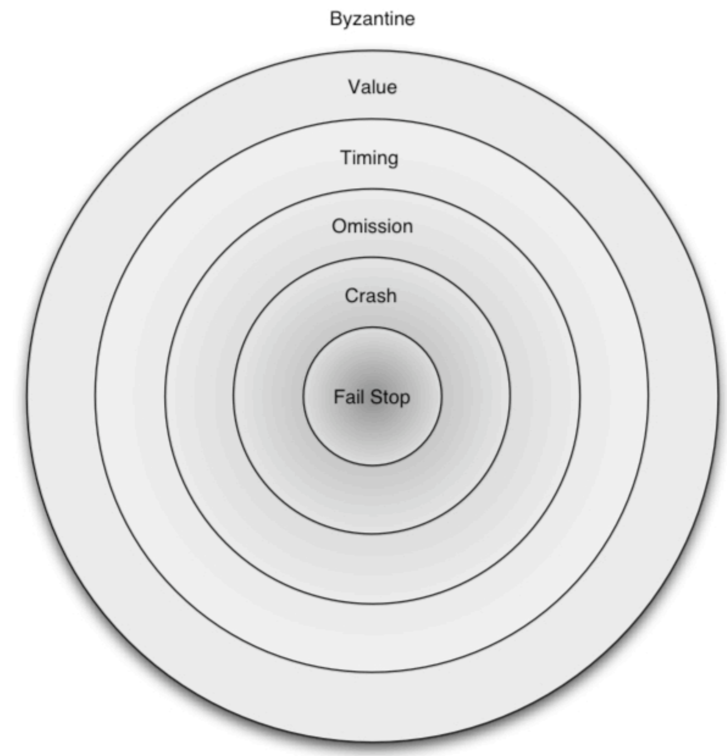
Chain of Dependability Threats (Avizienis)



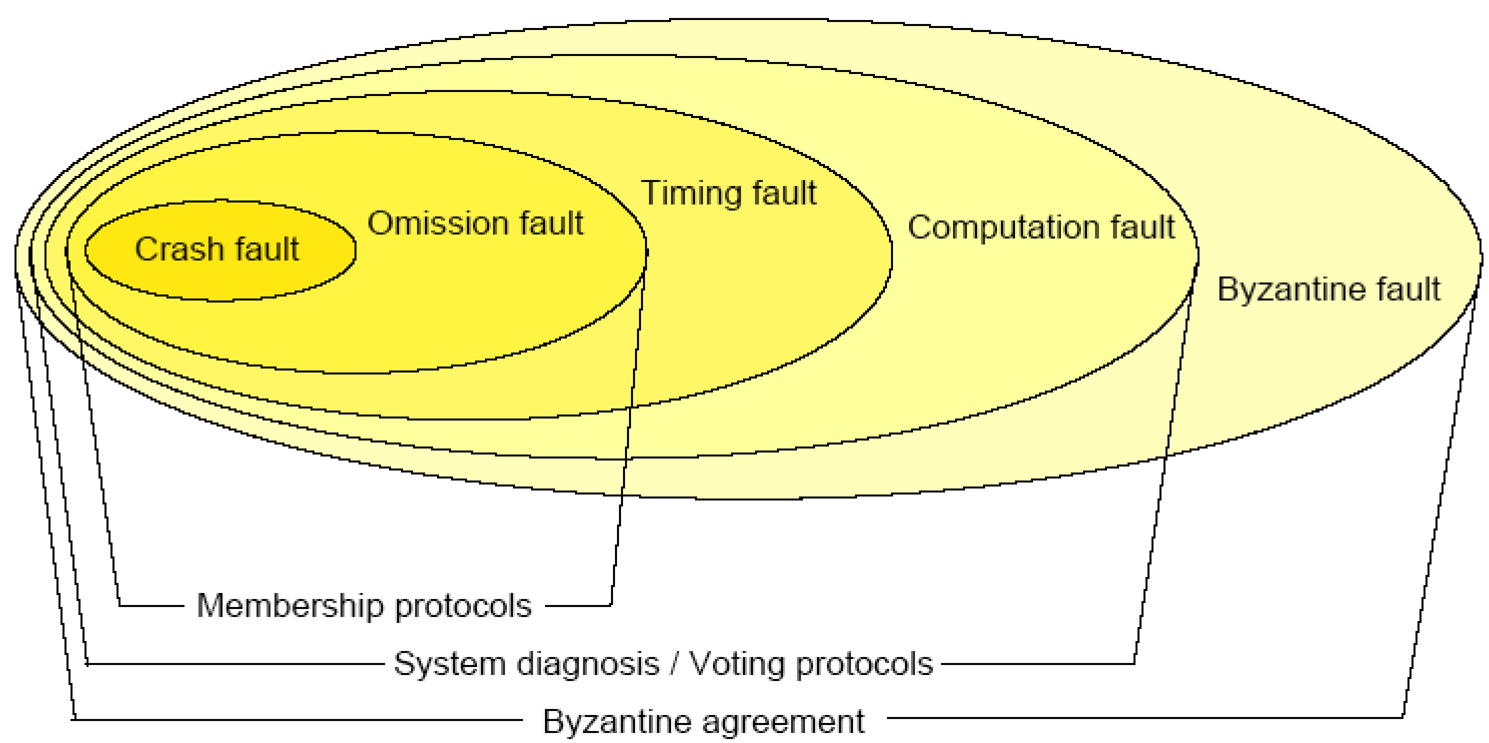
Faults

- 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

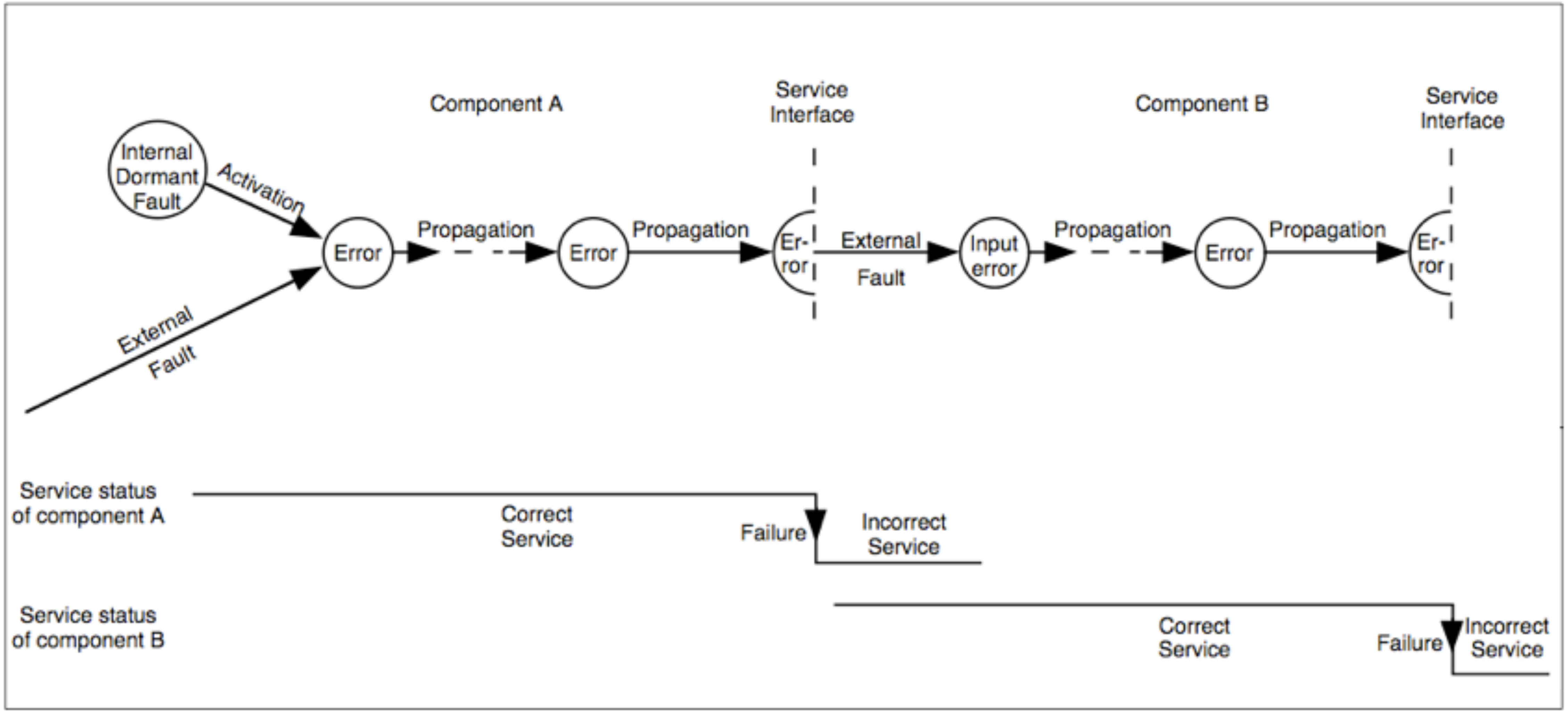
System-Level Fault Model



- Fault model idea originates from hardware
  - How many faults of different classes can occur ? What do I tolerate ?
  - Timing of faults: Fault delay, repeat time, recovery time, ...
- Also mappable to software or even complete systems
  - Activities as black box, only look on input and output messages
- Link faults are mapped to the participating components
- Every participating component would need a fault model - pick the most urgent ones



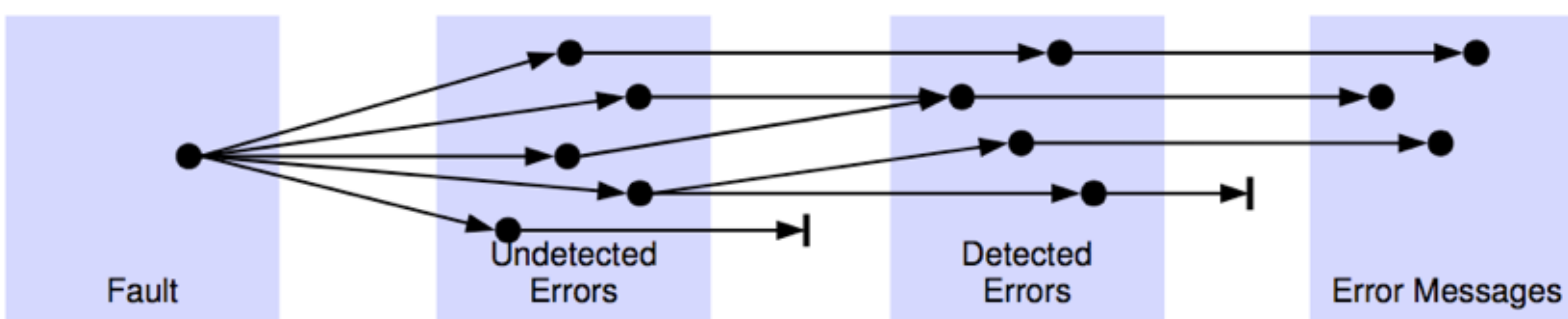
Error Propagation



(C) Avizienis

Error Message Occurrence (Hansen & Siewiorek)

- Same fault can lead to different (detected or undetected) errors
- Errors become detected by error detection mechanism
  - Some undetected errors are detected by several detectors
  - Some detectors report several undetected errors as one
  - Some undetected errors are never uncovered
- Detected errors might not be logged, if the system stops too fast



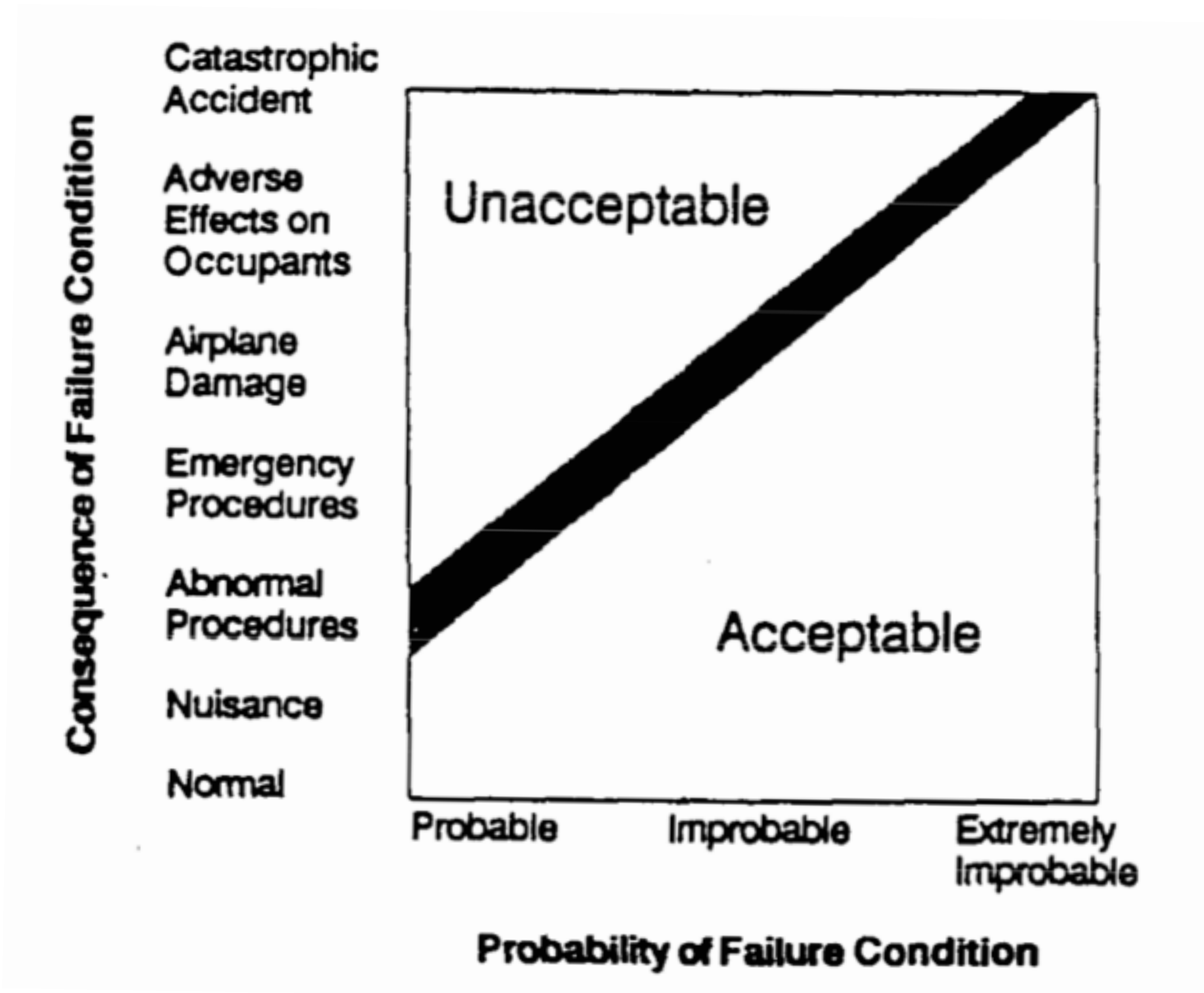
Failures

- 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 **domain** - what is influenced
  - Service result - **value failures**
  - Service timeliness - **timing failures**
  - Service availability - **stopping failures**
- **User perception** in the mode - consistent / inconsistent for all users
- Failure mode **consequences** for ranking the identified issues

Failure Severity (‚Schweregrad des Ausfalls‘)

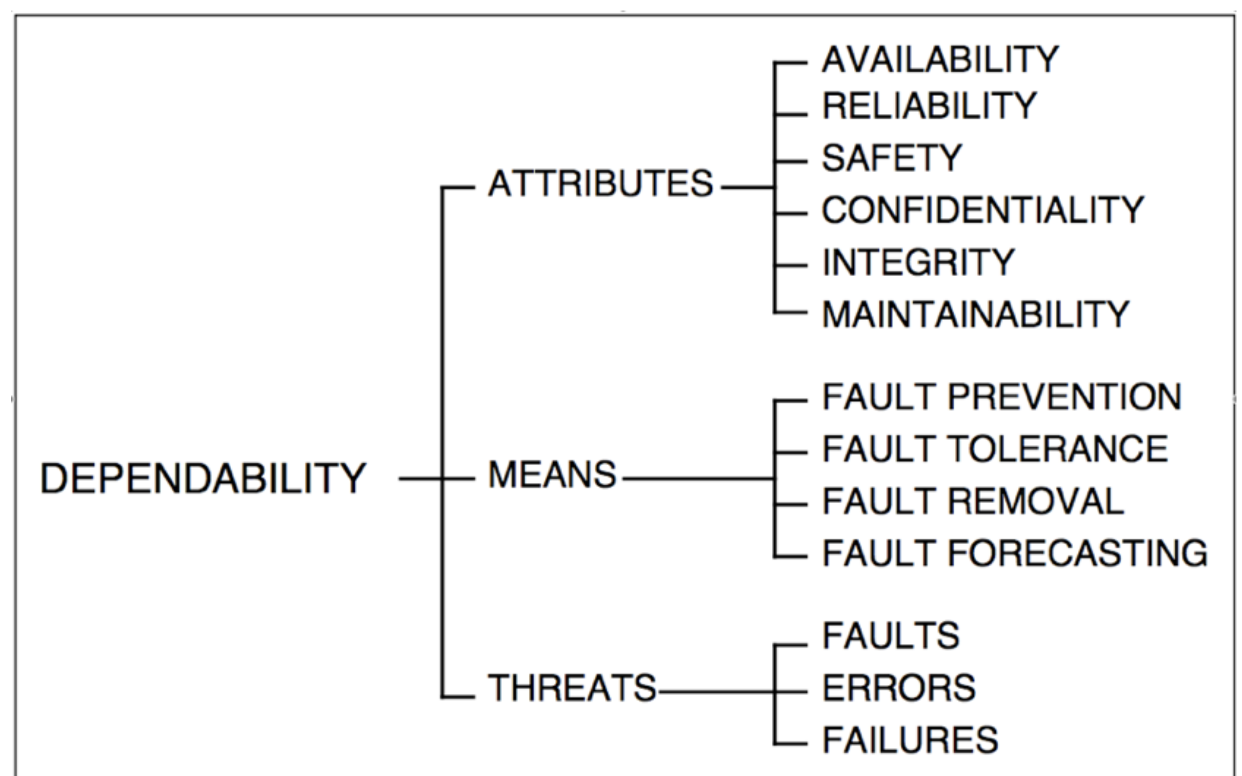
- Denotes consequences of failure
- **Benign failures** (‚unkritische Ausfälle‘)
  - Failure costs and operational benefits are similar
  - Sometimes also umbrella term for failures only detected by inspection
  - A system with only such failures is **fail-safe**
- **Catastrophic failures** (‚kritische 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

Example: DO-178B Standard



3 - 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



Fault Tolerance

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

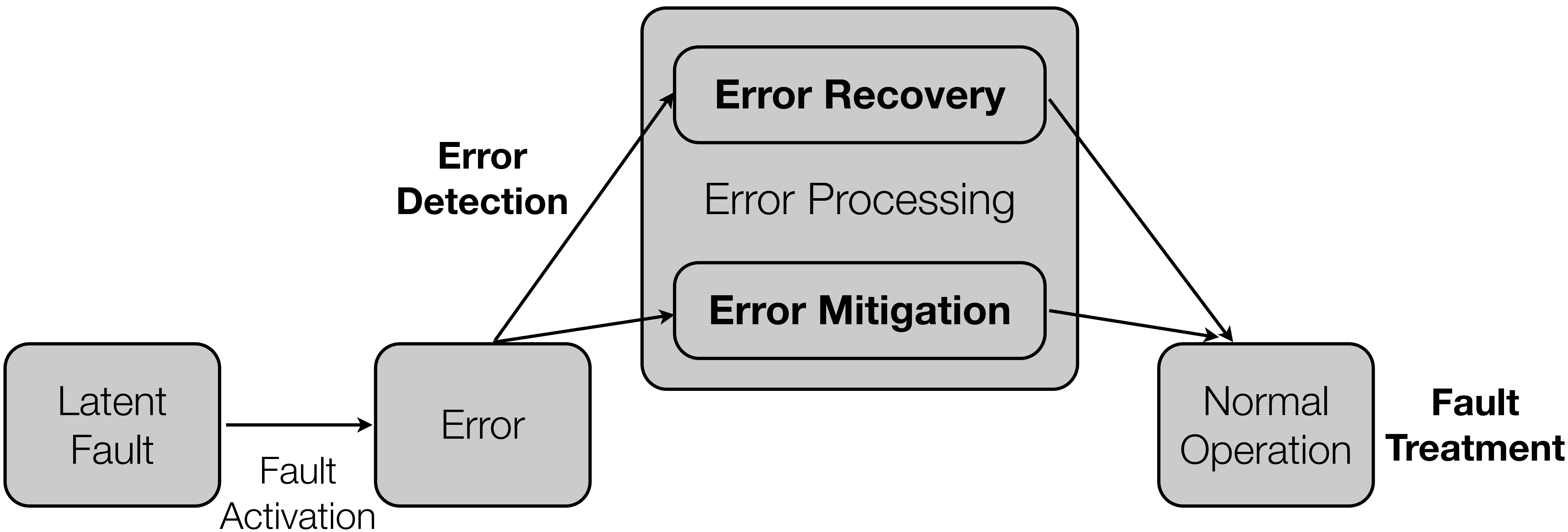
  or

- A system S is called **k-fault-tolerant** with respect to a set of algorithms $\{A_1, A_2, \dots, A_p\}$ and a set of faults $\{F_1, F_2, \dots, F_p\}$ 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)

Phases of Fault Tolerance (Hanmer)



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 with compensation: 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**)

„Fail-Fast“

- A common concept from system engineering, company management, ...
- *„Report failure and stop immediately without further action“*
    - Discussed by Jim Gray in 1985 as part of his famous article *„Why do computers stop and what can be done about it ?“*
- Useful when benefit from recovery is not good enough for its costs, or if error propagation is highly probable
    - Single units of a redundant set
    - Deeply interwired IT system components
    - Components under heavy request load
    - And ... crappy start-up companies

4 - Fault Tolerance Patterns

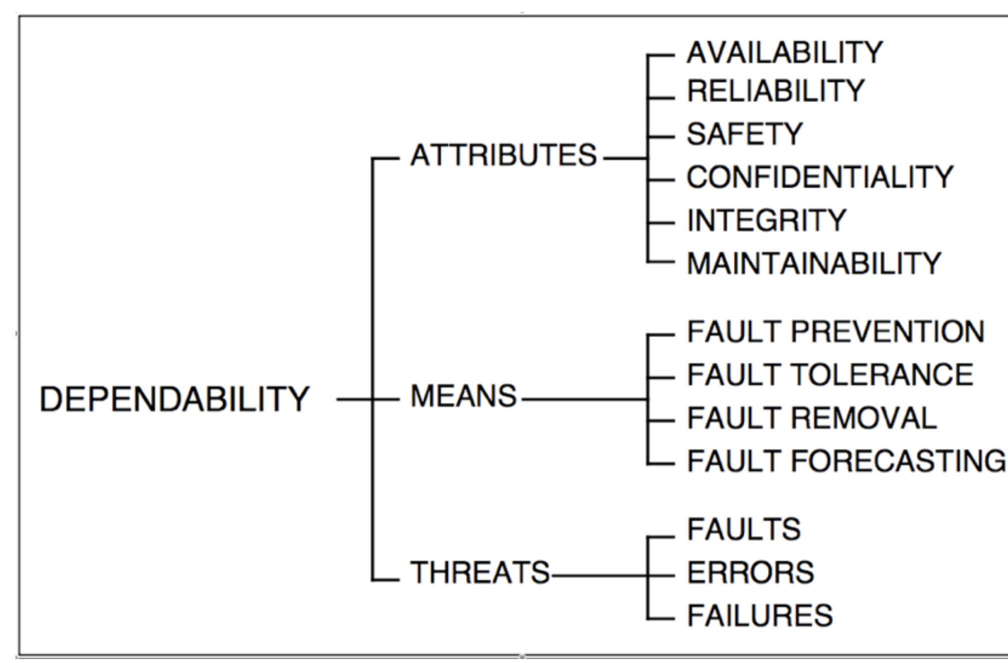
- **Architectural patterns**
  - Considerations that cut across all parts of the system
  - Need to be applied in early design phase
- **Detection patterns**
  - Detect the presence of root faults, error states, and failures
  - Errors vs. failures -> a-priori knowledge vs. comparison of redundant elements
- **Error Recovery Patterns**
  - Methods to continue execution in a new error-free state
  - Undoing the error effects + creating the new state

4 - Fault Tolerance Patterns

- **Error Mitigation Patterns**
  - Do not change application or system state,
    but mask the error and compensate for the effects
  - Typical strategies for timing or performance faults
- **Fault Treatment Patterns**
  - Prevent the error from reoccurring by repairing the fault
  - System verification
  - Diagnosis of fault location and nature
  - Correction of the system and / or the procedures

5 - 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



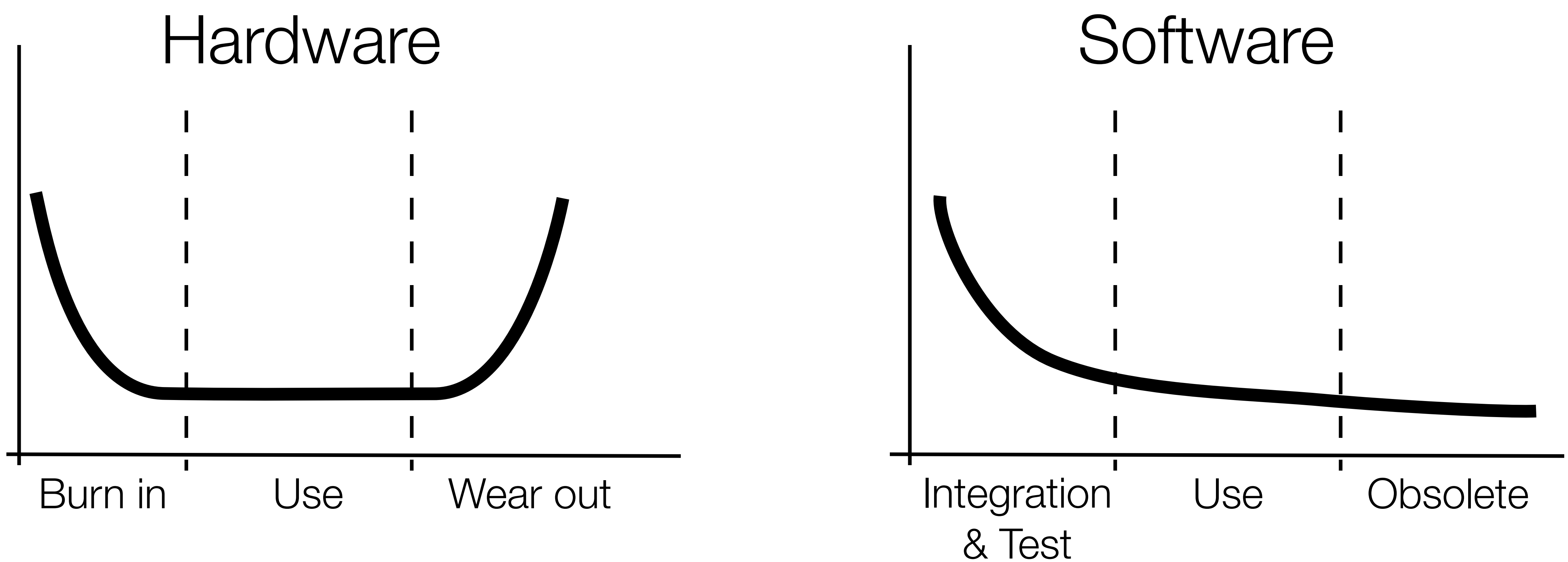
In Detail

- **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** - Statement if a system is operational at a point in time / fraction of time
  - Describe system behavior in presence of error treatment mechanisms
  - **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: $A_s = Uptime / Lifetime$

Why Exponential ?

- Distribution function that models 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‘ behavior, assumed for the majority of hardware life time
  - Weibull distribution as alternative, can also model **tear-in** and **wear-out**
- Some natural phenomena have constant failure rate (e.g. cosmic ray particles)

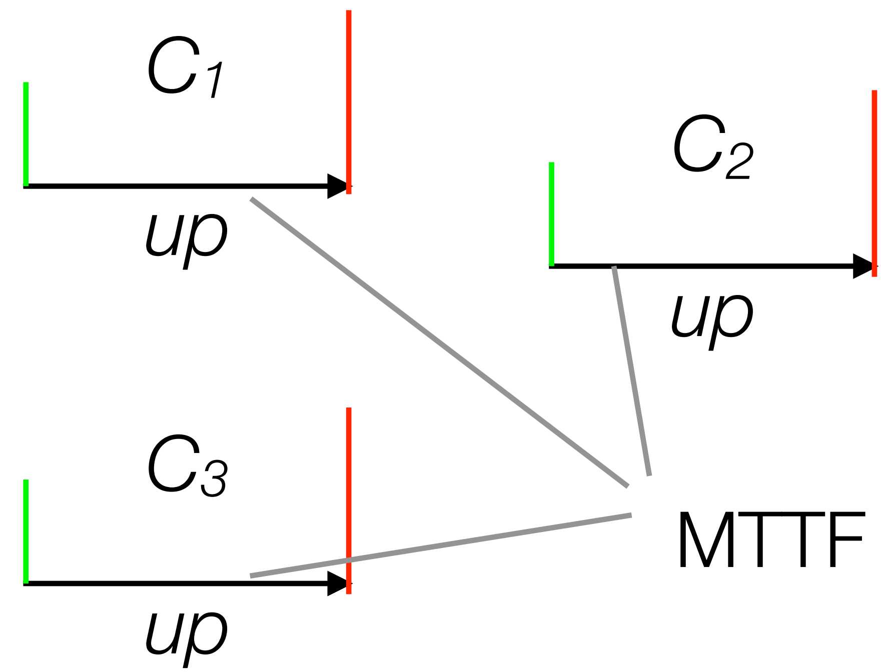
Variable Failure Rate in Real World

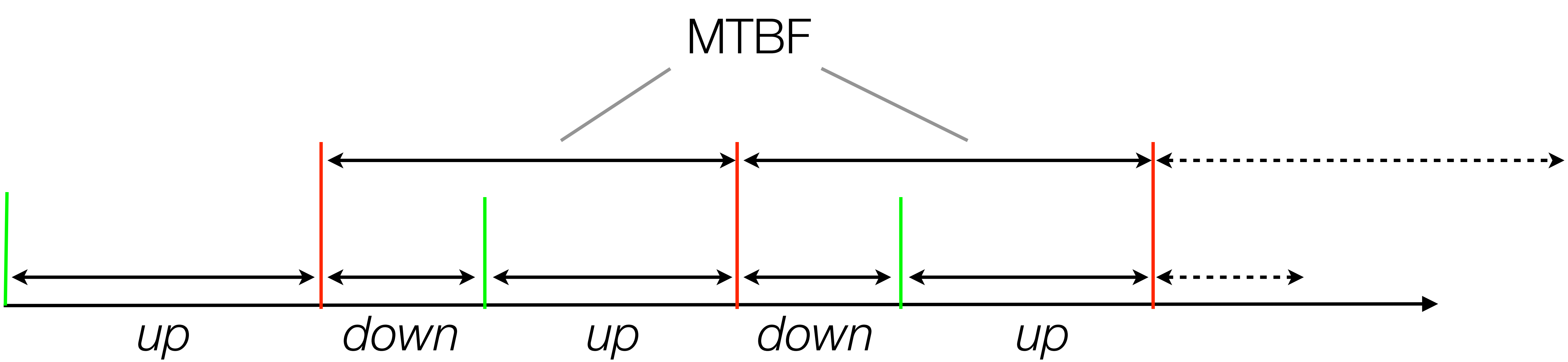


- Failure rate is treated as constant parameter of the exponential distribution
- (maybe invalid) simplification, mostly combined solution in practice:
  - Exponential distribution when failure rate is constant
  - Weibull distribution when failure rate is monotonic decreasing / increasing

Steady-State Availability

- **Mean time to failure (MTTF)** -
  Average time it takes to fail
  -> average uptime
- **Mean time to recover / repair (MTTR)** -
  Average time it takes to recover
- **Mean time between failures (MTBF)** -
  Average time between two successive failures
- **Availability** = Uptime / Lifetime
  = MTTF / MTBF





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]

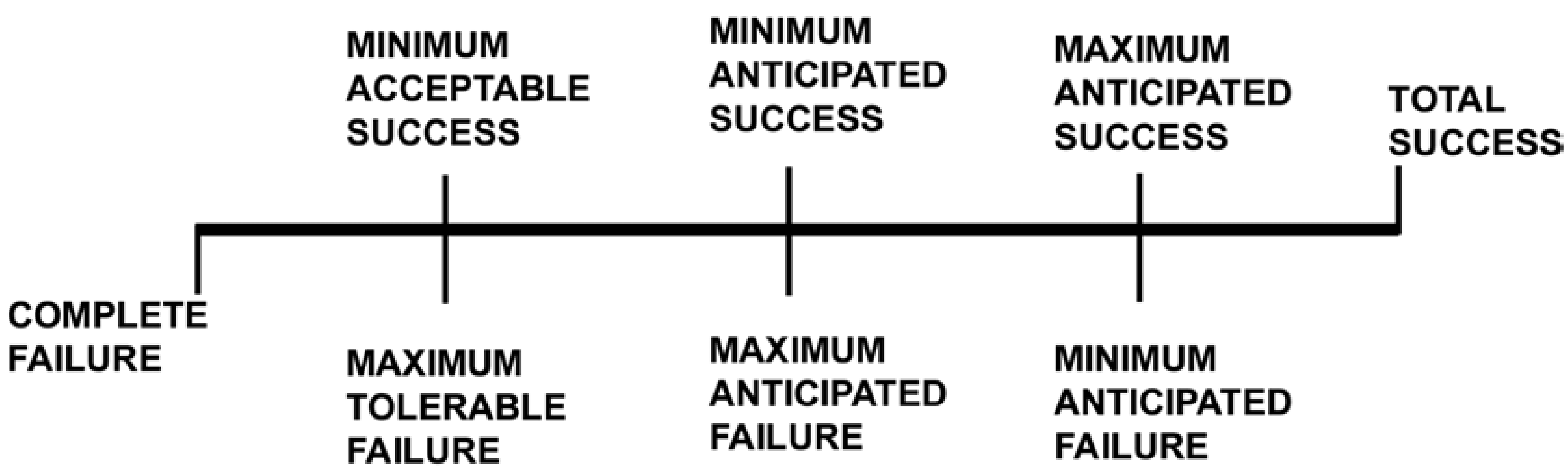
- Armando Fox on ‚Recovery-Oriented Computing'
  - A = MTTF / (MTTF + MTTR)
    - 10x decrease of MTTR as good as 10x increase of MTTF ?
    - MTTF's are not claimable, but MTTR claims are verifiable
    - Proving MTTF numbers demands system-years of observation and experience
    - Lowering MTTR directly 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"

6 - Dependability Modeling

- Default approach: Utilize a formalism to model system dependability
  - Quantify the availability of components, calculate system availability based on this data and a set of assumptions (the availability model)
    - Most models expose the same expressiveness
    - Each formalism allows to focus on certain aspects
    - Structure-based models: Reliability block diagram, fault tree
    - State-based models: Markov chain, petri net
- System understanding evolved from hardware to software to IT infrastructures
  - Example: Organization management influence on business service reliability
    - Information Technology Infrastructure Library (ITIL)
    - CoBiT(Control Objectives for Information and related Technology)

Dependability Modeling

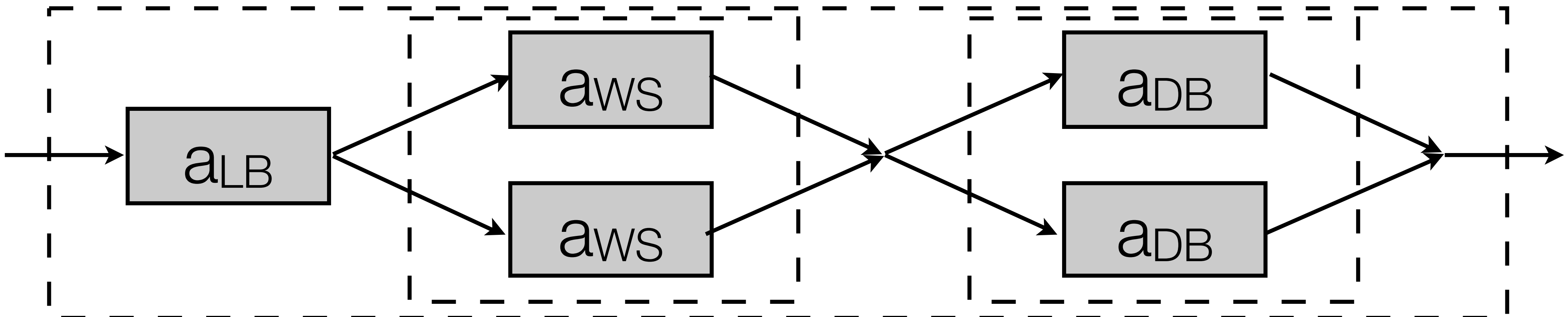
- The *Failure Space-Success Space* concept
  - Often easier to agree on what constitutes a system failure
  - Success tends to be associated with system efficiency, which makes it harder to formulate events in the model („The car drives fast.“, „The car stops driving.“)
  - In practice, there are more ways to success than to failure



Dependability Modeling

- System analysis approaches
  - **Inductive methods** - Reasoning from specific cases to a general conclusion
    - Postulate a particular fault or initiating event, find out system effect
    - Determine **what** system (failure) states are possible
    - Trivial approach: „parts count“ method
    - Examples: Failure Mode and Effect Analysis (FMEA), Preliminary Hazards Analysis (PHA), Event Tree Analysis, Reliability Block Diagrams (RBD), ...
  - **Deductive methods** - Postulate a system failure, find out what system modes or component behaviors contribute to this failure
    - Determine **how** a particular system state can occur
    - Examples: Fault Tree Analysis (FTA)

Examples

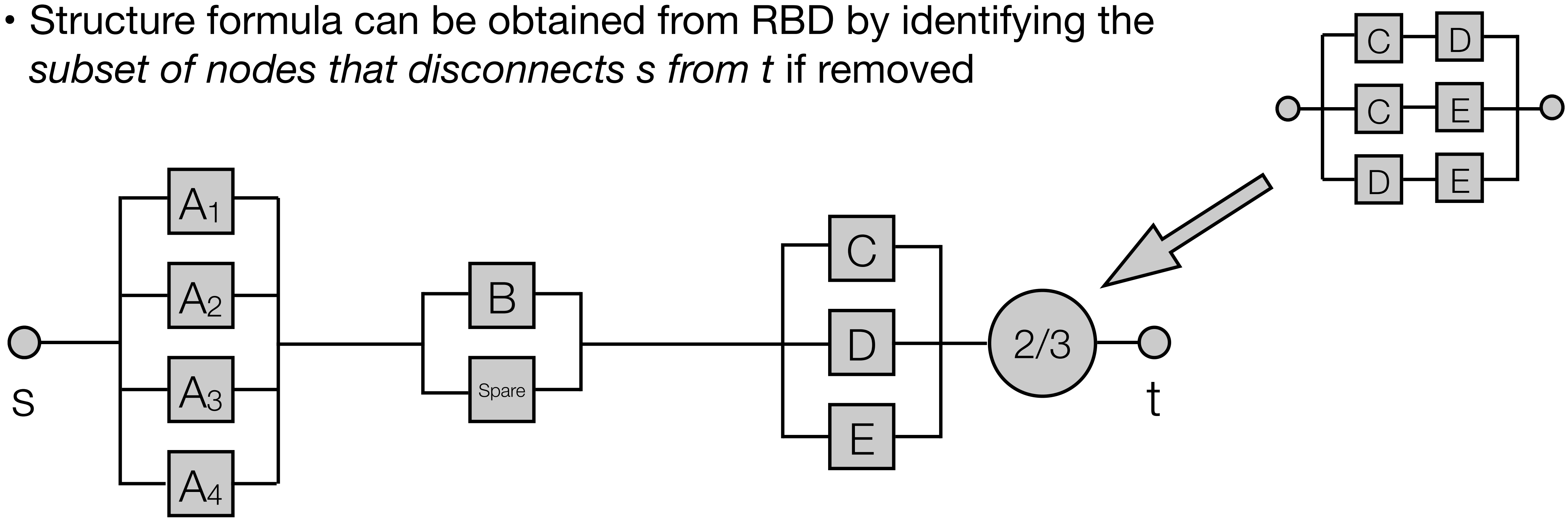


$$\phi_S = c_{LB} \wedge (c_{WS1} \vee c_{WS2}) \wedge (c_{DB1} \vee c_{DB2})$$

$$\begin{aligned} A_{site} &= a_{LB} \times A_{WSset} \times A_{DBset} \\ &= a_{LB} \times [1 - (1 - a_{WS})^{n_{WS}}] \times [1 - (1 - a_{DB})^{n_{DB}}] \end{aligned}$$

Reliability Block Diagrams (RBD)

- Model logical interaction for success-oriented analysis of system reliability
- Building blocks: **series structure, parallel structure, k-out-of-n structure**
- System is available only if there is a path between **s** and **t**
- Granularity based on data and *lowest actionable item* concept
- Structure formula can be obtained from RBD by identifying the *subset of nodes that disconnects s from t* if removed

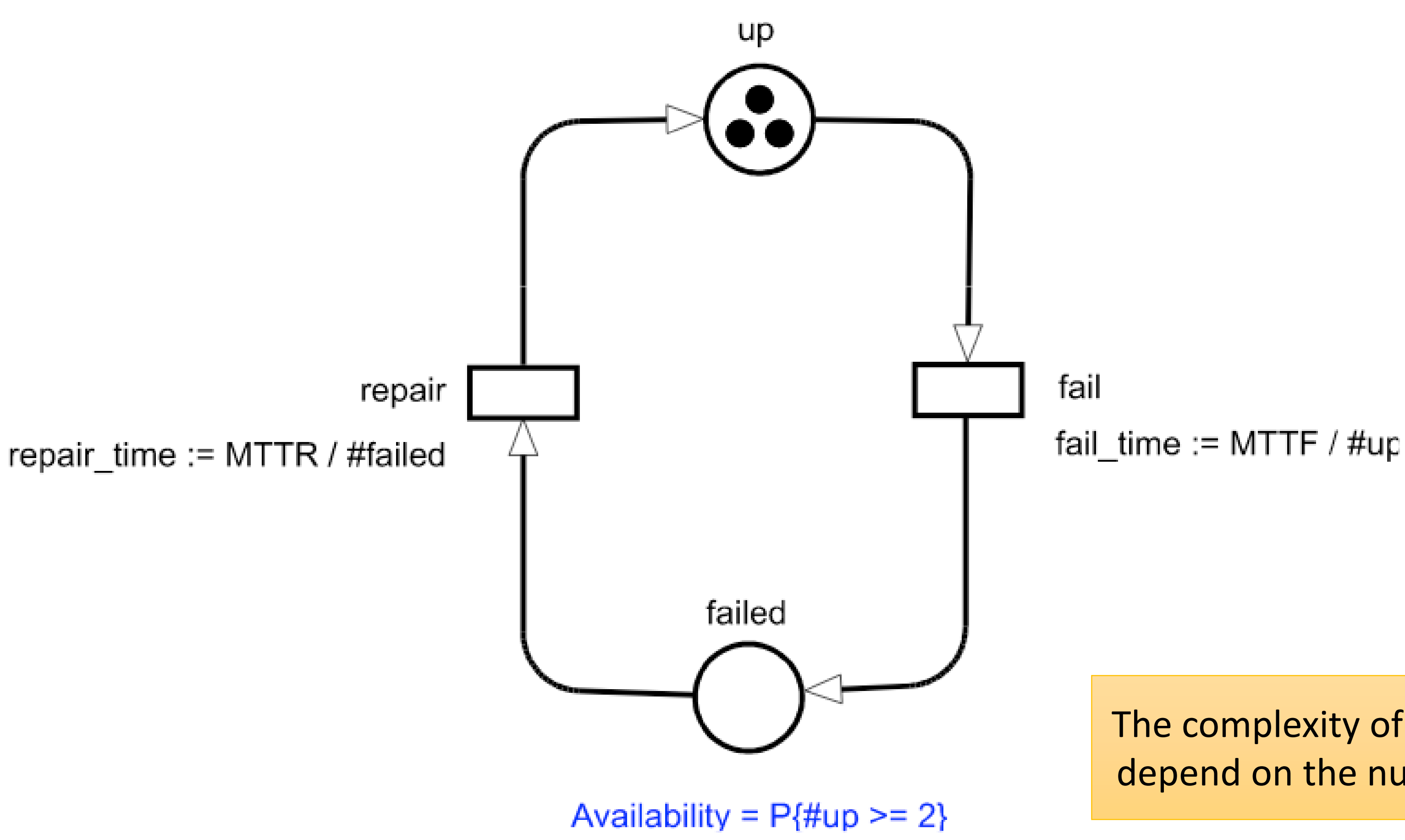


Deductive Analysis - Fault Trees

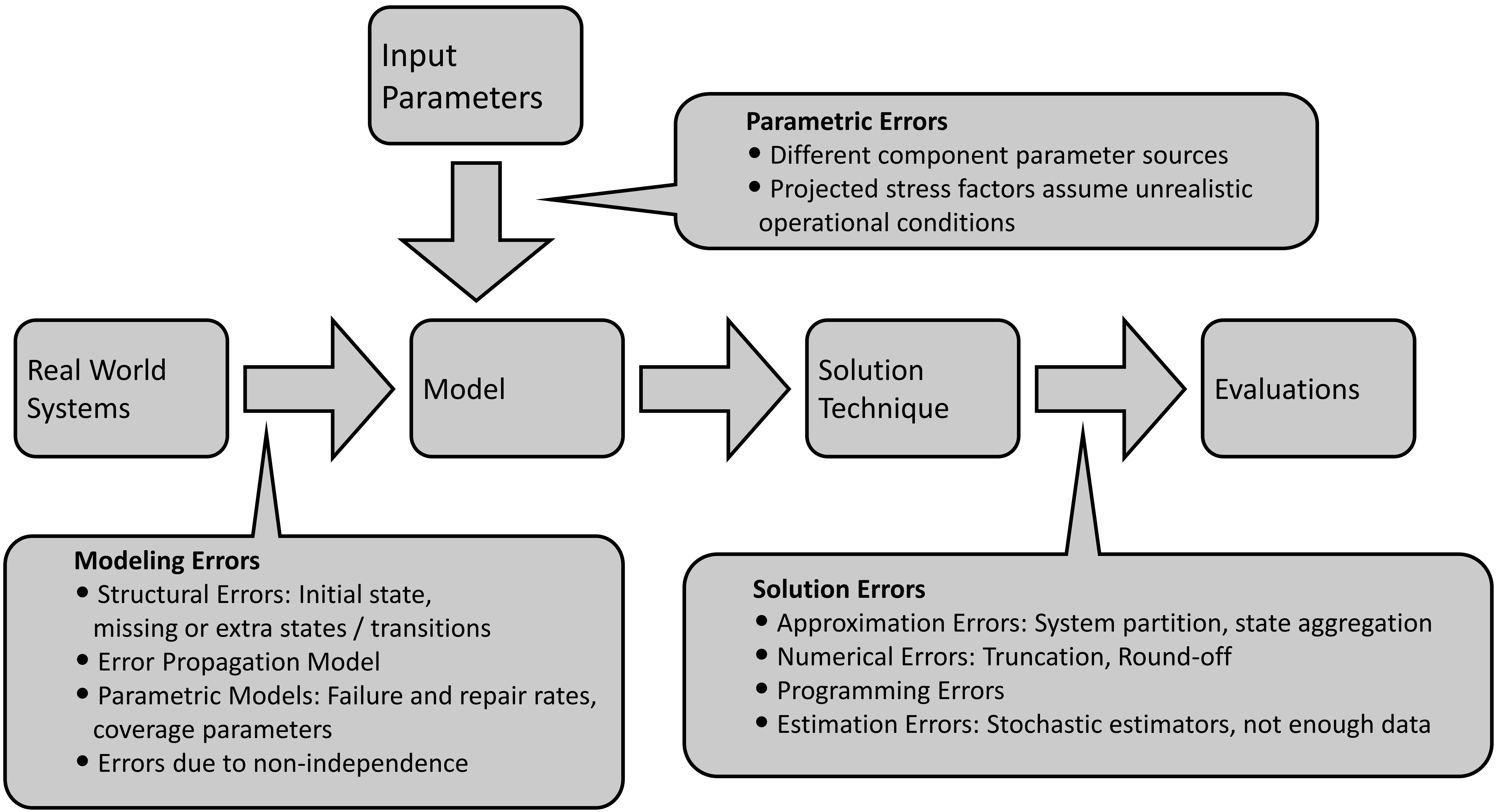
- Structure analysis effort grows exponentially with the number of components
- Fault Trees
  - Invented 1961 by H. Watson (Bell Telephone Laboratories)
    - Facilitate analysis of the launch control system of the intercontinental Minuteman missile
  - Used by Boeing since 1966, meanwhile adopted by different industries
  - Root cause analysis, risk assessment, safety assessment
- Basic idea
  - Technique for describing **the possible ways** in which an **undesired system state** can occur
  - Complex system failures are broken down into basic events

7 - State-Based Modeling

- Structural vs. state-based modeling
- State Transition Diagrams
- Markov Chains
- Petri Nets



The complexity of the petri net does not depend on the number of components!


Input Parameters
Parametric Errors
• Different component parameter sources
• Projected stress factors assume unrealistic operational conditions
Real World Systems
Model
Solution Technique
Evaluations
Modeling Errors
• Structural Errors: Initial state, missing or extra states / transitions
• Error Propagation Model
• Parametric Models: Failure and repair rates, coverage parameters
• Errors due to non-independence
Solution Errors
• Approximation Errors: System partition, state aggregation
• Numerical Errors: Truncation, Round-off
• Programming Errors
• Estimation Errors: Stochastic estimators, not enough data

8 - Qualitative Dependability Investigation

- Different approaches that focus on structural (qualitative) system evaluation
  - Root cause analysis
    - Broad research / industrial topic targeting error diagnosis
    - Specialized topic in quality methodologies
  - Development process investigation
    - Procedures for ensuring industry quality in production
    - Software development process
  - Organizational investigation
    - Non-technical influence factors on system reliability

FMEA

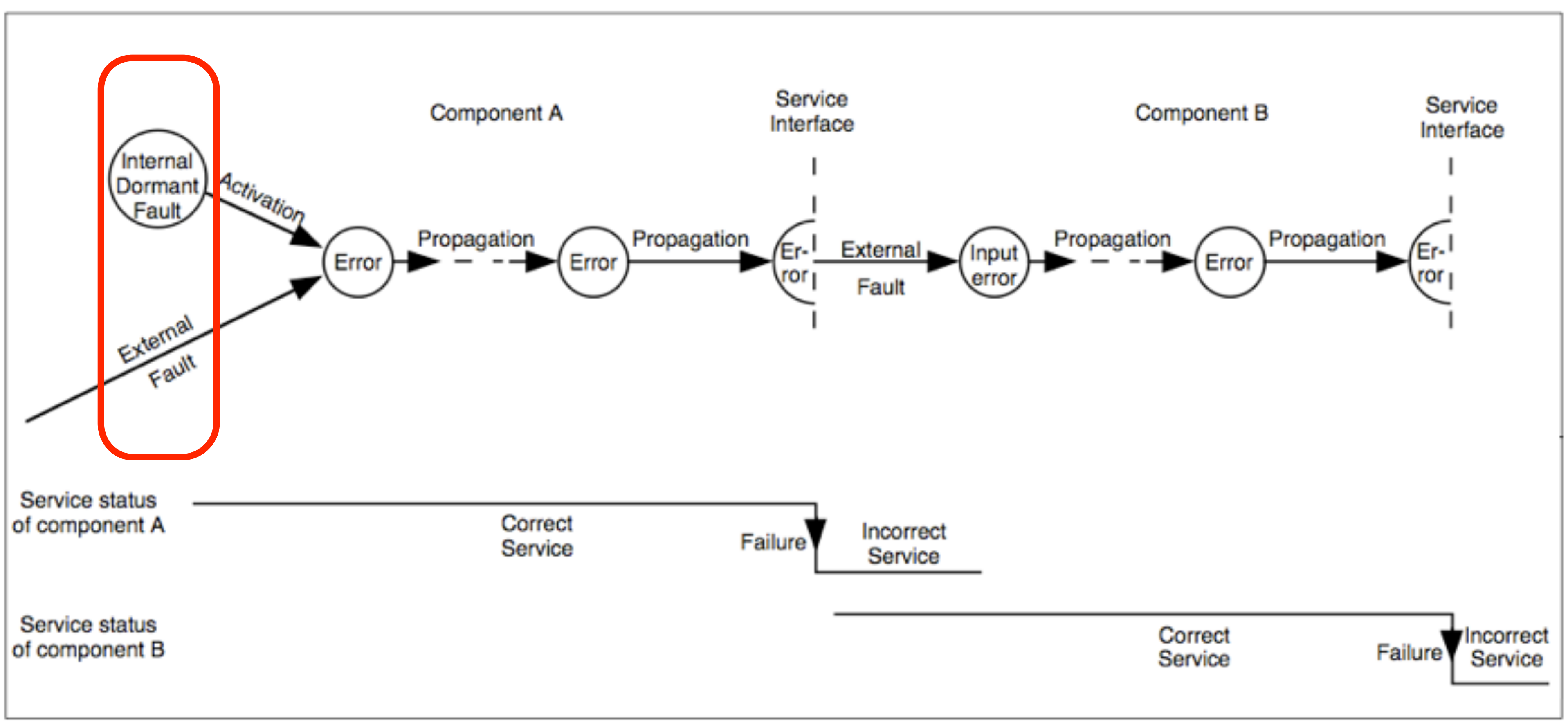
- **Failure Mode and Effects Analysis**
- Engineering quality method for early concept phase - identify and tackle weak points
- Introduced in the late 1940s for military usage (MIL-P-1629)
  - Later also used for aerospace program, automotive industry, semiconductor processing, software development, healthcare, ...
- Main goal is to identify and prevent critical failures
- Performed by cross-functional team of **subject matter experts**
- Most important task in many reliability programs
  - Six Sigma certification, reliability-centered maintenance (RCM) approach
  - Automotive industry (ISO16949, SAE J1739)
  - Medical devices

Hazard & Operability Studies (HAZOPS)

- Process for identification of potential hazard & operability problems, caused by **deviations from the design intend**
  - Difference between deviation (failure) and its cause (fault)
  - Conduct intended functionality in the safest and most effective manner
  - Initially developed to investigate chemical production processes, meanwhile for petroleum, food, and water industries
  - Extended for complex (software) systems
- Qualitative technique
  - Take full description of process and systematically question every part of it
  - Assess possible deviations and their consequences
  - Based on **guide-words** and multi-disciplinary meetings

Root Cause Analysis

- What caused the fault ? - Starting point of dependability chain
  - Peeling back the layers
  - Must be performed systematically as an investigation
  - Establish sequence of events / timeline



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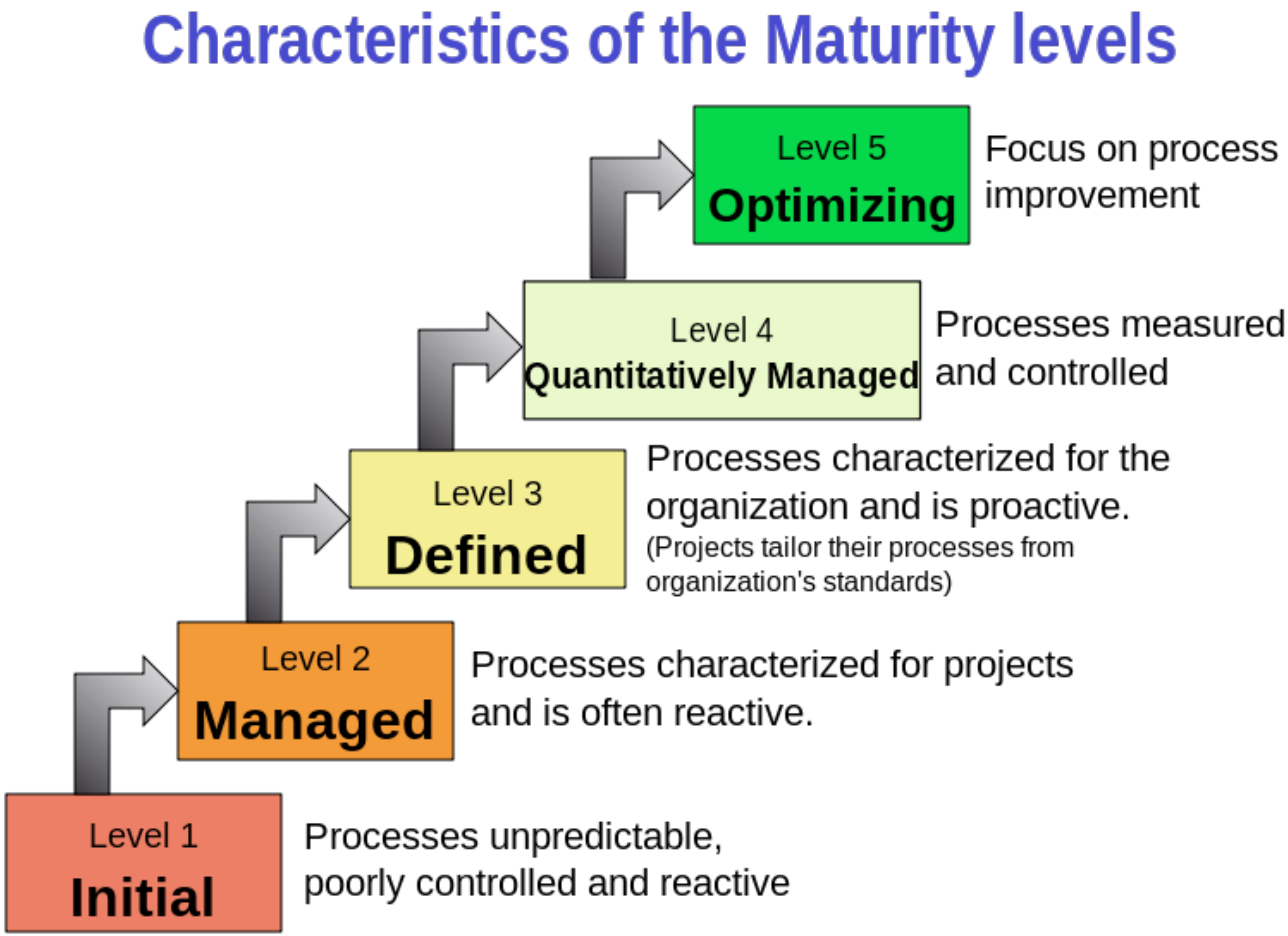
Reliability Models for IT Infrastructures

- System reliability in a commercial environment is determined by many factors:
  - Software and hardware reliability
  - Training of maintenance personnel
  - „Business processes“ how maintenance is handled
  - The way the IT department is organized
  - ...
- Impact of management organization on reliability is an emerging research field
- Standards for IT organization, based on best practices
  - Describe which processes have to be established in an IT department
  - Provide reference models for organization of IT department

CMMI Maturity Levels



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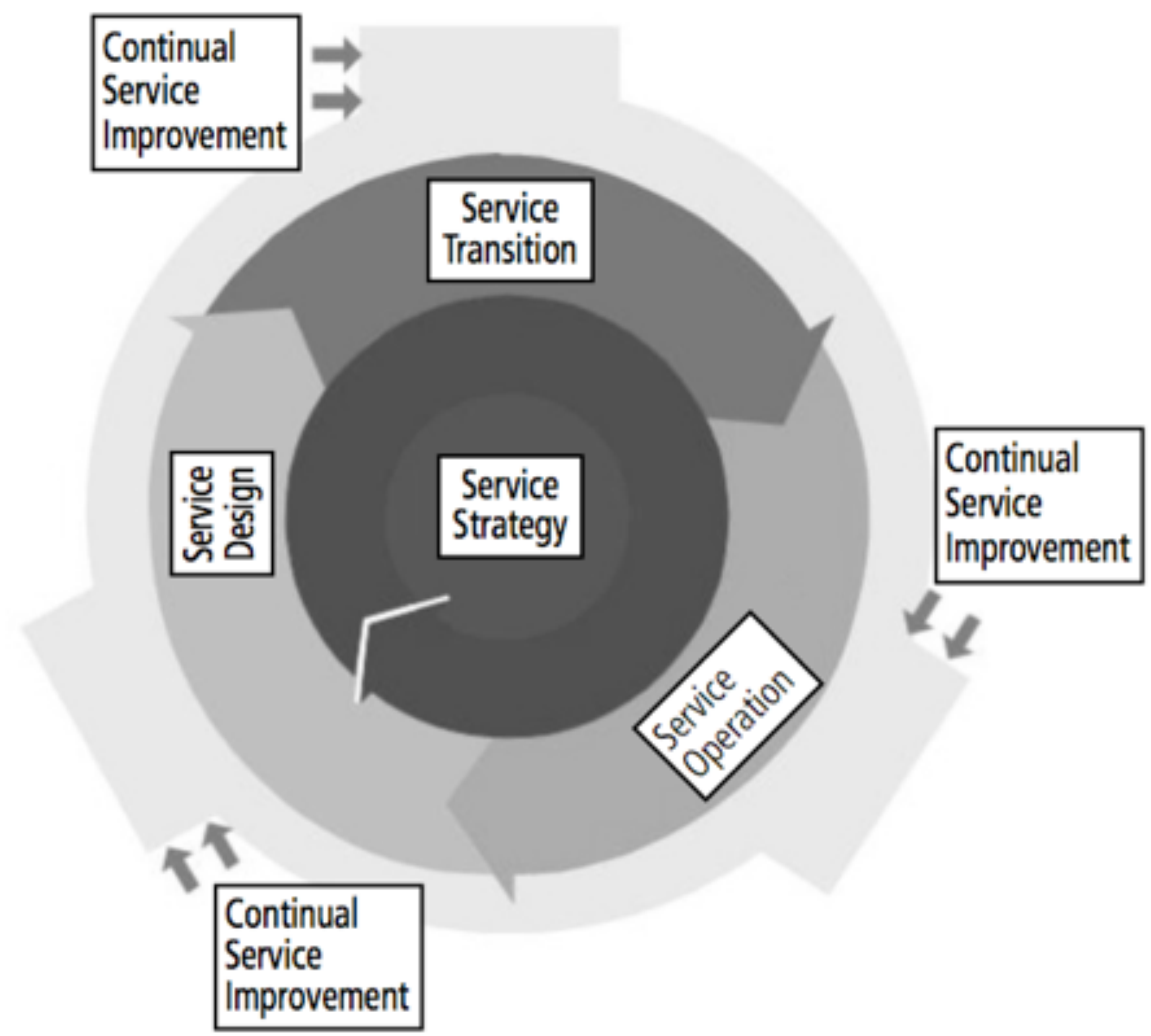
ITIL

- Information Technology Infrastructure Library (ITIL), latest version v3
  - Started as set of recommendations by the UK Government
  - Concepts and guides for **IT service management**
  - Supports to deliver business-oriented quality IT services
- Core publications: **Service Strategy**, **Service Design**, **Service Transition**, **Service Operation**, **Continual Service Improvement**
- Broad tool support from vendors
- High costs for certification and training
- Methodology sometimes over-respected at the expense of pragmatism



9 - Predicting System Reliability

- Feasibility evaluation for given model, identification of potential problem sources
- Comparison of competing designs
- Identification of potential reliability problems - low quality, over-stressed parts
- Input to other reliability-related tasks
  - Maintainability analysis, testability evaluation
  - Failure modes and effects analysis (FMEA)
- Ultimate goal is the prediction of system failures by a reliability methodology
- Approach depends on nature of component (electrical, electronic, mechanical)

Reliability Data

- **Field (operational) failure data**
  - Meaningful source of information, experience from real world operation
  - Operational and environmental conditions may be not fully known
- **Service life data with / without failure**
  - Helpful in assessing time characteristics of reliability issues
- **Data from engineering tests**
  - Example: Accelerated life tests
  - Results from controlled environment
  - Trustworthy for analysis purposes
- Lack of failure information is the ‚greatest deficiency‘ in reliability research [Misra]

Reliability Prediction Models

- Economic requirements affect field-data availability
  - Customers do not need generic field data, so collection is extra effort
- Numerical reliability prediction models available for specific areas
  - **Hardware-oriented reliability modeling**
    - MIL-HDBK-217, Bellcore Reliability Prediction Program, ...
  - **Software-oriented reliability modeling**
    - Jelinski-Moranda model, Basic Execution model, software metrics, ...
- Prediction models look for corrective factors, so they are always focused
- Demands confidence in understanding of environmental conditions
- Reconciliation is often needed between the different values of failure data from various sources

Software Reliability Assessment

- Software bugs are permanent faults, but behave as transient faults
  - Activation depends on software usage pattern and input values
  - Timing effects with parallel or distributed execution
  - Software aging effects
- Fraction of system failures reasoned by software increased in the last decades
- Possibilities for software reliability assessment
  - **Black box models** - No details known, observations from testing or operation
    - Reliability growth models
  - **Software metric models** - Derive knowledge from static code properties

```
x = x + 1;
```

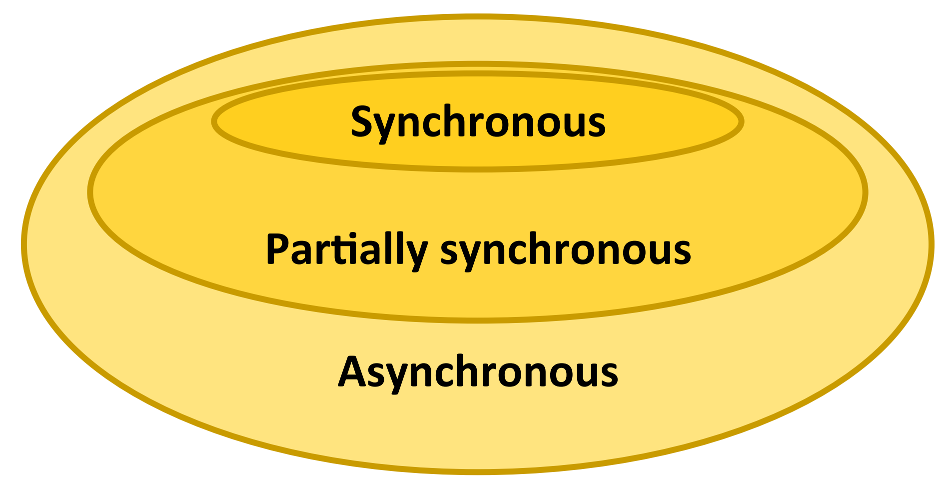
$N_{OP}=n_{OP}=3$
$N_{OD}=3$
$n_{OD}=2$

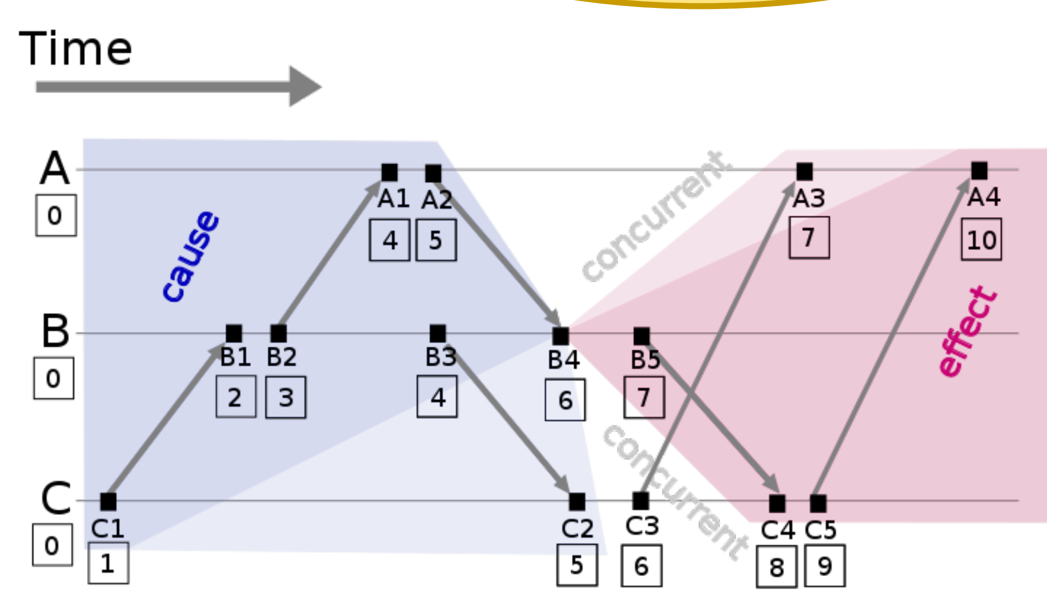
Halstead Metric

- Statistical approach - Complexity is related to number of operators and operands
- Only defined on method level, OO code analysis must consider additional structure
  - Program **length** N = *Number of operators* N_{OP} + *total number of operands* N_{OD}
  - **Vocabulary** size n = *Number of unique operators* n_{OP} + *number of unique operands* n_{OD}
  - Program **volume** $V = N * \log_2(n)$
    - Describes size of an implementation by vocabulary and (mainly) by program length
    - In-place changes are ok ...
  - **Difficulty** level $D = (n_{OP} / 2) * (N_{OD} / n_{OD})$, program level $L = 1 / D$
    - Error proneness is proportional to number of unique operators
      -> since most languages only offer a few, this should be small
    - Also proportional to the level of operand reuse through the code

10 - Distributed Systems Theory

- Fallacies of Distributed Computing
    - The network is reliable, Latency is zero, Bandwidth is infinite, The network is secure, Topology doesn’t change, There is one administrator, Transport cost is zero, The network is homogeneous
- Timing Models
    - Logical time, Lamport clocks
- Fault Models
- Consensus Problems
    - 2PC
    - Paxos



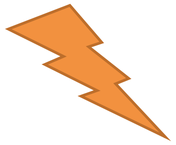


11 - Fault-Tolerant Distributed Systems

- Consistency Models
  - Strict consistency, sequential consistency, eventual consistency
- Trade-Offs
  - Brewer, CAP Theorem
- Replication
  - State Machine Replication, …

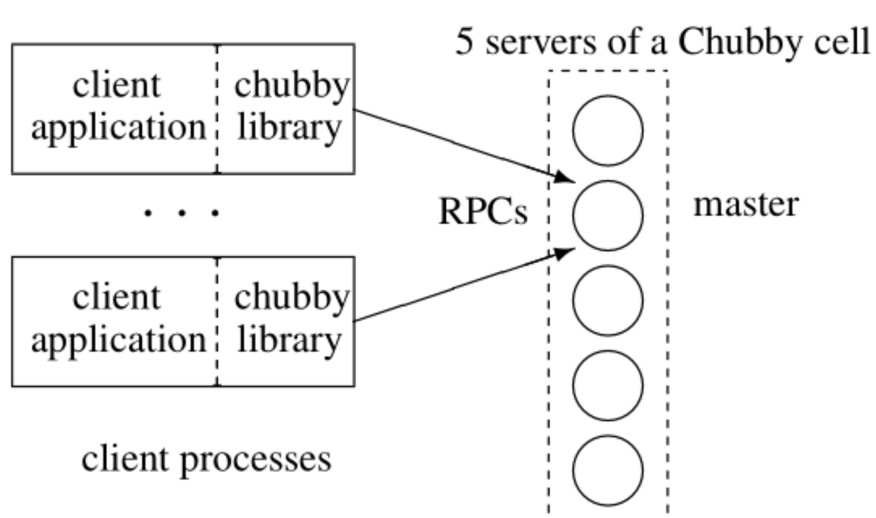
P1	W(x) → a		
P2			R(x) → a

P1	W(x) → a		
P2		R(x) → NIL	R(x) → a



12 - Dependable Distributed Applications

- Frameworks - Erlang / FT-CORBA
- Coordination Services
  - Chubby, Zookeeper
- Distributed Storage
  - Cassandra, RIAK, HDFS …



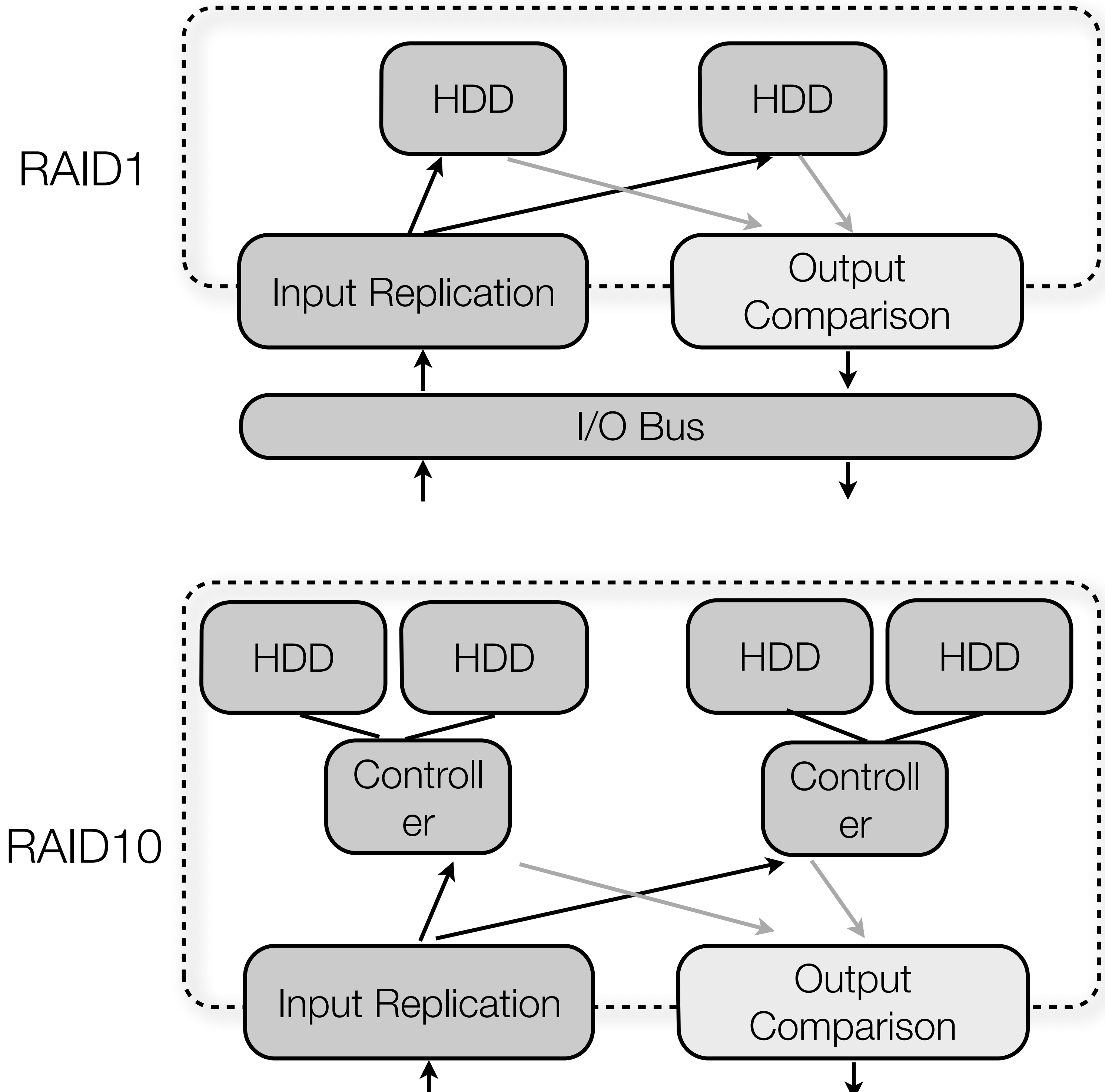
13 - Hardware Diagnosis

- Contains of fault detection (what ?) and fault location (where ?)
- Fault detection
  - Replication checks - Test operation / execution against alternate implementation
  - Timing checks - Test operation / execution against timing constraints
  - Reversal checks - Make use of operation reversibility
  - Coding checks - Utilize redundant (but different) representation of data
  - Reasonableness checks - Check against known system / data properties
  - Structural checks - Ensure consistent structure of data, diagnostic tests, ...
  - Diagnostic checks - Use set of inputs for which the outputs are known
  - Algorithmic checks - Check invariants of an algorithm

14 - Hardware Redundancy

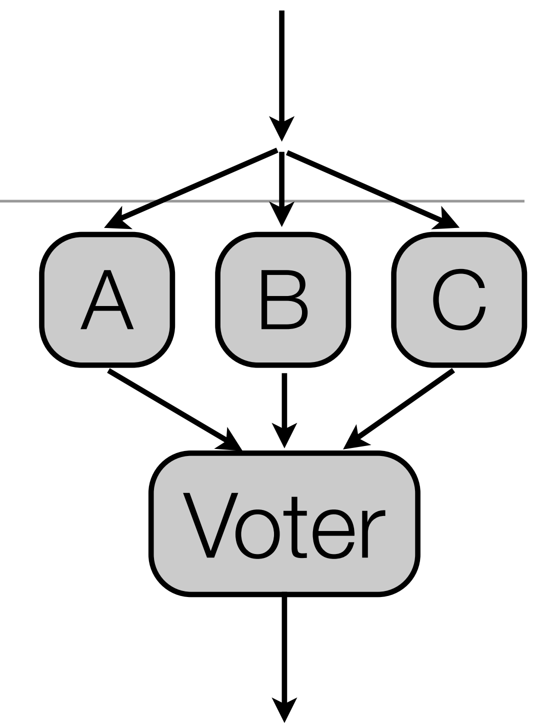
- Redundancy for **error detection** and **forward error recovery**
- Redundancy types: **spatial**, **temporal**, **informational** (presentation, version)
  - Redundant not mean identical functionality, just perform the same work
- **Static redundancy** implements error mitigation
  - Fault does not show up, since it is transparently removed
  - Examples: Voting, error-correcting codes, N-modular redundancy
- **Dynamic redundancy** implements error processing
  - After fault detection, the system is reconfigured to avoid a failure
  - Examples: Back-up sparing, duplex and share, pair and spare
- **Hybrid approaches**

Sphere of Replication



- Components outside the sphere must be protected by other means
- Level of output comparison decides upon fault coverage
- Larger sphere tends to decrease the required bandwidth on input and output
  - More state changing happens just inside the sphere
- Vendor might be restricted on choice of sphere size

Masking / Static Redundancy: Voting



- **Exact voting:** Only one correct result possible
  - **Majority vote** for uneven module numbers
  - **Generalized median voting** - Select result that is the median, by iteratively removing extremes
  - **Formalized plurality voting** - Divide results in partitions, choose random member from the largest partition
- **Inexact voting:** Comparison at high level might lead to multiple correct results
  - **Non-adaptive voting** - Use allowable result discrepancy, put boundary on discrepancy minimum or maximum (e.g. 1,4 = 1,3)
  - **Adaptive voting** - Rank results based on past experience with module results
    - Compute the correct value based on „trust“ in modules from experience
    - Example: Weighted sum $R=W_1*R_1 + W_2*R_2 + W_3*R_3$ with $W_1+W_2+W_3=1$

N-Modular Redundancy (with perfect voter)

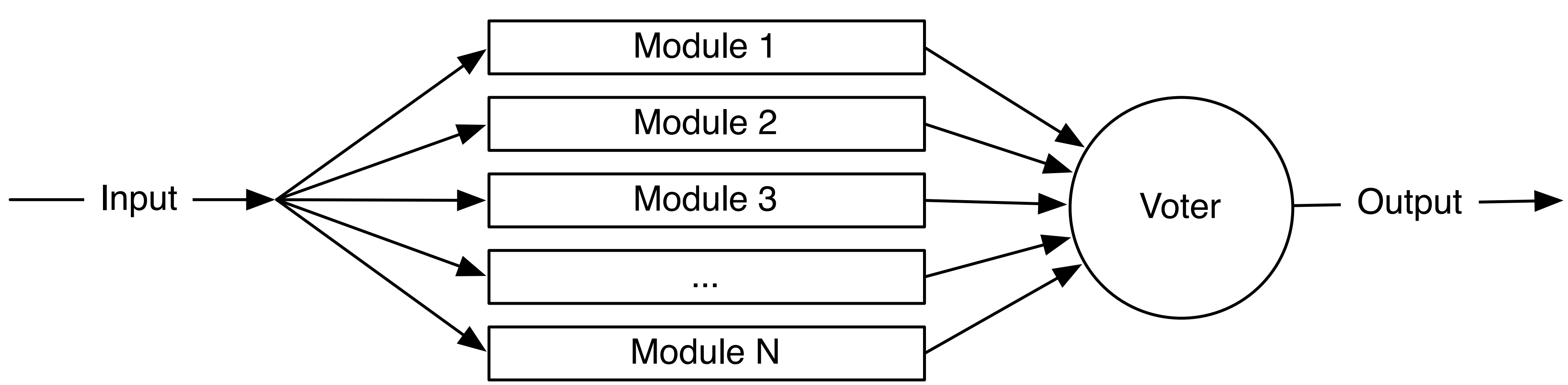
$$R_{NMR} = \sum_{i=0}^{m} \binom{N}{i} (1-R)^i R^{N-i}$$

$$\binom{n}{k} = \frac{n!}{k!(n-k)!}$$

$$R_{2-of-3} = \binom{3}{0} (1-R)^0 R^3 + \binom{3}{1} (1-R) R^2$$

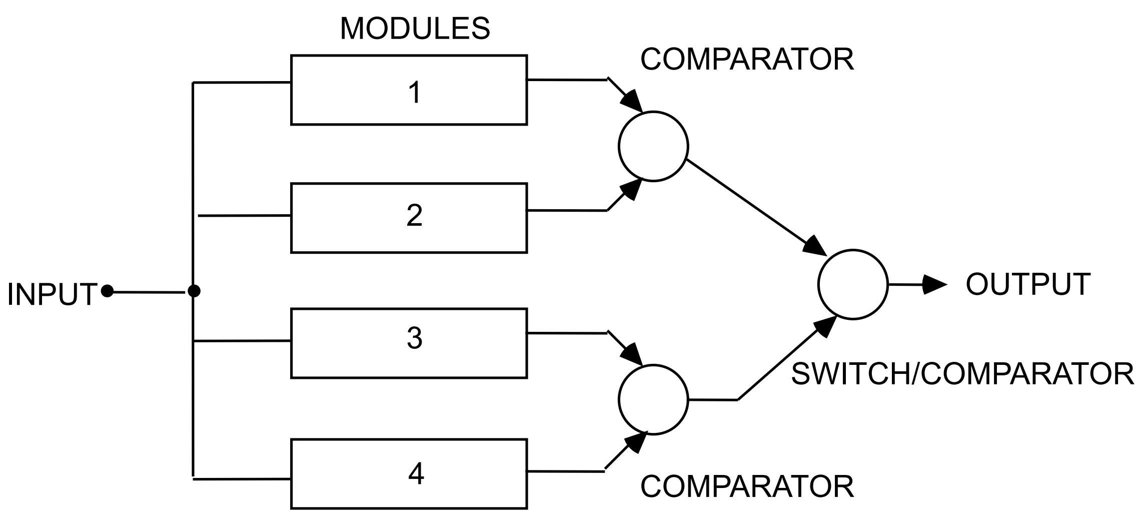
$$R_{2-of-3} = R^3 + 3(1-R)R^2$$

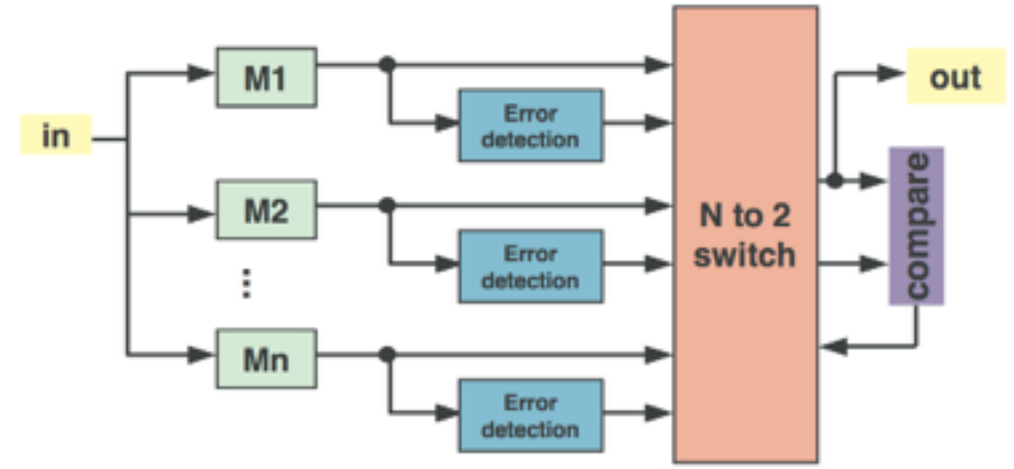
$$R_{3-of-5} = ...$$



Pair and Spare

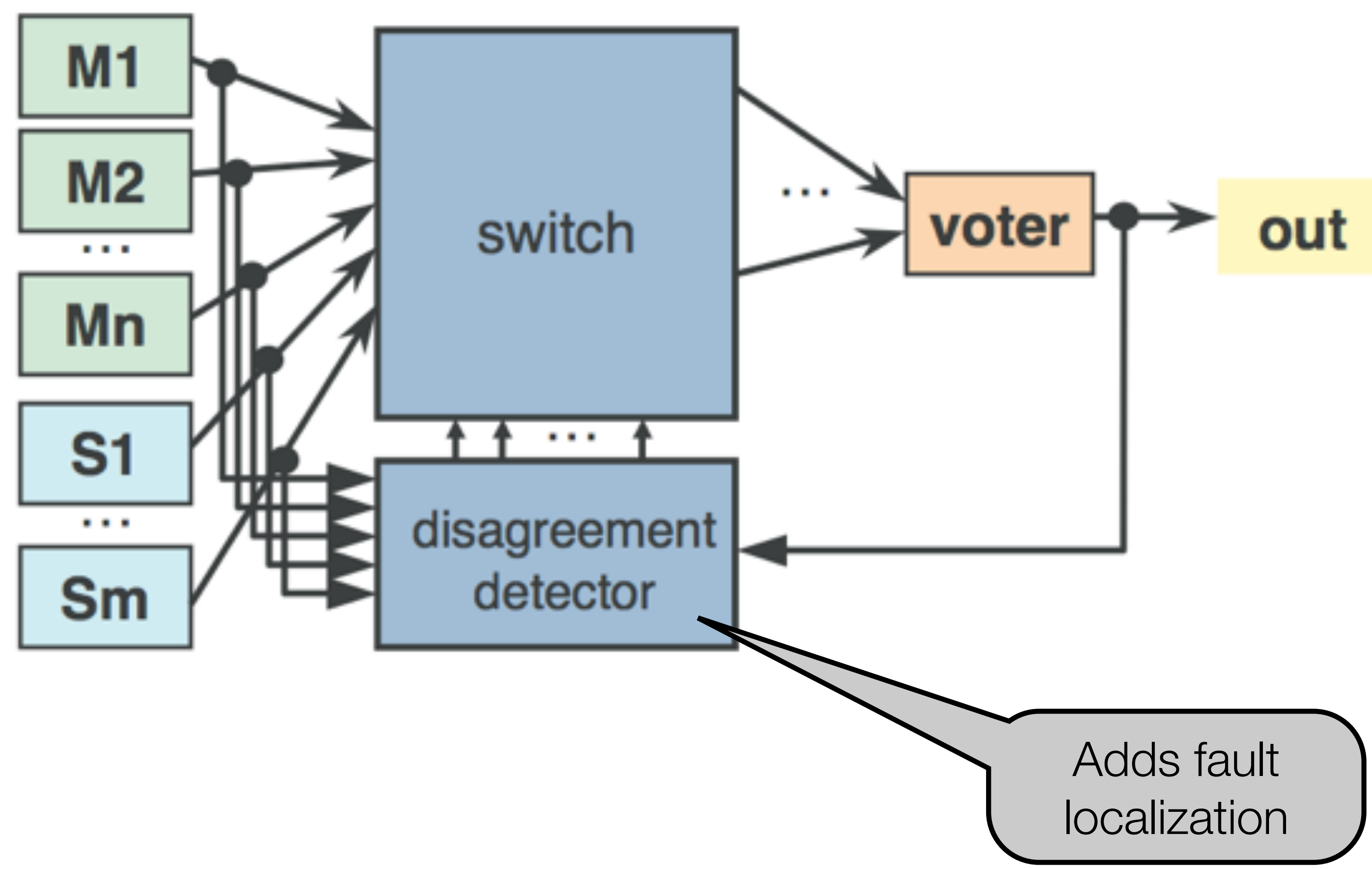
- Special cases for combination of duplex (with comparator) and sparing (with switch)
- **Pair and spare** - Multiple duplex pairs, connected as standby sparing setup
  - Two replicated modules operate as duplex pair (lockstep execution), connected by comparator as voting circuit
  - Same setting again as spare unit, spare units connected by switch
  - On module output mismatch, comparators signal switch to perform failover
  - Commercially used, e.g. Stratus XA/R Series 300





Hybrid Approaches

- **N-modular redundancy with spares**
  - Also called **hybrid redundancy**
  - System has basic NMR configuration
  - Disagreement detector replaces modules with spares if their output is not matching the voting result



  - Reliability as long as the spare pool is not exhausted
  - Improves fault masking capability of NMR
    - Can **tolerate two faults with one spare**, while classic NMR would need 5 modules with majority voting to tolerate two faults

Coding Checks in Memory Hardware

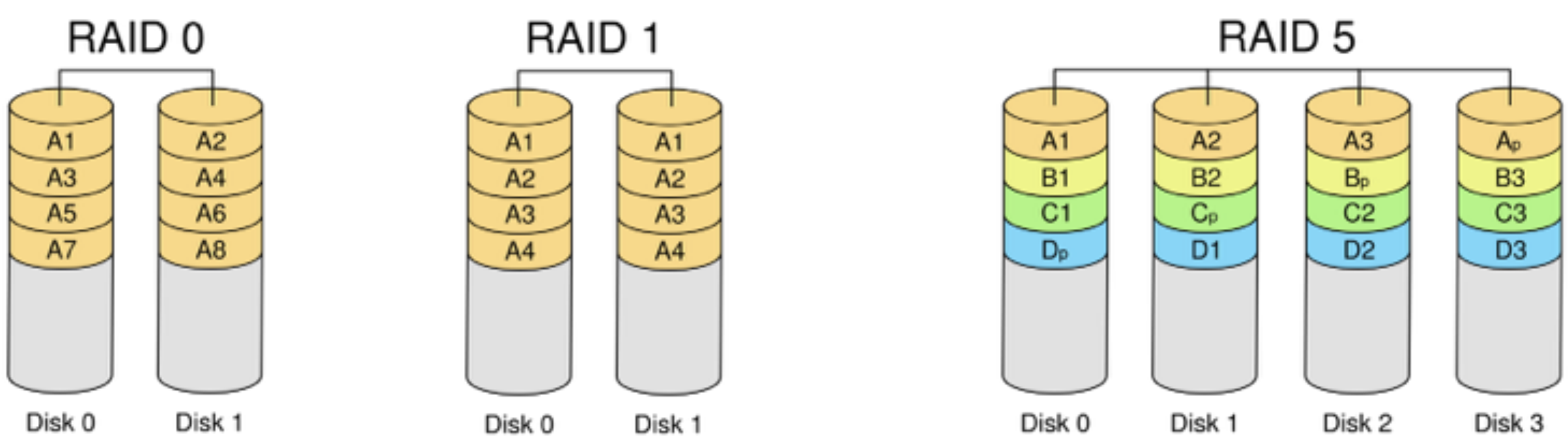
- **Primary memory**
  - Parity code
  - m-out-of-n resp. m-of-n resp. m/n code
  - Checksumming
  - Berger Code
  - Hamming code
- **Secondary storage**
  - RAID codes
  - Reed-Solomon code

Memory Redundancy

- Standard technology in DRAMs
  - Bit-per-byte **parity**, check on read access
  - Implemented by additional parity memory chip
  - **ECC** with Hamming codes - 7 check bits for 32 bit data words, 8 bit for 64 bit
    - Leads to 72 bit data bus between DIMM and chipset
    - Computed by memory controller on write, checked on read
    - Study by IBM: ECC memory achieves R=0.91 over three years
    - Can correct single bit errors and detect double bit errors
- Hewlett Packard **Advanced ECC** (1996)
  - Can detect and correct single bit and double bit errors

RAID

- **Redundant Array of Independent Disks (RAID)** [Patterson et al. 1988]
  - Improve I/O performance and / or reliability by building *raid groups*
  - Replication for information reconstruction on disk failure (*degrading*)
  - Requires computational effort (dedicated controller vs. software)
  - Assumes failure independence



Parity With XOR

- Self-inverse operation
  - 101 XOR 011 = 110, 110 XOR 011 = 101

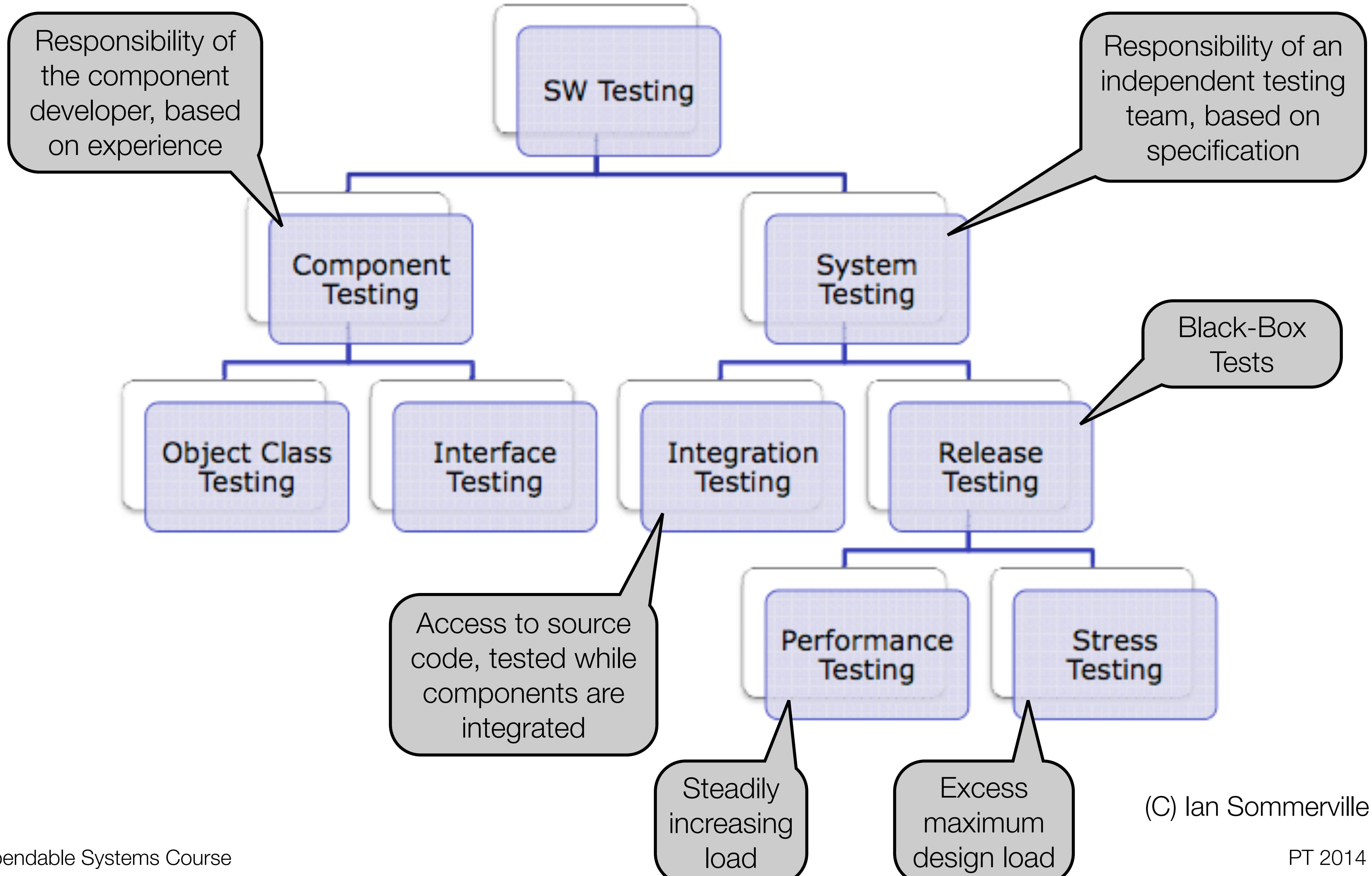
Disk	Byte							
1	1	1	0	0	1	0	0	1
2	0	1	1	0	1	1	1	0
3	0	0	0	1	0	0	1	1
4	1	1	1	0	1	0	1	1
Parity	0	1	0	1	1	1	1	1

Disk	Byte							
1	1	1	0	0	1	0	0	1
Parity	0	1	0	1	1	1	1	1
3	0	0	0	1	0	0	1	1
4	1	1	1	0	1	0	1	1
Hot Spare	0	1	1	0	1	1	1	0

15 - Software Dependability

- Fault elimination
  - Reduce number of dormant faults at development time
- Fault-tolerant software
  - Techniques to achieve fault tolerance for software faults
  - Application of redundancy idea to software modules
- Software fault tolerance
  - Techniques to achieve fault tolerance by software mechanisms
  - Typically for hardware failures on lower levels in the system stack
  - Redundancy managed by operating system, cluster framework, application code

Fault Elimination through Software Testing



(C) Ian Sommerville

Testing Through Software Fault Injection

- Intentionally trigger erroneous behavior of the execution environment
  - Typical approach for communicating software entities
  - Orientation towards implementation details - program state, functional behavior
  - Several non-intrusive implementation techniques, such as AOP
  - Injection can be done as part of execution under real conditions
  - Huge variety of fault classes, including SWIFI fault classes
  - New approaches support remote fault injection (e.g. fuzzing)
- **Compile-time injection:** Leads to erroneous image being executed
- **Run-time injection:** Demands some altering of application state during runtime
- Typical triggers: Time-out, exception, debugging trap, code insertion

Software Fault Model [Goloubeva]

- Example: Control loop writing computation result to a variable
  - **Temporary fault**: Write NULL to result variable after end of usage
  - **Permanent fault**: Compute and store incorrect output from input data
- Single vs. multiple faults depends on granularity level of investigation
- On **source code level**
  - Program: Structured collection of features with syntax and semantic
  - Syntax allows to describe fault model
  - Negation of semantic properties defines a fault model
  - Examples: Calling non-existent functions, Functions not returning a value, values out of their type range, missing input parameters
- On **executable level**, e.g. stack overflow due to recursion

Fault-Tolerant Software - Another categorization [Lyu 95]

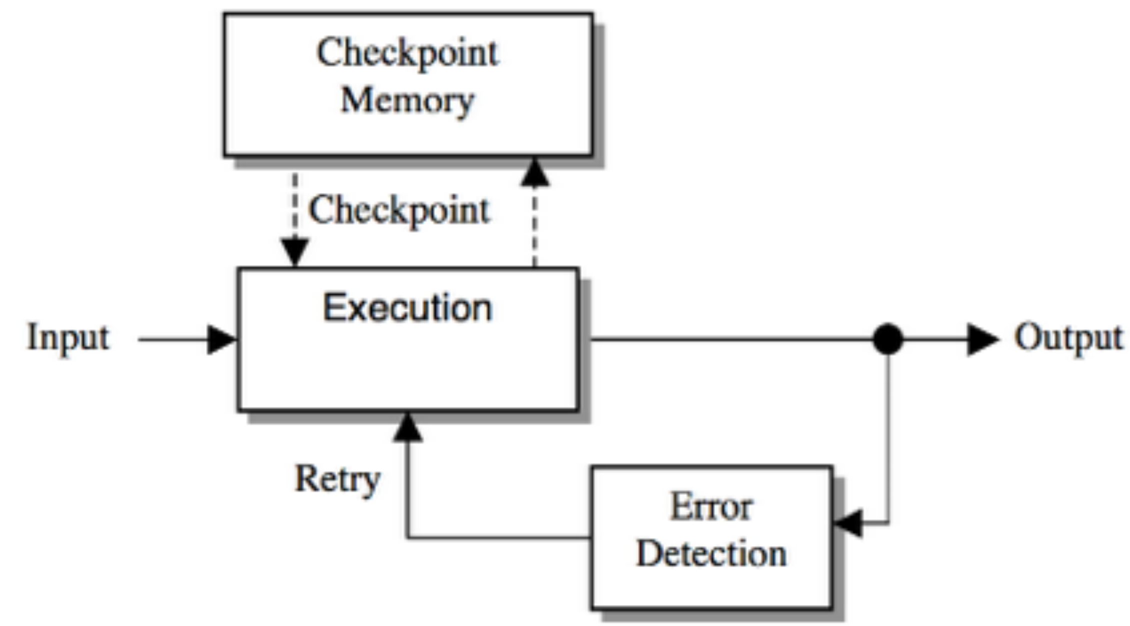
- **Single version techniques**
  - Add mechanisms for detection, containment, and handling of errors to the software component itself
  - Examples: Software structure and actions approaches, error detection, exception handling, checkpointing and restart, process pairs, data diversity
- **Multi version techniques**
  - Rely on structured utilization of variants of the same software
  - Examples: Recovery blocks, N-version programming
- Principles can be applied to any software layer
  - Identify source of most design faults
  - Typically no problem with parallel application, beside cost factor

Single-Version Approaches - Wrapper

- Piece of software that encapsulates a given program when it is being executed
- Typical approach for operating systems and middleware stacks
- Structure: **Wrapper software** and **wrapped entity**
- Inputs and outputs are checked by the wrapper
- Examples:
  - Dealing with buffer overflow, checking scheduler correctness (e.g., EDF), bypassing known bugs, checking output correctness
- When pre- or postconditions are violated, usually an exception is being raised
- Wrapper forms an **acceptance test** in the **dependability rings**
- Good approach for fixing issues in the operational phase of software

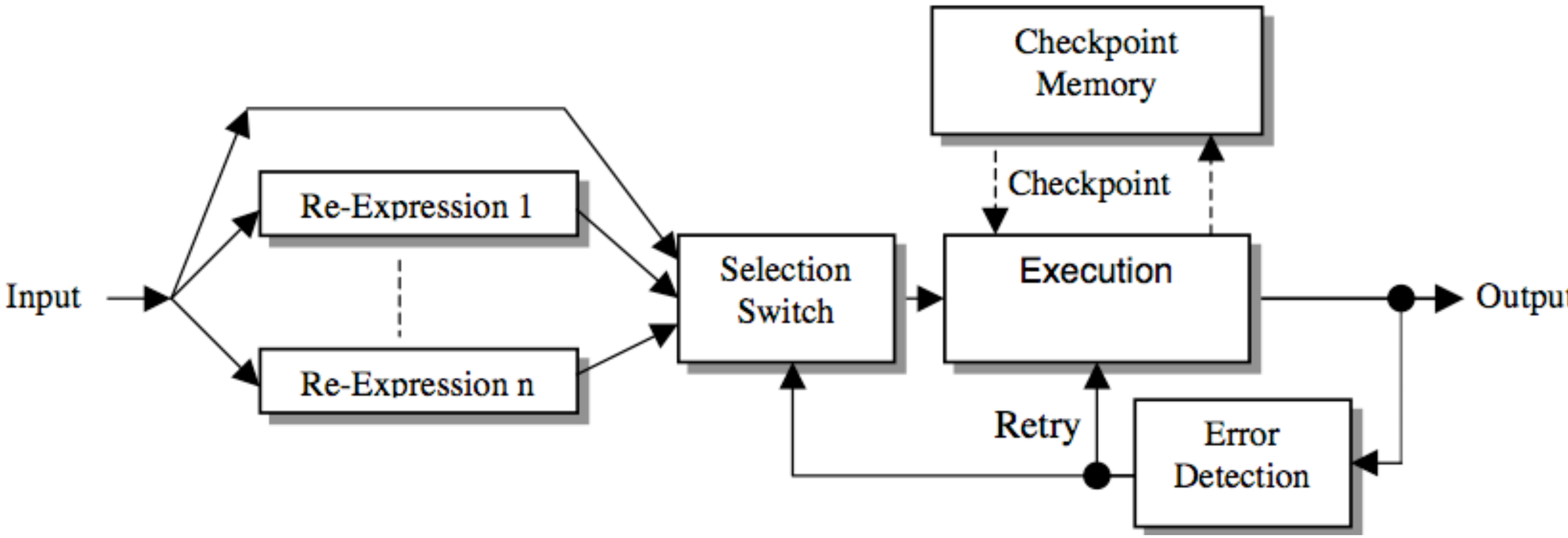
Single Version Approaches - Checkpointing

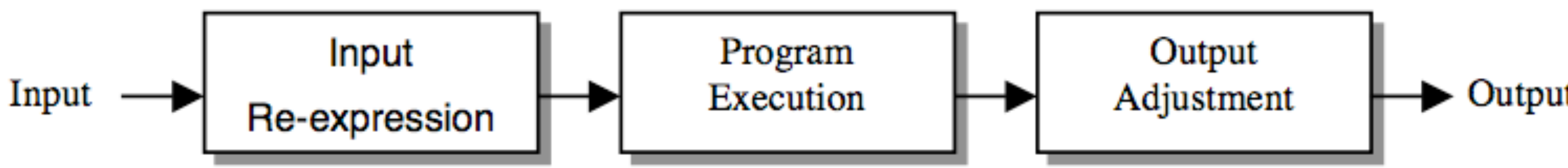
- Save application state data at recovery points
  - Can be reloaded on crash or any other kind of data loss
  - Possible on different levels: local per process, partial, complete, distributed
- Optimum checkpointing interval
  - Checkpointing too frequent: Majority of time spent for data saving
  - Checkpointing too rare: May take long time to recover
- Several specialized solutions for C / C++ language, easier with reflection support
- Popular approach in clusters / high-performance computing
  - Latest trend: In-memory checkpointing

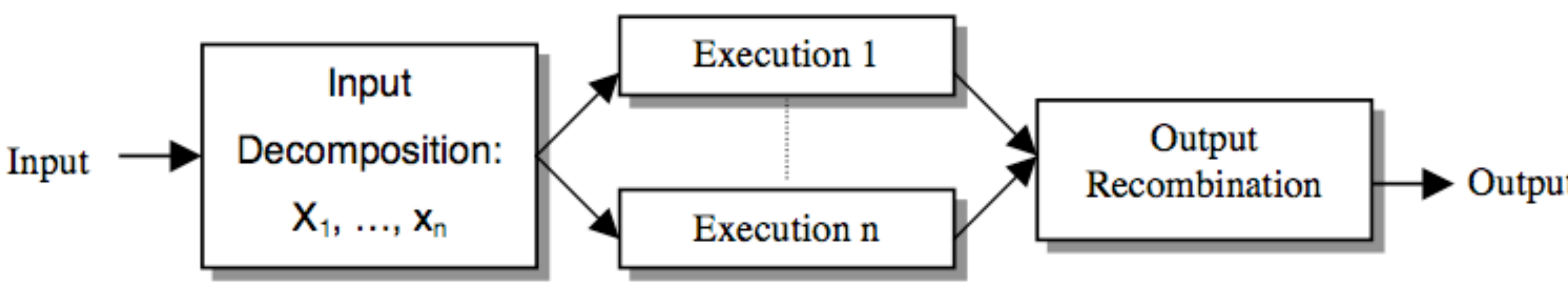


taken from
Software Fault Tolerance: A Tutorial

Single Version Approaches - Data Diversity [Ammann 88]







taken from *Software Fault Tolerance: A Tutorial*

Single Version Approaches - High-Level Instruction Duplication [Goloubeva]

- Introduce data and code redundancy through high-level transformation
  - Duplicate every variable
  - Perform every write operation on both copies of the variable
  - After each read operation, the copies must be checked for consistency
    - Should be close to read operation, in order to avoid error propagation
    - Includes also expression evaluation
  - Procedure parameters treated as variables
- Independent from underlying hardware, targets cache / main memory faults

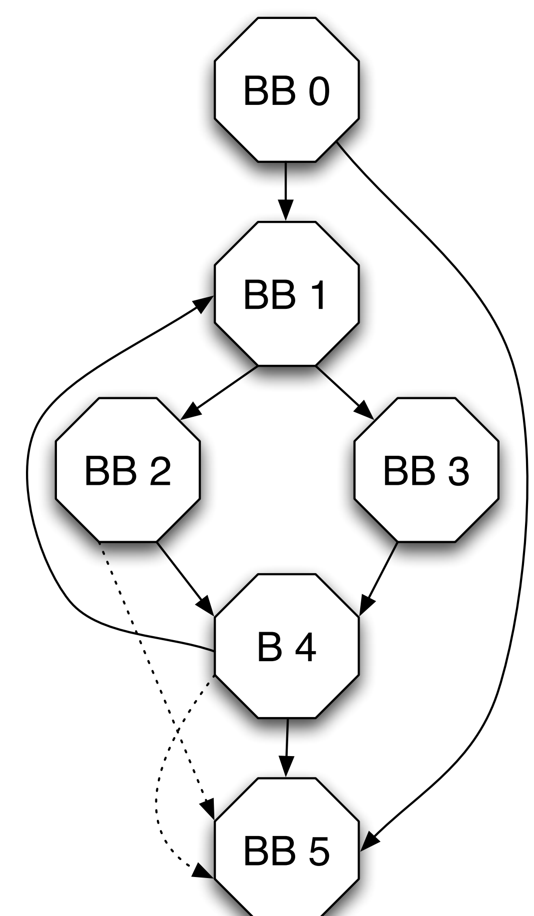
```
a=b;
.. becomes ...
a0=b0;
a1=b1;
if (b0 != b1)
  error();
...
```

```
a=b+c;
... becomes ...
a0=b0+c0;
a1=b1+c1;
if ((b0!=b1)||(c0!=c1))
  error();
```

Control Flow Error

- Control flow error (CFE) leads to unexpected instruction execution
- Terminology:
  - Basic block (BB) - branch-free serial code fragment
    - Branch / jump instruction is modeled as last instruction of a basic block
  - Control flow graph (CFG) - one node per basic block
  - Illegal branch - Node transition is not part of the CFG
  - Wrong branch - Node transition is already part of the CFG
  - Inter-block error - Erroneous branch to different block
  - Intra-block errors - Erroneous branch inside a block

```
i=0;
while(i<n) {
------------------
  if (a[i] < b[i])
------------------
    x[i]=a[i];
------------------
  else
    x[i]=b[i];
------------------
  i++;
}
------------------
```



Multi-Version Approaches
Recovery Blocks

- Redundant system implementations are typically used simultaneously,
  best answer is picked i.e. by voting

- Alternative way:
  Sequential execution of *recovery blocks*

  - Introduced in 1974 by Horning et. al.

  - Dynamic fault tolerance approach, related to stand-by sparing in hardware

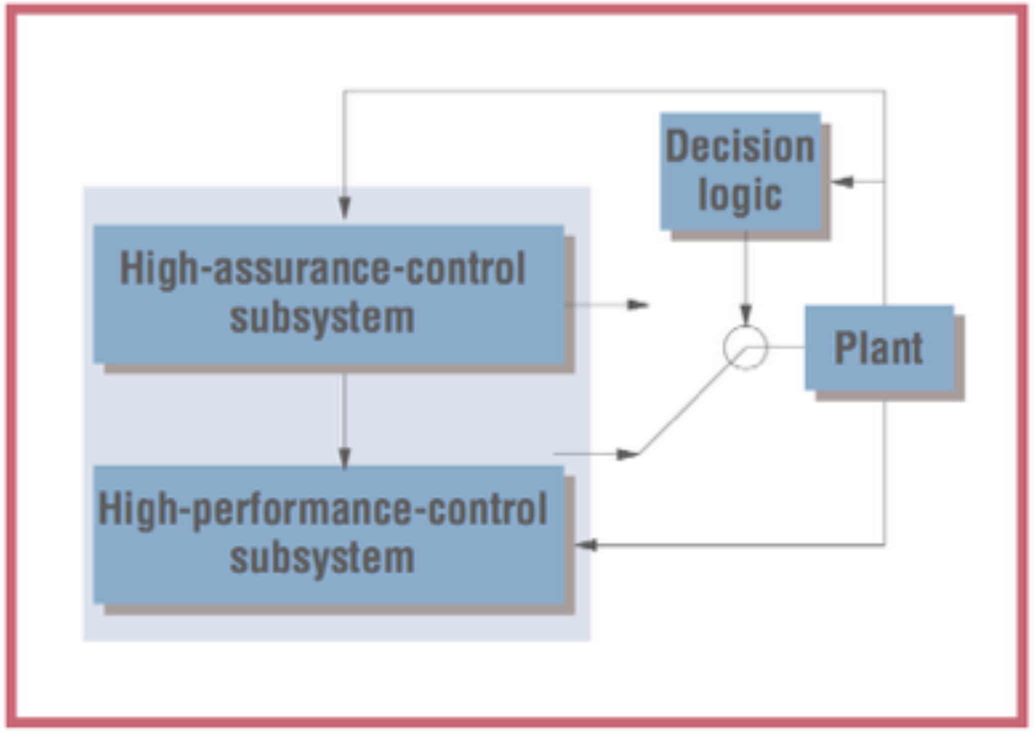
```
establish Checkpoint
  Primary Module
Acceptance Test, else
  load Checkpoint
  Alternative Module 1
Acceptance Test, else
  load Checkpoint
  Alternative Module 2
  ...
else      Failure Exception
```

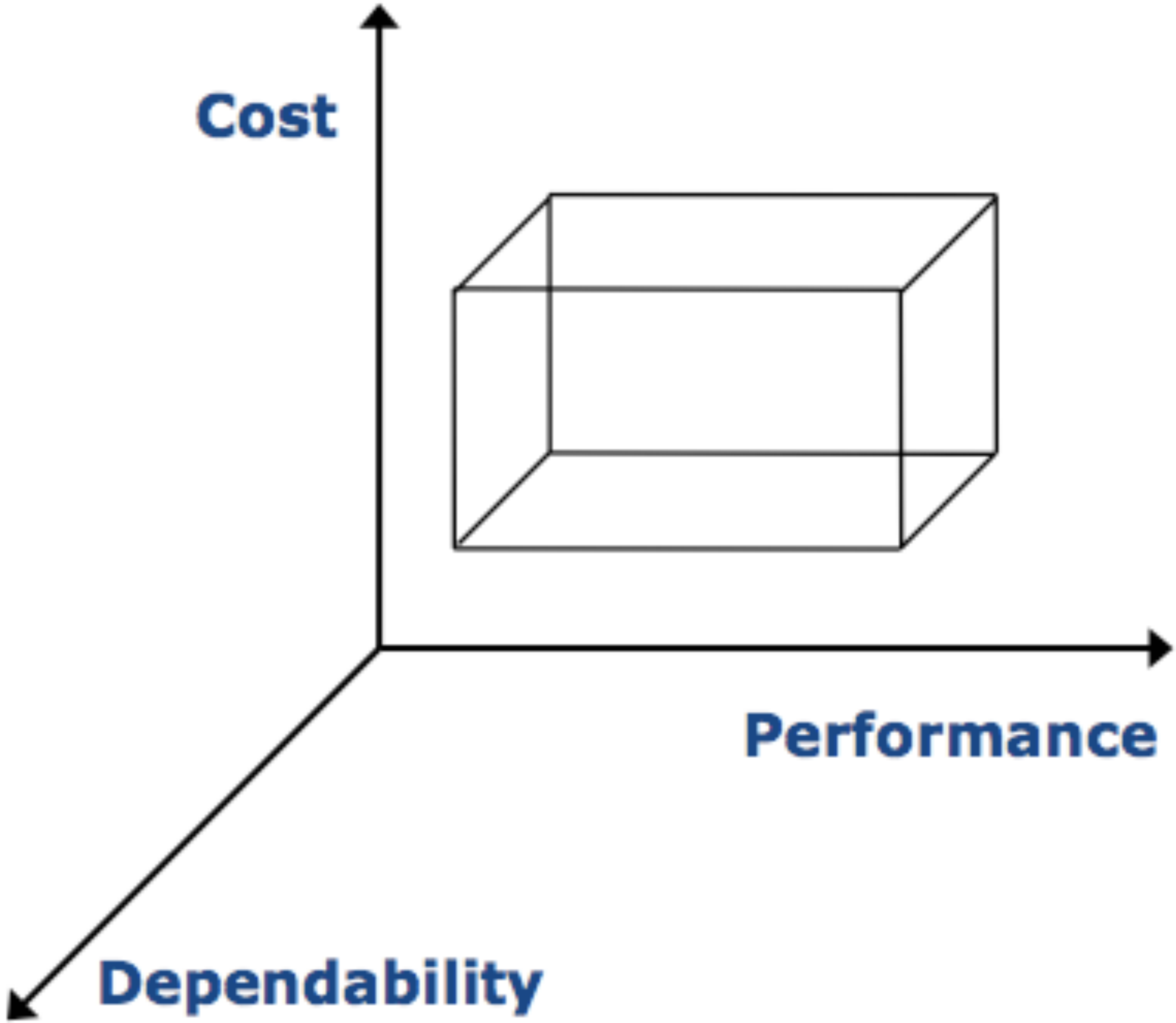
Multi-Version Approaches - N-Version Programming

- Common mode errors are only catchable by **design diversity**
- Design diversity is a complex issue
  - Design philosophies, software tools, programming languages, test philosophies
- Typical approaches try to utilize randomness - separate teams on different locations
- **N-Version Programming**
  - Suggested by Elmendorf in 1972, developed by Avizienis & Chen in 1977
  - Static approach, combination of decision mechanism and forward recovery
  - At least two independently designed and functionally equivalent variants
  - Variants are executed in parallel, decision mechanism selects the „best“ result
  - Can support reliability, but also system security against **malicious logic**

Simplex

- Idea: Using simplicity to control complexity
  - Forward recovery approach, based on feedback loop
  - **HAC subsystem** - Simple construction, formal methods, reliable hardware
  - **HPC subsystem** - Complex technology, advanced features
- HPC can use HAC output, but not vice versa
- Decision logic based on control loop output
- Typically performance degredation with HAC
- Example: Boeing 777 primary and secondary flight controller




Cost
Performance
Dependability