Reliable Computing I

Lecture 2: Reliability Metrics

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Today's Lecture

- Definition, metrics, and terminology

fault-tol·er·ant \'fȯlt-'täl(-ə)-rənt\
adj : able to function in the absence of a major component

Goals of Fault Tolerant Systems

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- How can we deal with problems?
- Option 1: Make problems less likely
  - Tough to do!
  - Testing and design for test (DFT) can help avoid physical defects
  - Careful design reviews can help to avoid design bugs
  - Training and practice can help to avoid operator error
- Option 2: Fail, but don't corrupt anything
  - Example: ATM should shut down instead of passing out money
- Option 3: Transparently tolerate problems
  - Use hardware and/or software to mask fault effects
  - Key: use redundancy (a.k.a. spares or backups)
  - Example: having a co-pilot on an airplane

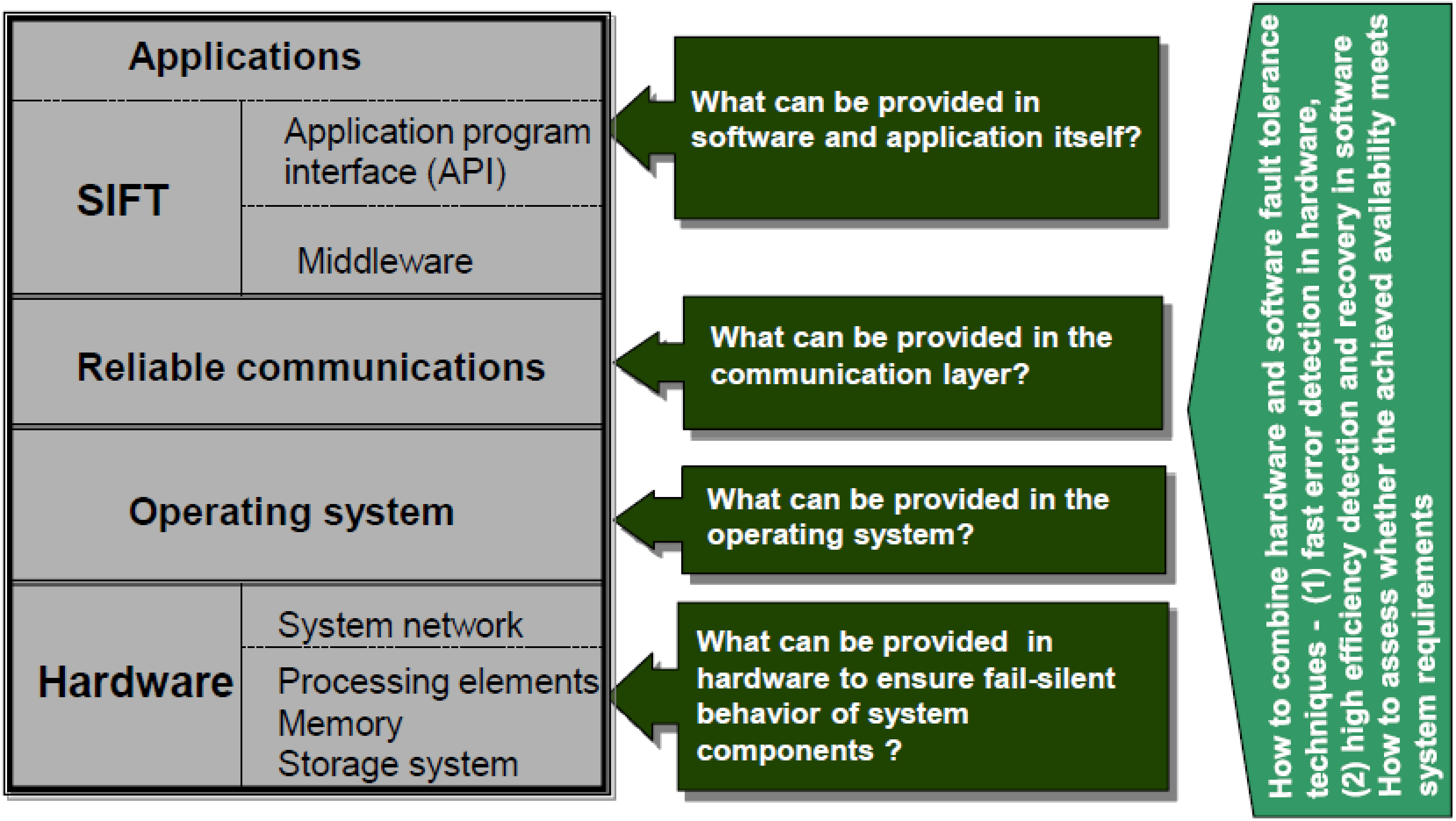
Reliable Computing System

- Correct outputs
  - Desired performance, power consumption
- Changing/varying environmental conditions
  - Power supply, radiation, noise
- Manufacturing process conditions
  - Defects, process variation
- Design errors

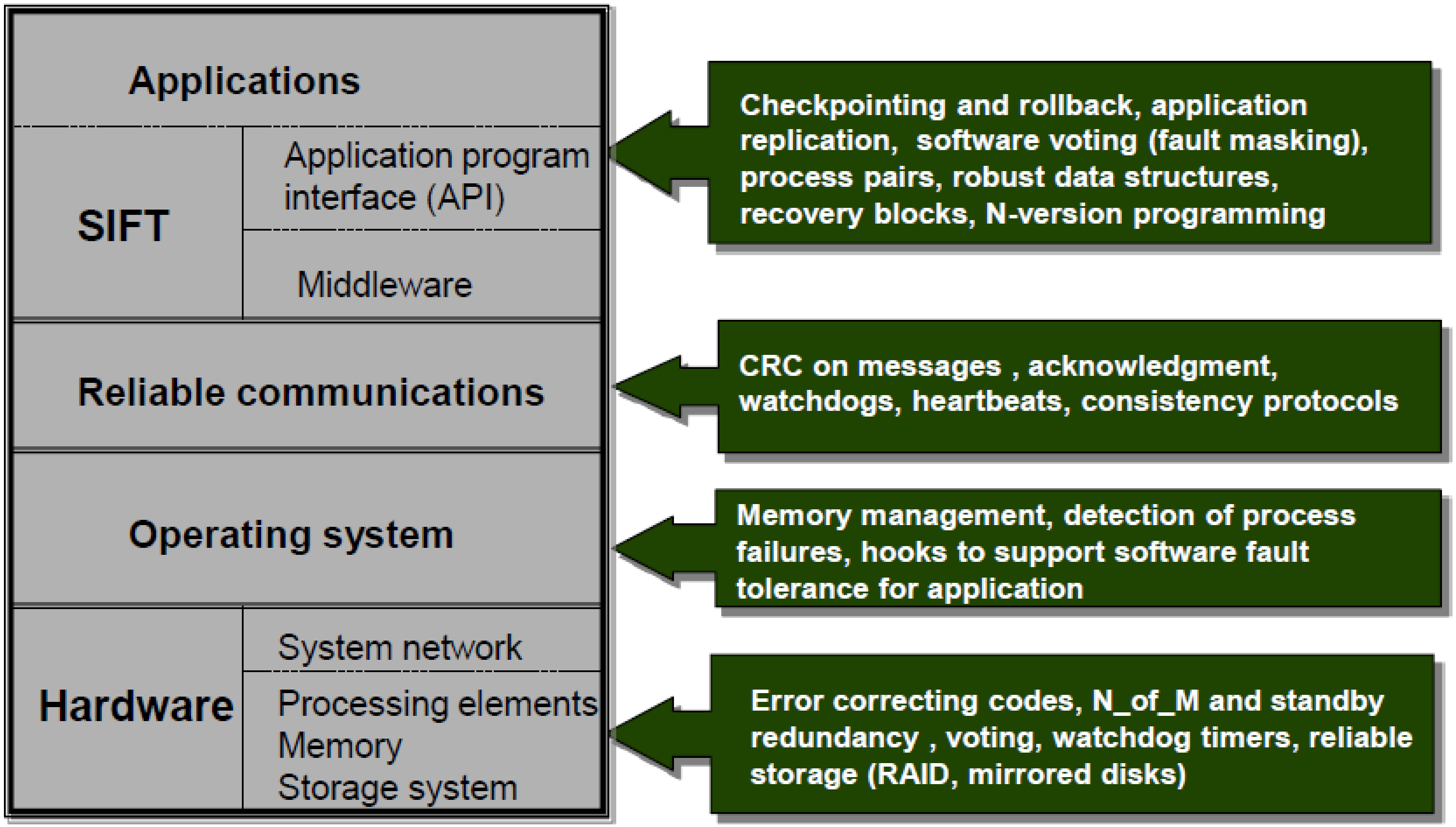
Reliability approaches

- Fault avoidance: eliminate problem sources
  - Remove defects: Testing and debugging
  - Robust design: reduce probability of defects
  - Minimize environmental stress: Radiation shielding etc
  - Impossible to avoid faults completely
    - Occurrence of failures minimized
- Fault tolerance: add redundancy to mask effect
  - Failures during system operation
  - Recovery & repair
  - Examples:
    - Error correction coding
    - Backup storage
    - Spare tire

System View of Dependable Computing

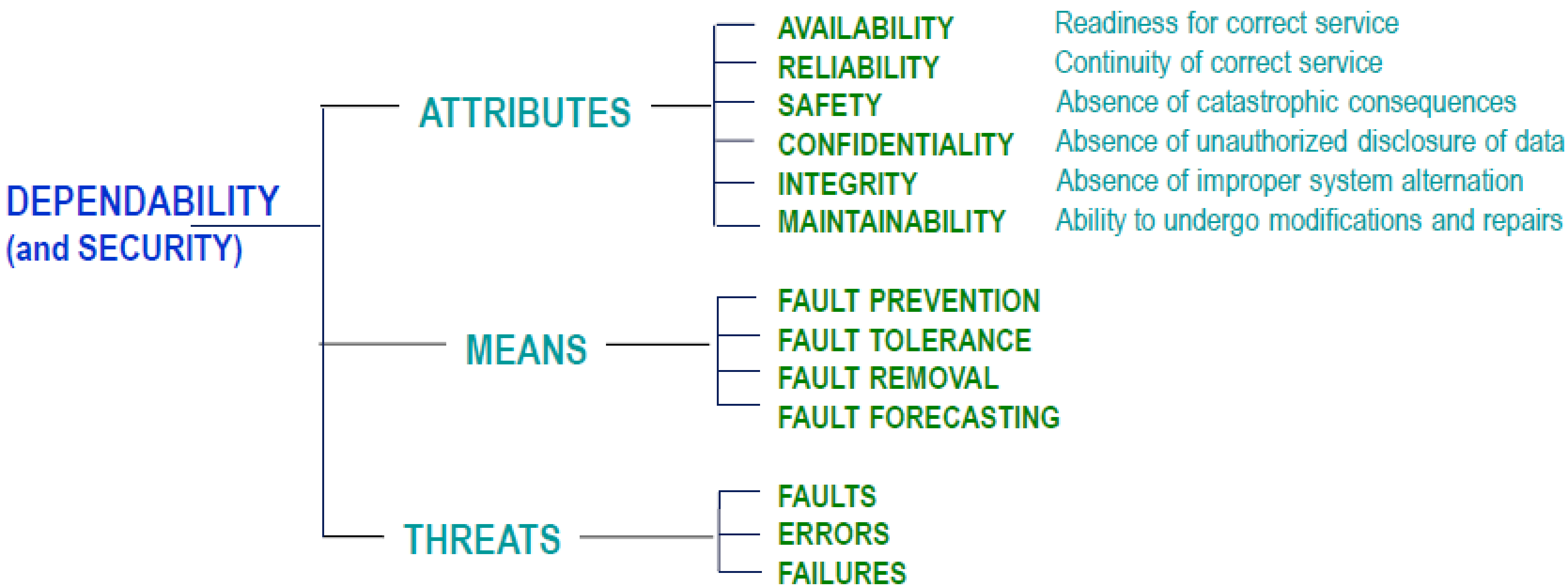


How do We Achieve the Objectives?

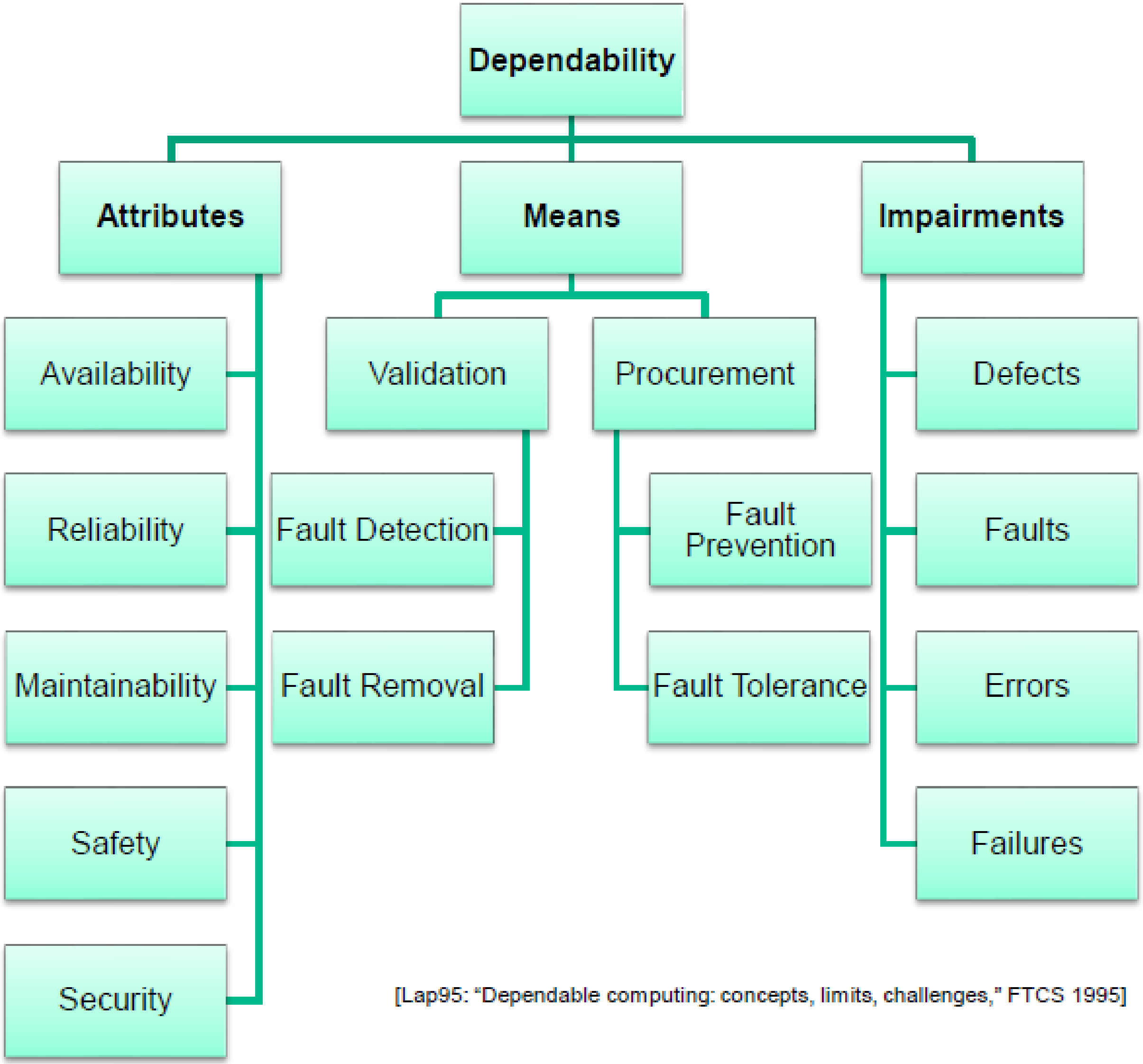


Dependable Computing

- Original definition of dependability (that stresses the need for justification of trust) states that: *the dependability is the ability to deliver service that can justifiably be trusted*
- The alternate definition (that provides the criterion for deciding if the service is dependable) states that: *the dependability of a system is the ability to avoid service failures that are more frequent and more severe than is acceptable*



Dependable Systems



[Lap95: "Dependable computing: concepts, limits, challenges," FTCS 1995]

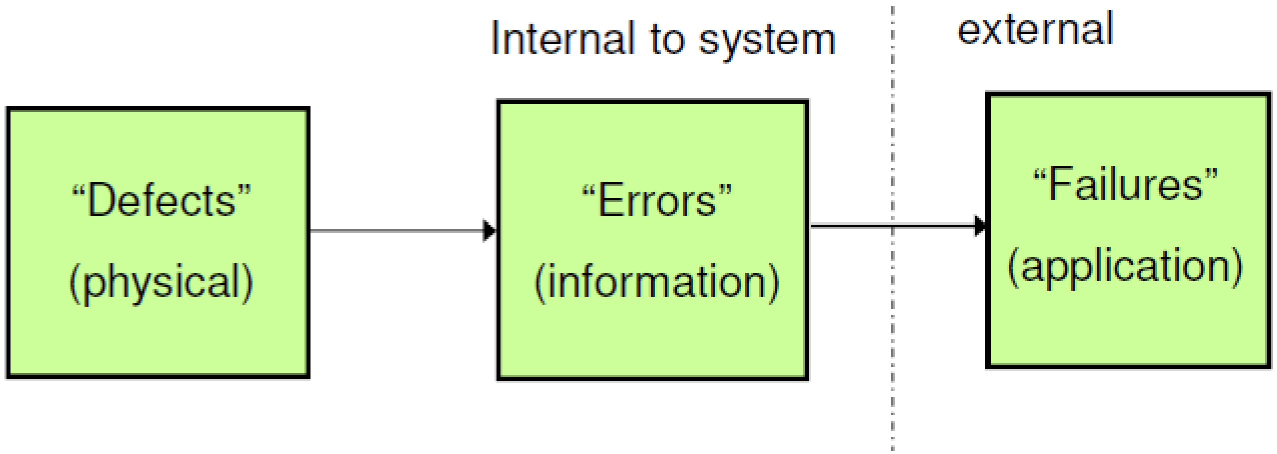
Intuitive Concepts

- Reliability – continues to work
- Availability – works when I need it
- Safety – does not put me in jeopardy
- Performability - combination of reliability & performance
  - "Graceful degradation": loss of performance due to minor failures
- Maintainability - ease of repairing a system after failure
- Testability - ease of detecting presence of a fault
- **Survivability** – will the system survive catastrophic events?

Something is wrong…

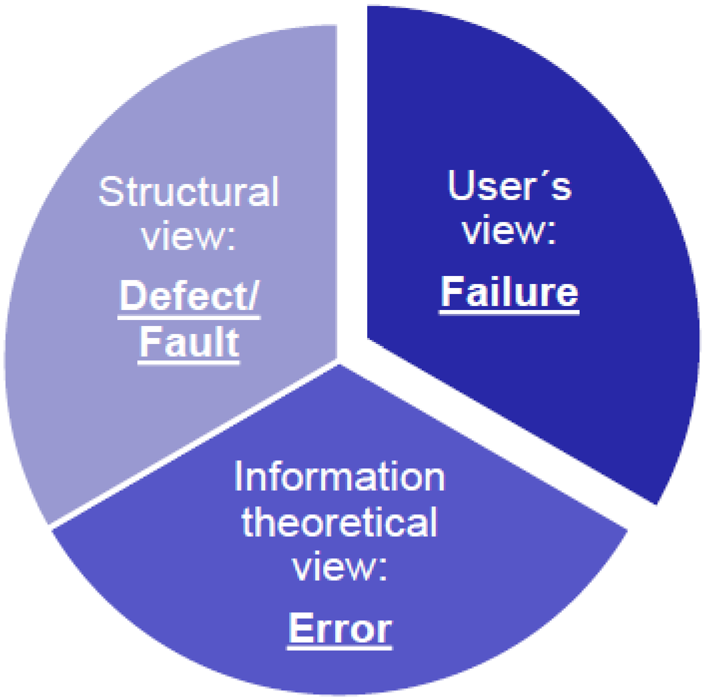
- Defect
  - Distortion of the physical shape
- Fault
  - Logical model of defects
- Error
  - Incorrect signal values/state/information in computation
- Failure
  - Deviation from designed characteristics
  - Observed malfunction during operation
  - Loss of intended function

Something is wrong…



- Latent fault: which has not yet produced error
  - Faulty component will produce error only when used by a process.
- Latent error: which has not yet produced failure.
  - An infected person may not show symptoms of a disease.

Something is wrong…



- **Fault**: abstraction of physical defect or bug to structural level
- **Error**: effect of an physical defect, bug
- **Failure**: malfunction of the system, breakdown

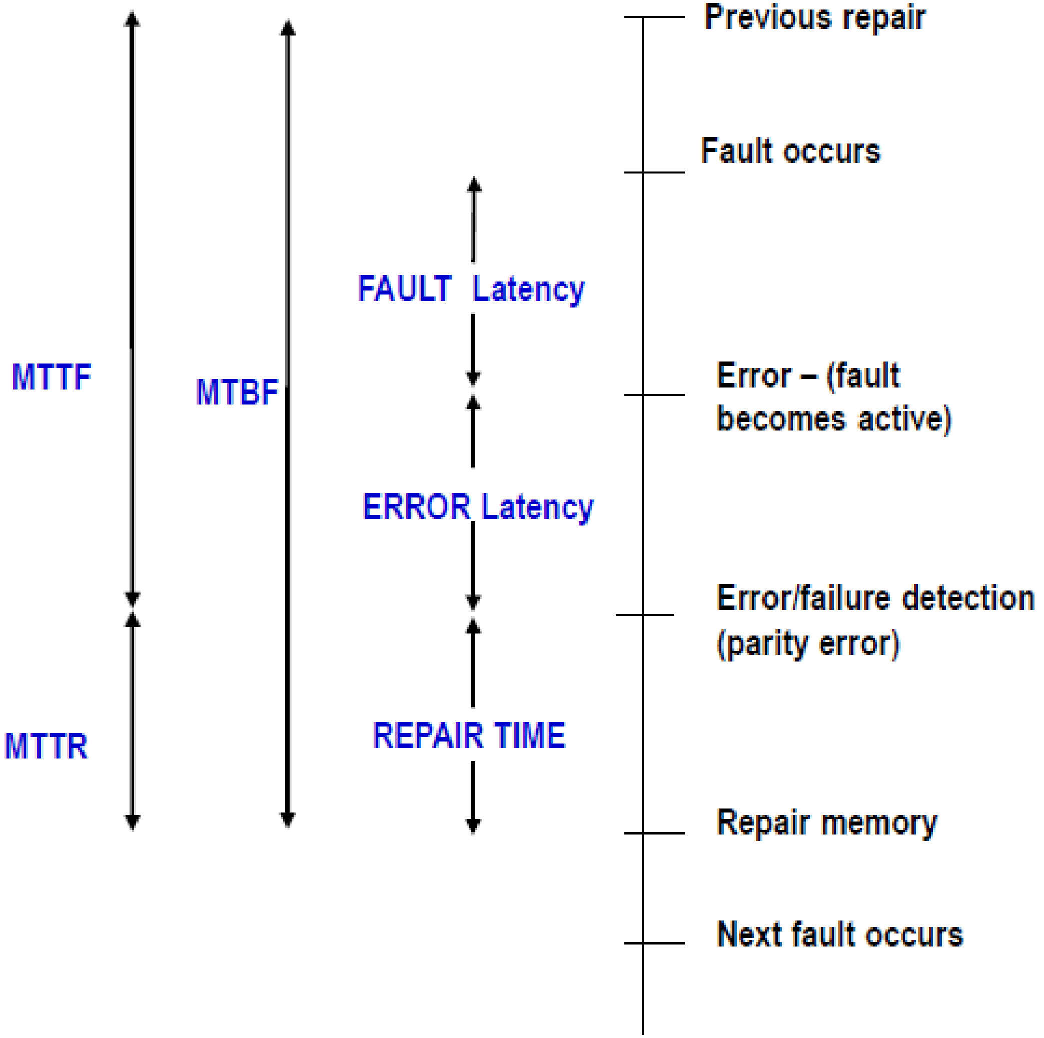
What to do about faults?

- Finding & identifying faults:
  - Fault detection: is a fault there?
  - Fault location: where?
  - Fault diagnosis: which fault it is?
- Automatic handling of faults
  - Fault containment: blocking error flow
    - Fault masking: fault has no effect
  - Fault recovery: back to correct operation

System Response to Faults

- Error on output: may be acceptable in non-critical systems if happens only rarely
- Fault masking: output correct even when fault from a specific class occurs
  - Critical applications: air/space/manufacturing
- Fault-secure: output correct or error indication
  - Retryable: banking, telephony, payroll
- Fail safe: output correct or in safe state
  - Flashing red traffic light, disabled ATM

Fault Cycle & Dependability Measures



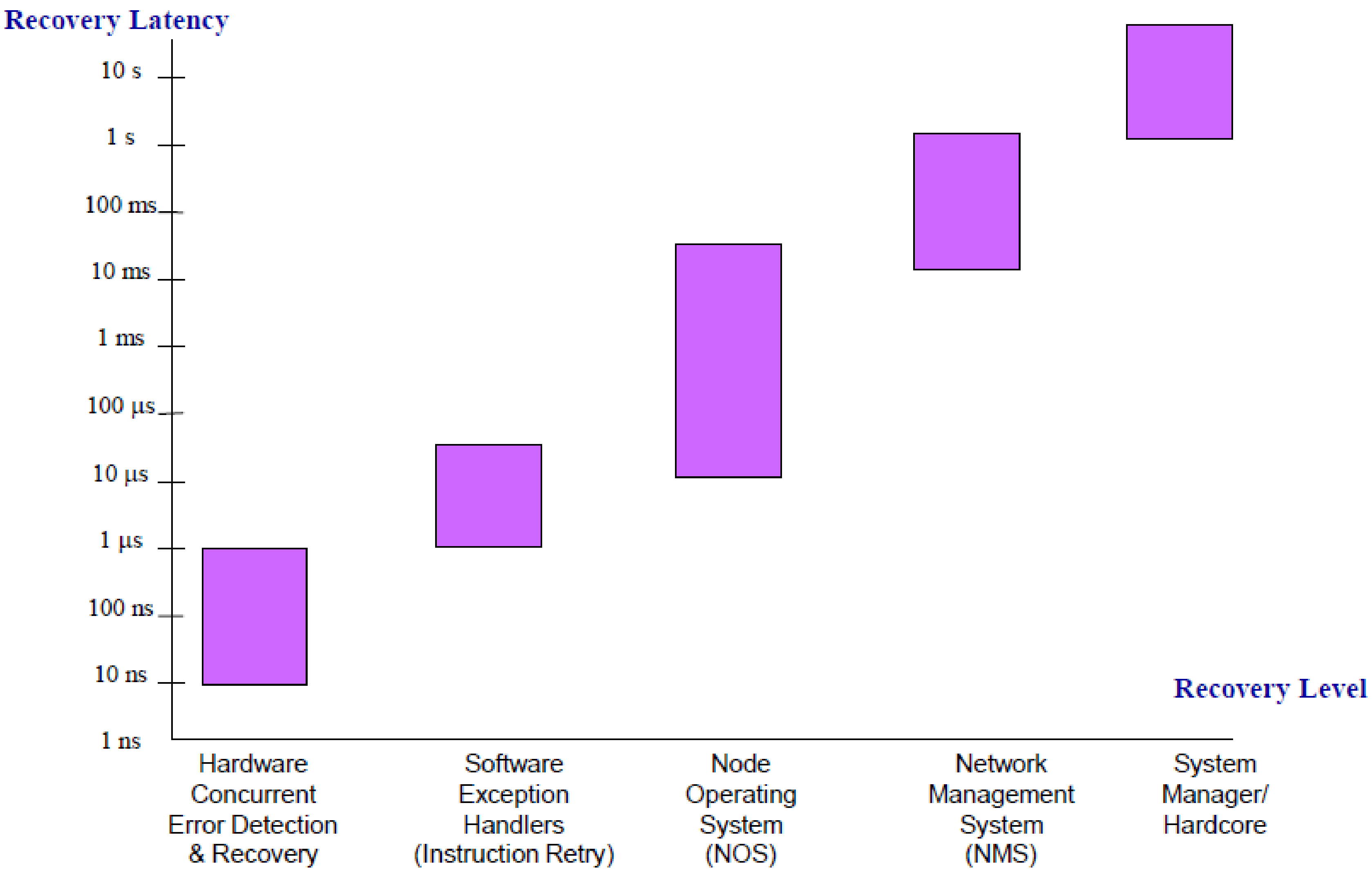
Reliability:
a measure of the continuous delivery of service;
R(t) is the probability that the system survives (does not fail) throughout [0, t];
expected value: ***MTTF(Mean Time To Failure)***

Maintainability:
a measure of the service interruption
M(t) is the probability that the system will be repaired within a time less than t;
expected value: ***MTTR (Mean Time To Repair)***

Availability:
a measure of the service delivery with respect to the alternation of the delivery and interruptions
A(t) is the probability that the system delivers a proper (conforming to specification)service at a given time t.
expected value: ***EA = MTTF / (MTTF + MTTR)***

Safety:
a measure of the time to catastrophic failure
S(t) is the probability that no catastrophic failures occur during [0, t];
expected value:
MTTCF(Mean Time To Catastrophic Failure)

Typical Recovery Latencies for a Hierarchical Fault Tolerant Design



First some probabilities…

- For each random variable X,
  - cumulative distribution function (CDF): $F(x) = P(X \leq x)$
    - Probability P that event X is less than or equal to value of x
  - Probability mass function (PMF): $F(x) = P(X = x)$
  - Probability density function (PDF): $f(x) = \frac{dF}{dx}$
    - Such that in general $P(a \leq x \leq b) = \int_a^b f(x)\,dx$
  - Mean or Expected value: $E[X] = \int_{-\infty}^{+\infty} xf(x)dx$
  - Variance: $\sigma_x^2 = E[(x - E[x])^2]$

Probability of Failure

- Random variable T is time to the next failure
  - Lifetime of a module (time until it fails)
- $F(t) = \text{Prob}\{T \le t\}$
  - Probability that component will fail before or at time t
- $f(t) = \frac{dF(t)}{dt}$, $\int_0^\infty f(t)dt = 1$, $f(t) \geq 0$ (for all $t \geq 0$)
  - The momentary rate of probability of failure at time t
- F and f are related through:
  - $f(t) = \frac{dF(t)}{dt}$ $\quad F(t) = \int_0^t f(s)ds$

Reliability R(t)

- Probability that the system has been operating correctly and continuously from time 0 until time t, given that it was operating correctly at time 0
  - $R(t) = \text{Prob}\ \{T > t\} = 1 - F(t)$
- MTTF: Mean Time To Failure
  - Expected value of the lifetime T

$$MTTF = E[T] = \int_0^{\infty} t \cdot f(t)dt$$

With $\frac{dR(t)}{dt} = -f(t)$ follows:

$$MTTF = -\int_0^{\infty} t \cdot \frac{dR(t)}{dt} \cdot dt = -tR(t)\,\Big|_0^{\infty} + \int_0^{\infty} R(t)dt = \int_0^{\infty} R(t)dt$$

Failure Rate λ

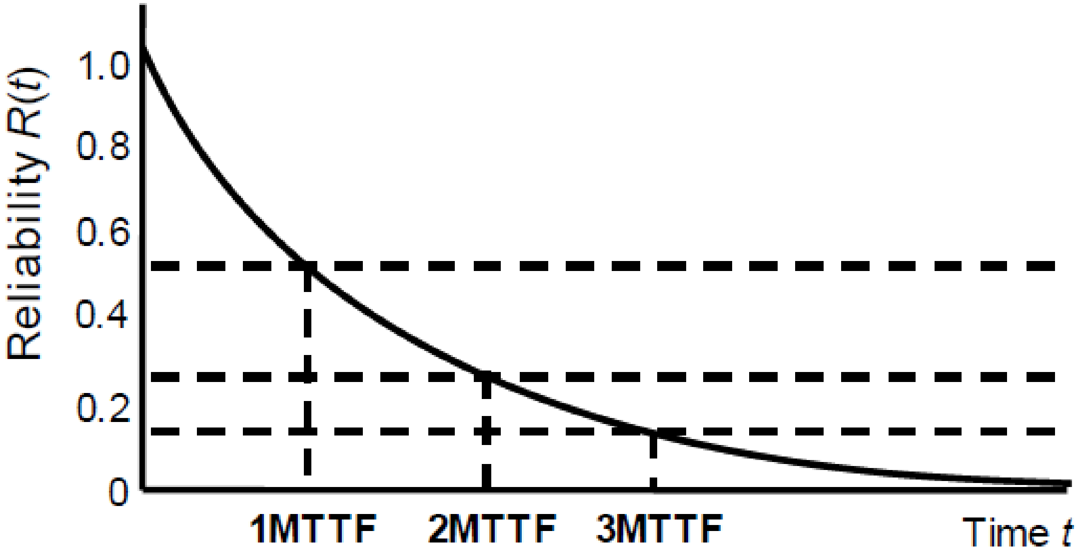
- Number of failures per time unit w.r.t. number of surviving components
  - Also known as hazard function, z(t)
- $\lambda(t) = z(t) = \frac{dF(t)/dt}{(1-F(t))} = \frac{f(t)}{R(t)}$

- A module has a constant failure rate if and only if T has an exponential distribution

$$R(t) = e^{-\lambda t}; F(t) = 1 - e^{-\lambda t}; R(0) = 1$$
$$f(t) = \lambda e^{-\lambda t}$$

Failure Rate $\lambda(t) = \lambda$

$$MTTF = \int_0^\infty t \cdot \lambda e^{-\lambda t} dt = \int_0^\infty e^{-\lambda t} dt = \frac{1}{\lambda}$$

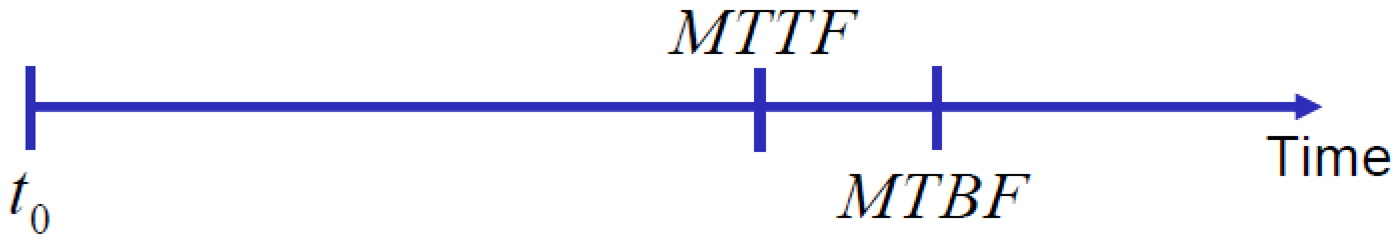


- Reliability $R(t) = e^{-\lambda t}$

Availability

- Availability A(t)
  - Fraction of time system is operational during the interval [0,t]
    - Excludes time for recovery or repair
- MTTR: Mean Time To Repair
- MTBF: Mean Time Between Failures
  - MTBF = MTTF + MTTR

$$A = \frac{E[Uptime]}{E[Uptime] + E[Downtime]} = \frac{MTTF}{MTTF + MTTR} = \frac{MTTF}{MTBF}$$



Other failure distribution models

- Weibull distribution
  - α : shape parameter
    - $\alpha < 1$: failure rate decreasing with time
    - $\alpha = 1$: failure rate constant
    - $\alpha > 1$: failure rate increasing with time
  - λ : scale parameter
  - PDF = $f(t) = \alpha\lambda(\lambda t)^{\alpha-1}e^{-(\lambda t)^{\alpha}}$
  - CDF = $F(t) = 1 - e^{-(\lambda t)^{\alpha}}$
  - Reliability = $R(t) = e^{-(\lambda t)^{\alpha}}$

Other failure distribution models

- Geometric distribution
  - Discrete times 0, 1, 2, …
    - Replacing $e^{-\lambda}$ by discrete probability q
    - Replacing t by n
  - PMF = $\mathrm{f(n) = q^{n} - q^{n+1} = q^{n}(1-q)}$
  - CDF = $\mathrm{F(n) = 1 - q^{n}}$
  - Reliability = $\mathrm{R(n) = q^{n}}$
  - $\mu = \frac{1}{1-q}$, $\sigma = \frac{q^{1/2}}{1-q}$
- Discrete Weibull distribution

Maintainability

- MTTR may be subdivided as follows
  - Time needed to detect a fault and isolate the responsible components (diagnosis)
  - Time needed to replace the faulty component
  - Time needed to verify that the fault has been removed and the system is fully operational
- Design for maintainability
  - System design which supports efficient fault detection, isolation and repair

Performability

- *Accomplishment levels* $L1$, $L2$,...,Ln defined in the application context
  - Representing a level of *quality of service* delivered by the application
  - *E.g.: Li* indicates *i* system crashes during mission time
- Performability is a vector ($P(L1)$,$P(L2)$,...,$P(Ln)$)
  - $P(Li)$: Probability that the system performs well enough that the application reaches level Li