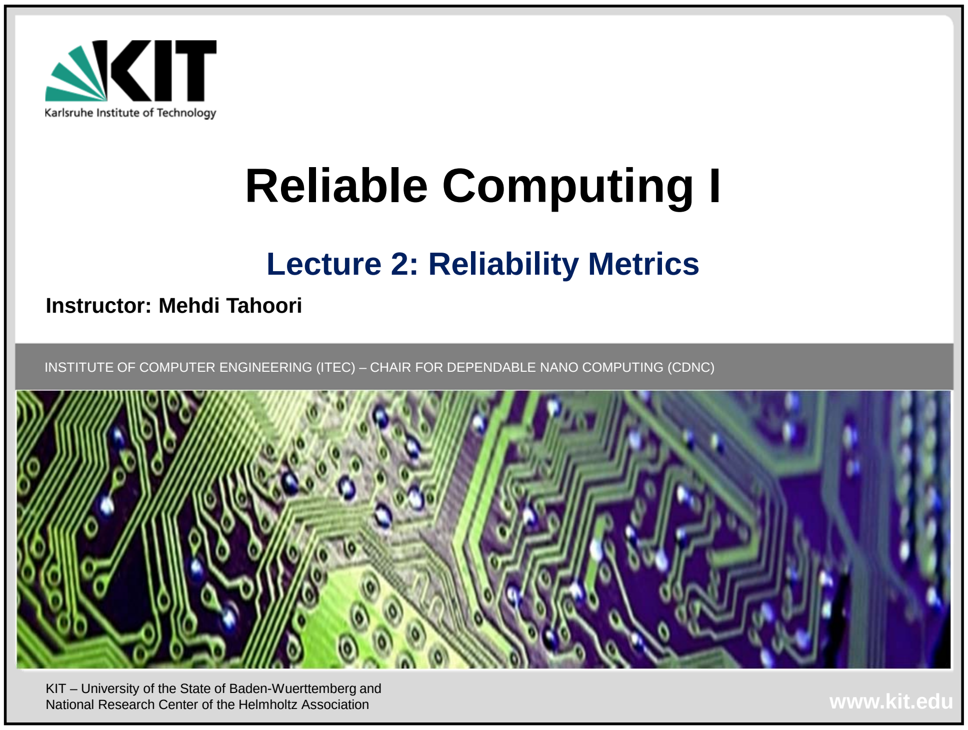

Karlsruhe Institute of Technology

Reliable Computing I

Lecture 2: Reliability Metrics

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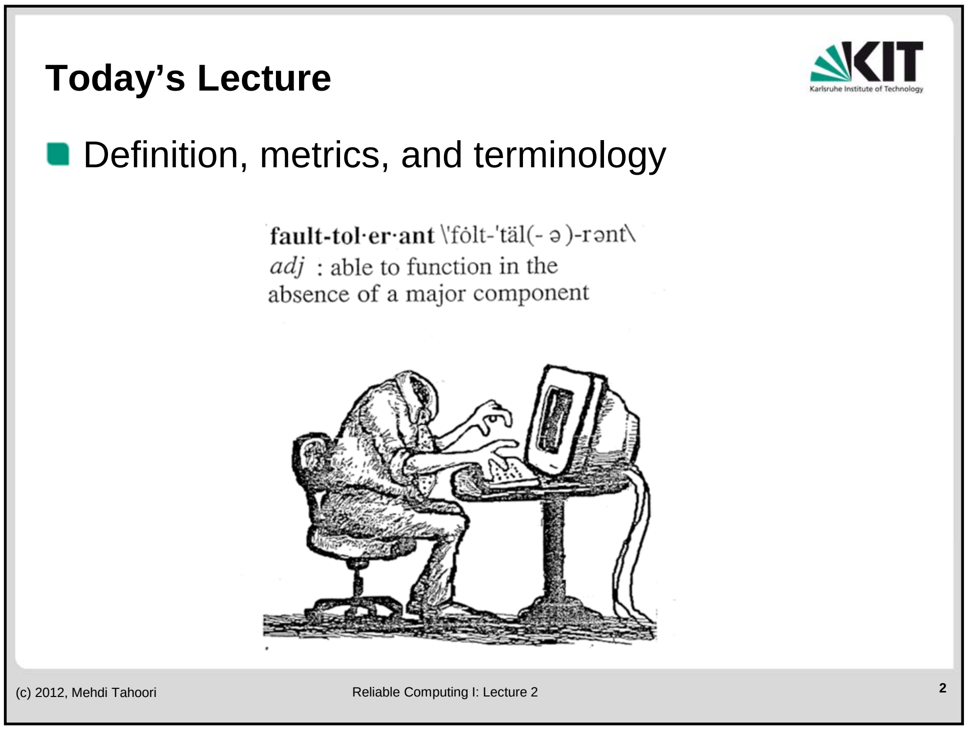

Today's Lecture

- Definition, metrics, and terminology

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

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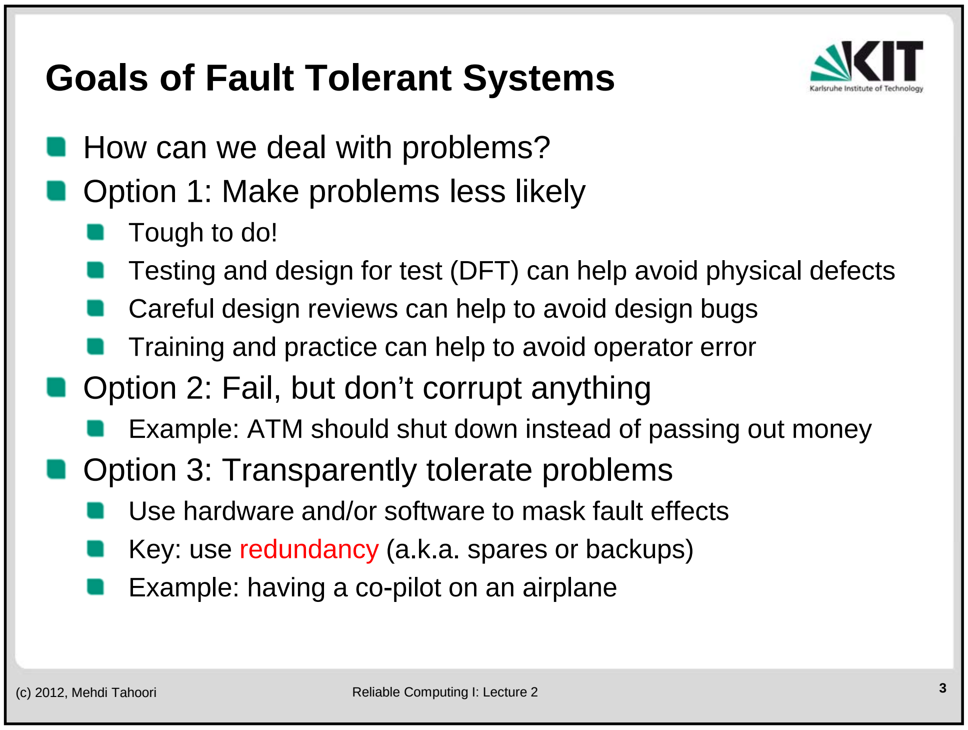
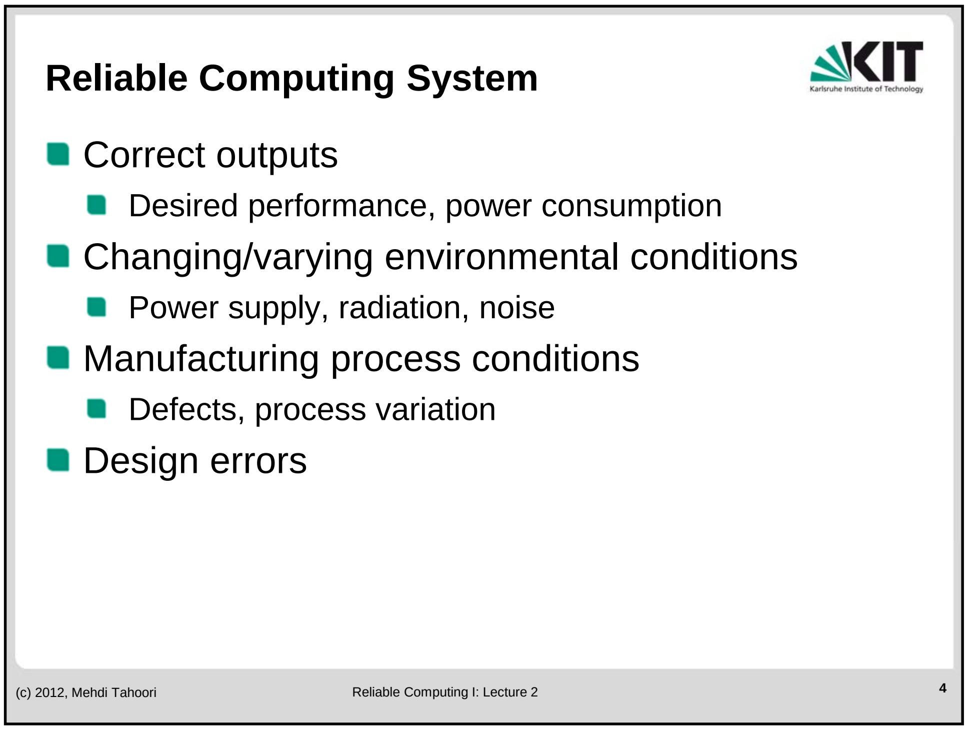


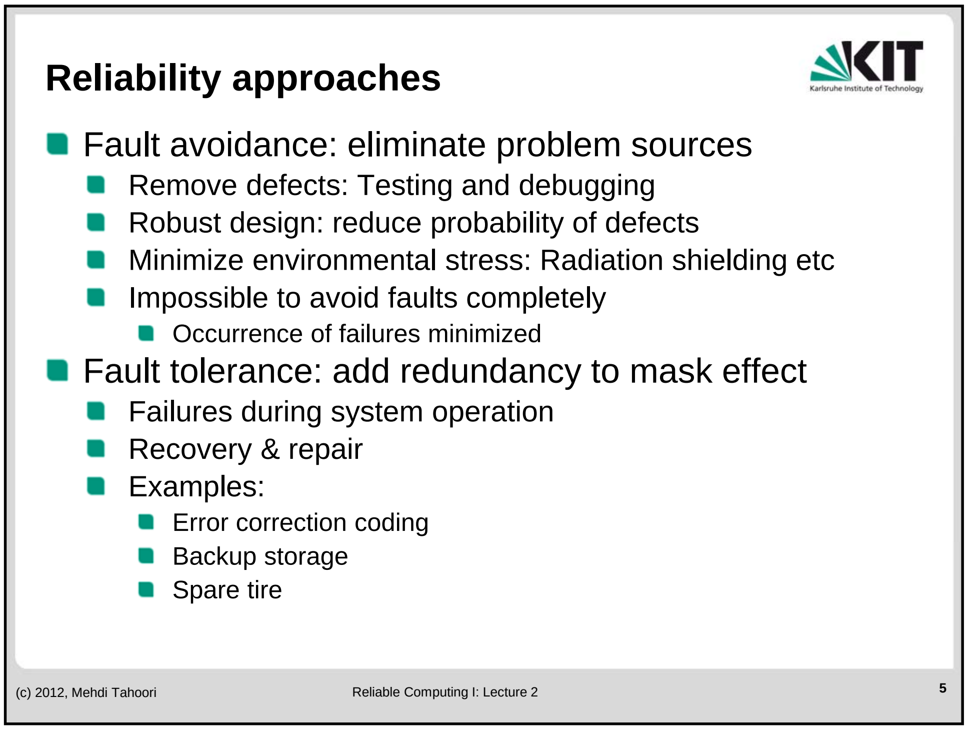
Goals of Fault Tolerant Systems

- 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

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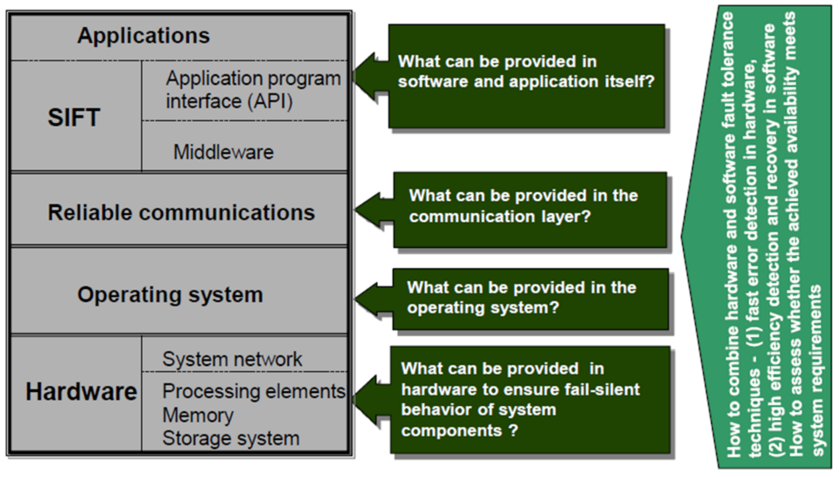
System View of Dependable Computing



What can be provided in software and application itself?

What can be provided in the communication layer?

What can be provided in the operating system?

What can be provided in hardware to ensure fail-silent behavior of system components ?

How to combine hardware and software fault tolerance techniques - (1) fast error detection in hardware, (2) high efficiency detection and recovery in software How to assess whether the achieved availability meets system requirements

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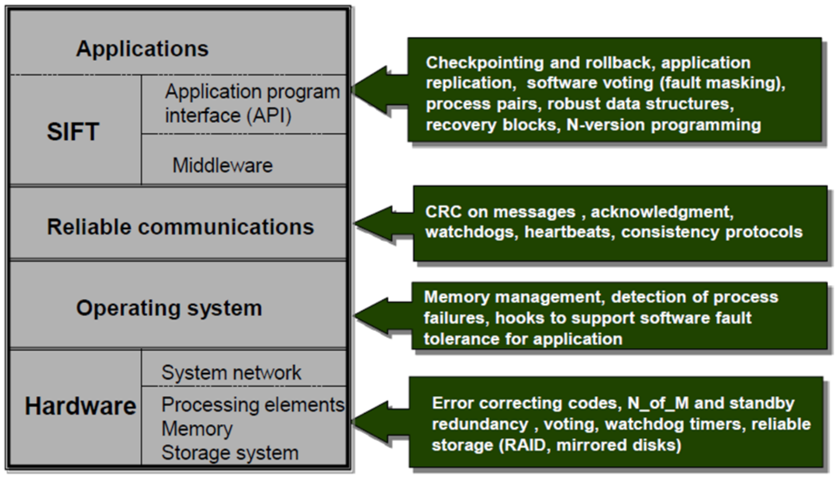
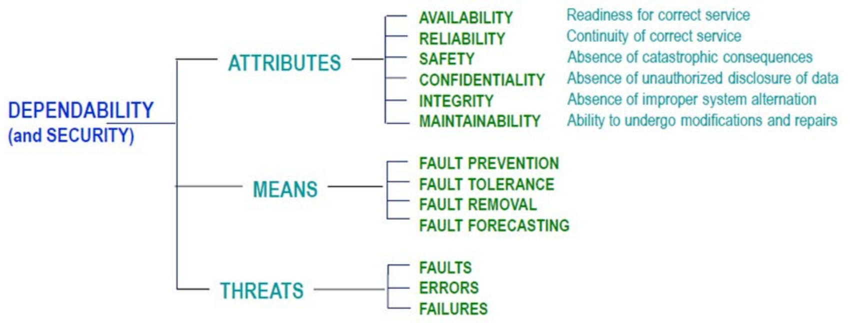
How do We Achieve the Objectives?

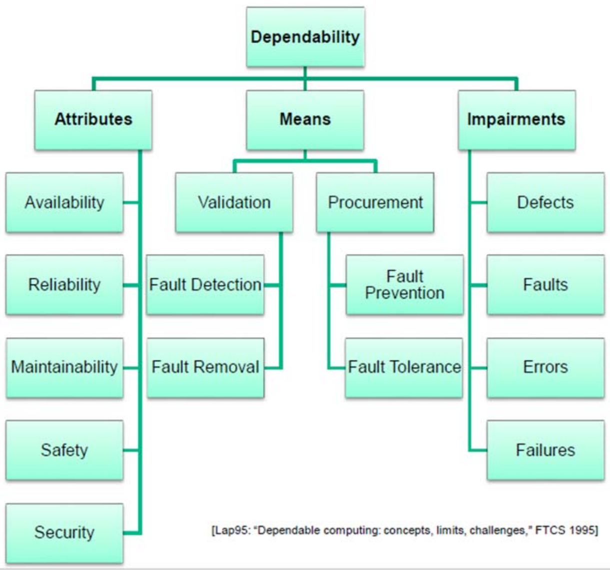

Applications
SIFT
Application program interface (API)
Middleware
Reliable communications
Operating system
Hardware
System network
Processing elements
Memory
Storage system
Checkpointing and rollback, application replication, software voting (fault masking), process pairs, robust data structures, recovery blocks, N-version programming
CRC on messages , acknowledgment, watchdogs, heartbeats, consistency protocols
Memory management, detection of process failures, hooks to support software fault tolerance for application
Error correcting codes, N_of_M and standby redundancy , voting, watchdog timers, reliable storage (RAID, mirrored disks)

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*


DEPENDABILITY
(and SECURITY)
ATTRIBUTES
AVAILABILITY
RELIABILITY
SAFETY
CONFIDENTIALITY
INTEGRITY
MAINTAINABILITY
Readiness for correct service
Continuity of correct service
Absence of catastrophic consequences
Absence of unauthorized disclosure of data
Absence of improper system alternation
Ability to undergo modifications and repairs
MEANS
FAULT PREVENTION
FAULT TOLERANCE
FAULT REMOVAL
FAULT FORECASTING
THREATS
FAULTS
ERRORS
FAILURES

Dependable Systems



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

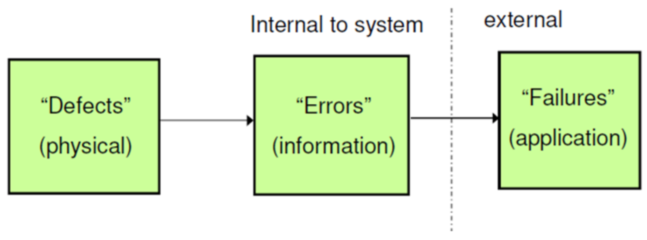
Intuitive Concepts

- 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?

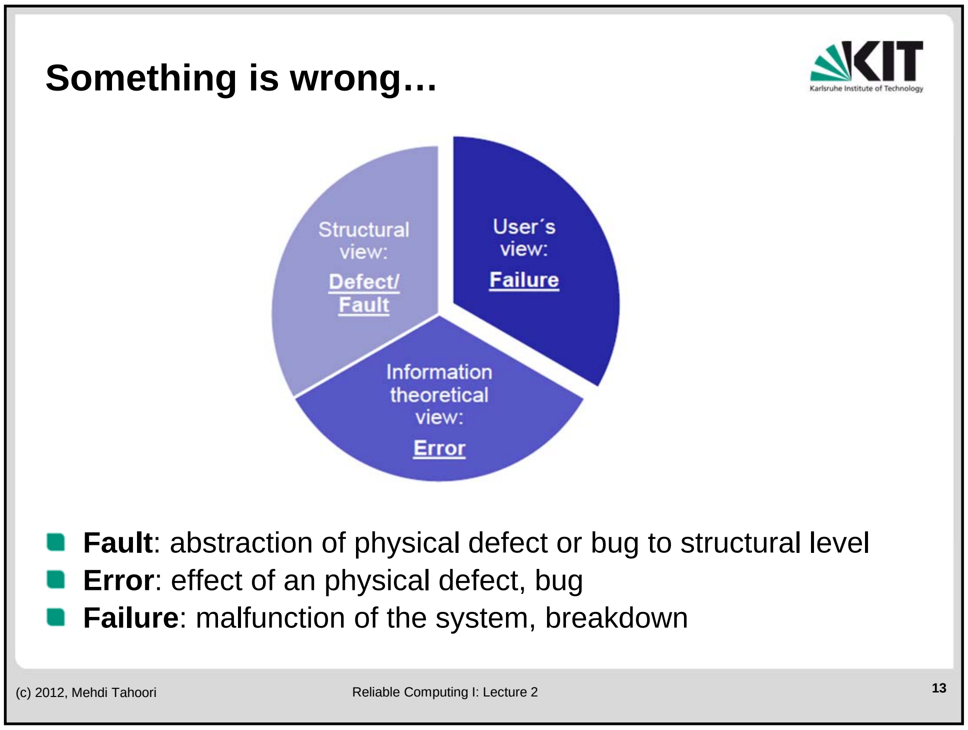
Something is wrong…

- 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

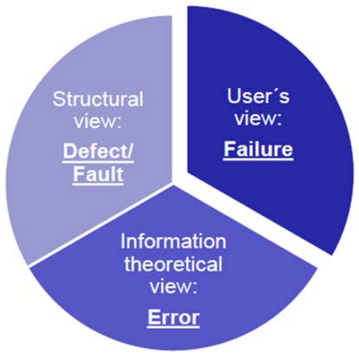
Something is wrong…



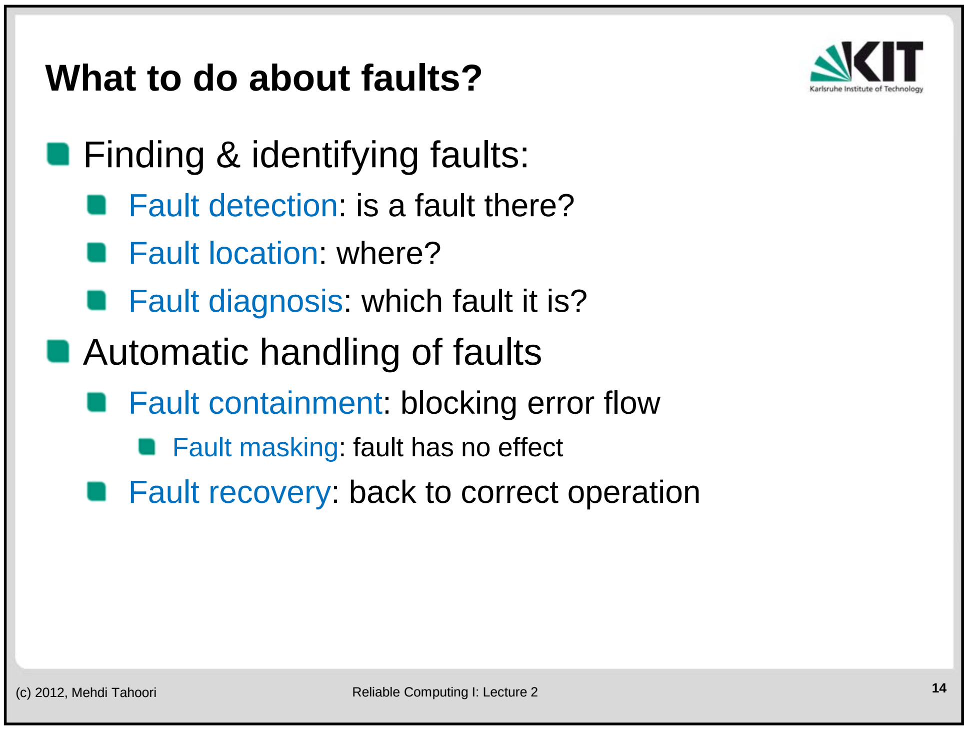
- Latent fault: which has not yet produced error
  - Faulty component will produce error only when used by a process.
- Latent error: which has not yet produced failure.
  - An infected person may not show symptoms of a disease.



Something is wrong…

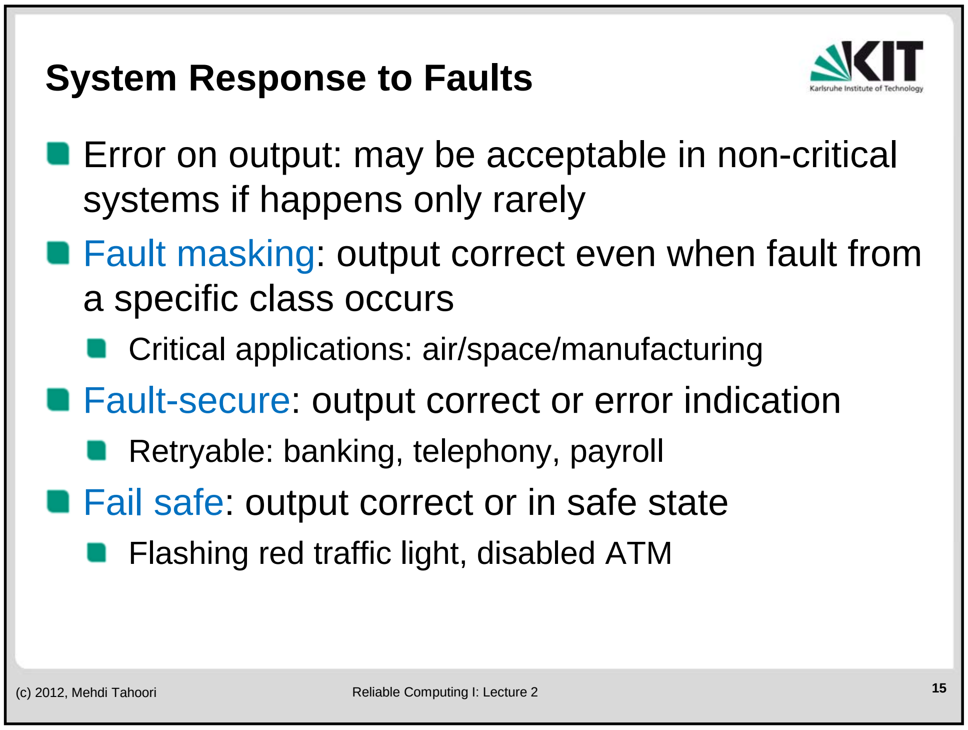


- **Fault**: abstraction of physical defect or bug to structural level
- **Error**: effect of an physical defect, bug
- **Failure**: malfunction of the system, breakdown



What to do about faults?

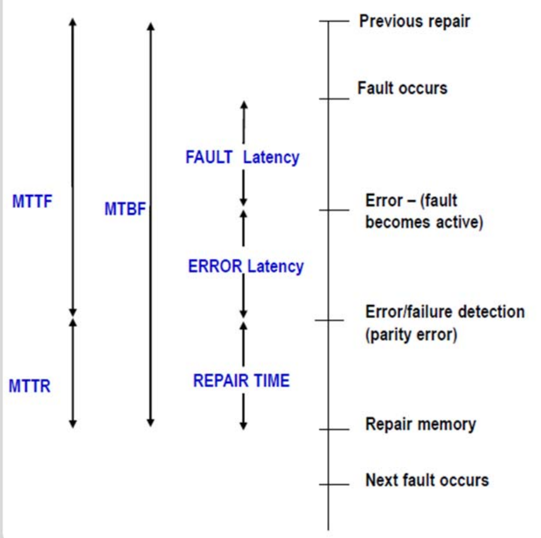
- Finding & identifying faults:
  - Fault detection: is a fault there?
  - Fault location: where?
  - Fault diagnosis: which fault it is?
- Automatic handling of faults
  - Fault containment: blocking error flow
    - Fault masking: fault has no effect
  - Fault recovery: back to correct operation



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



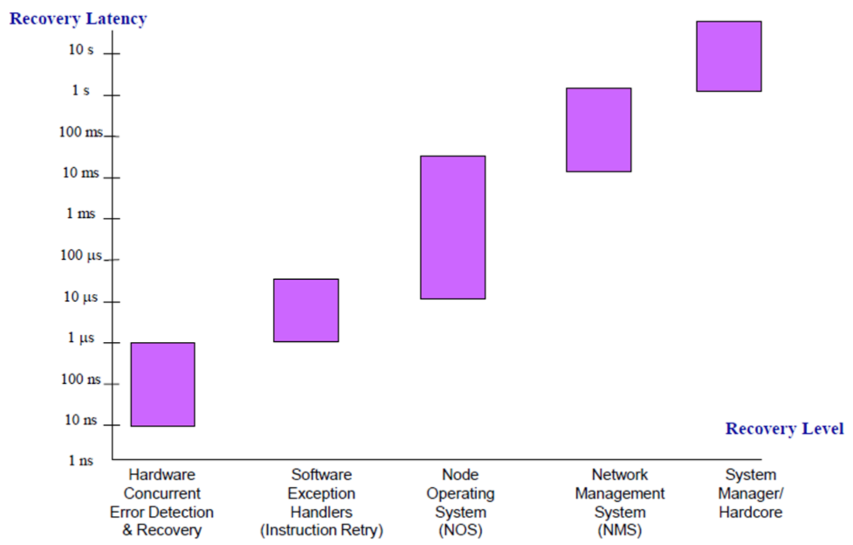
Reliability:
a measure of the continuous delivery of service;
R(t) is the probability that the system survives (does not fail) throughout [0, t];
expected value: *MTTF(Mean Time To Failure)*

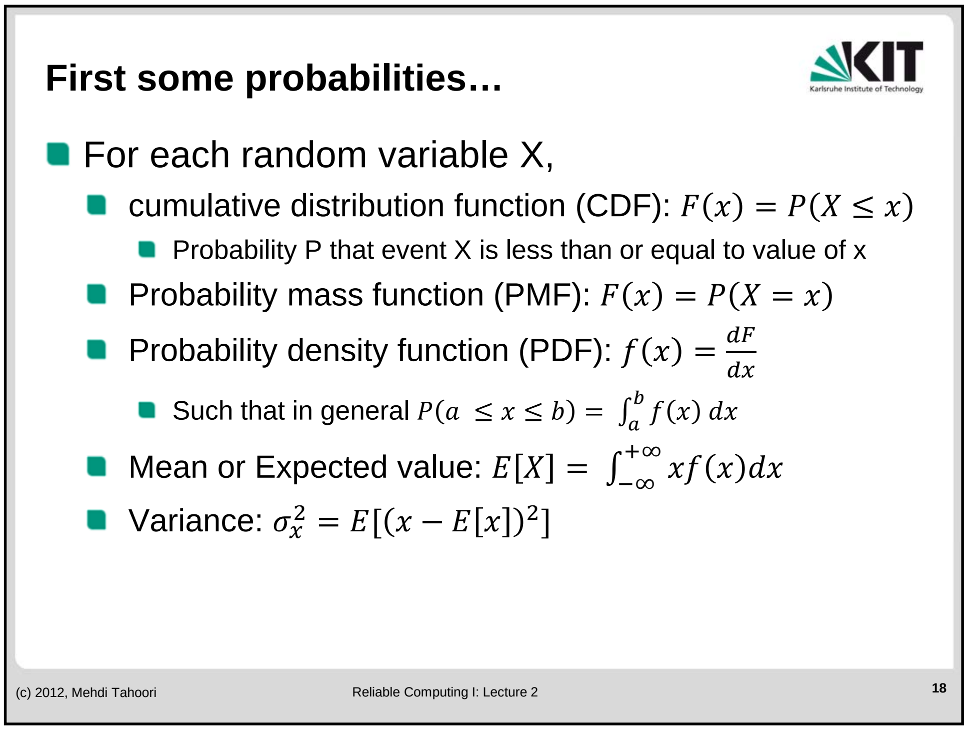
Maintainability:
a measure of the service interruption
M(t) is the probability that the system will be repaired within a time less than t;
expected value: *MTTR (Mean Time To Repair)*

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)

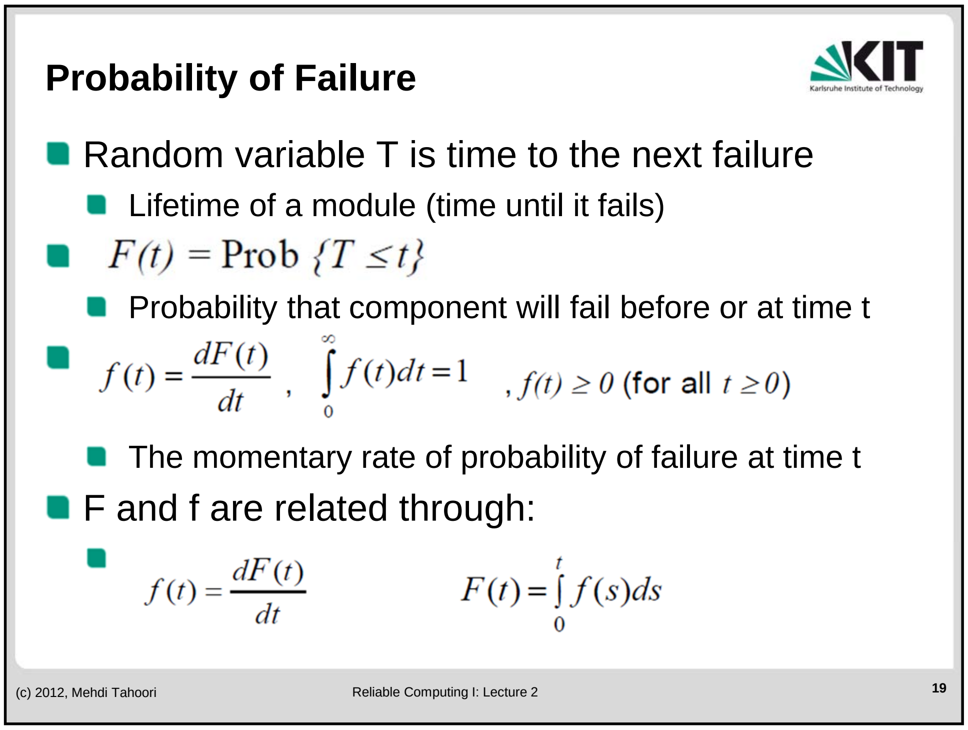
Typical Recovery Latencies for a Hierarchical Fault Tolerant Design





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: $E[X] = \int_{-\infty}^{+\infty} x f(x) dx$
  - 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
- $f(t) = \dfrac{dF(t)}{dt}$, $\int_0^\infty f(t)dt = 1$, $f(t) \ge 0$ (for all $t \ge 0$)
  - The momentary rate of probability of failure at time t
- F and f are related through:
  - $f(t) = \dfrac{dF(t)}{dt}$ $\qquad F(t) = \int_0^t f(s)ds$

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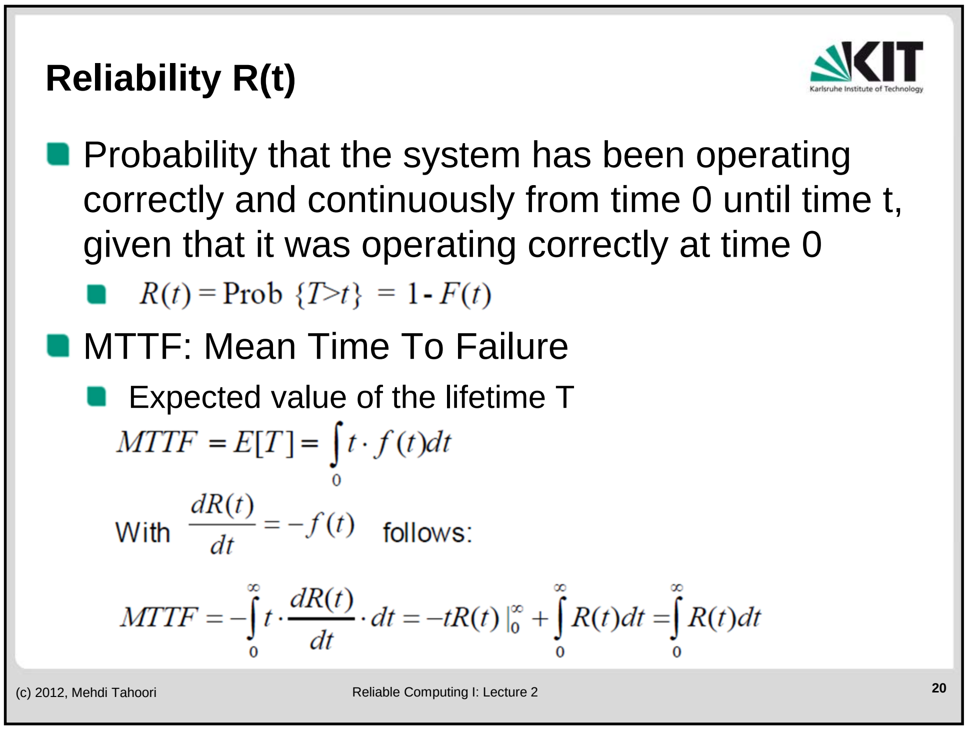

Reliability R(t)

- 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

$$MTTF = E[T] = \int_0 t \cdot f(t)dt$$

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

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

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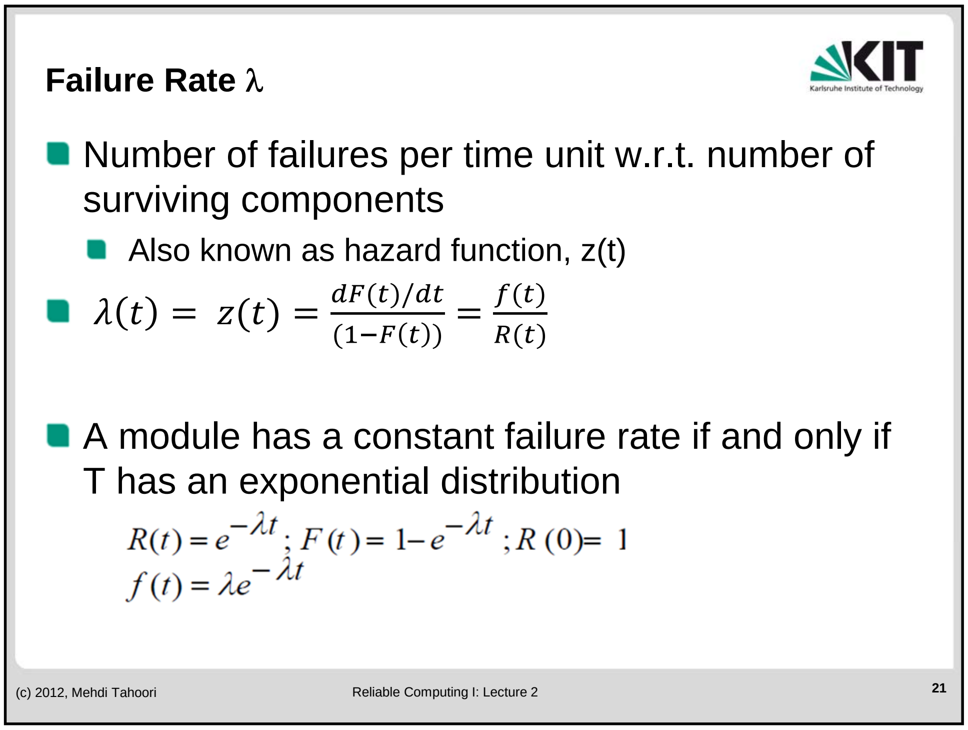
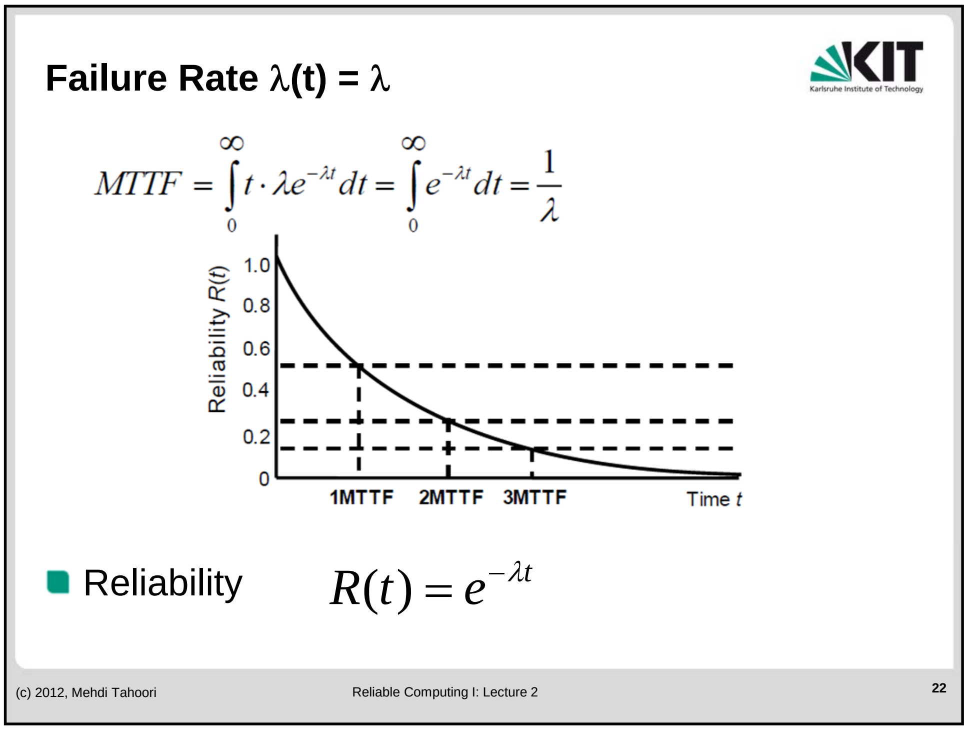


Failure Rate λ

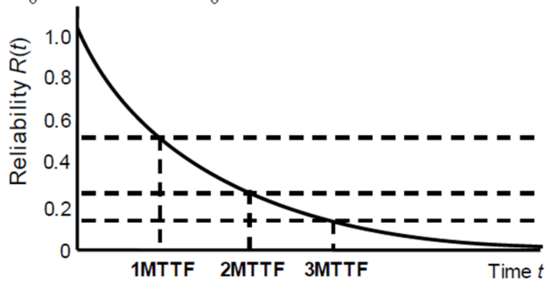
- Number of failures per time unit w.r.t. number of surviving components
  - Also known as hazard function, z(t)
- $\lambda(t) = z(t) = \frac{dF(t)/dt}{(1-F(t))} = \frac{f(t)}{R(t)}$
- A module has a constant failure rate if and only if T has an exponential distribution

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

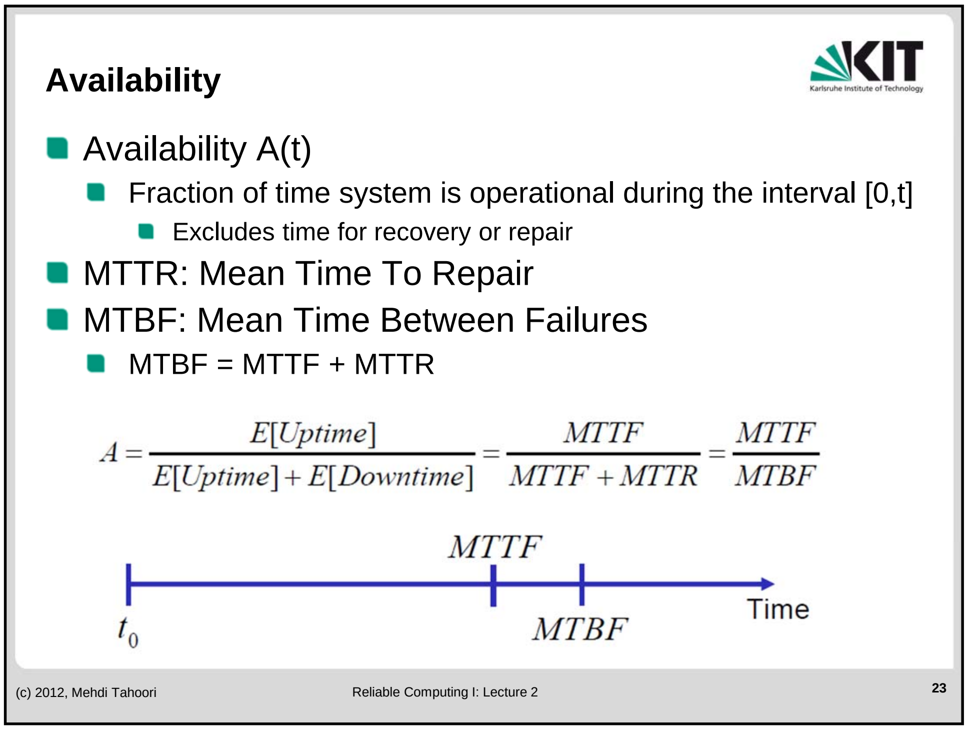


Failure Rate λ(t) = λ

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



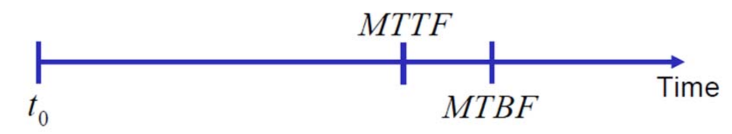
- Reliability $R(t) = e^{-\lambda t}$



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

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



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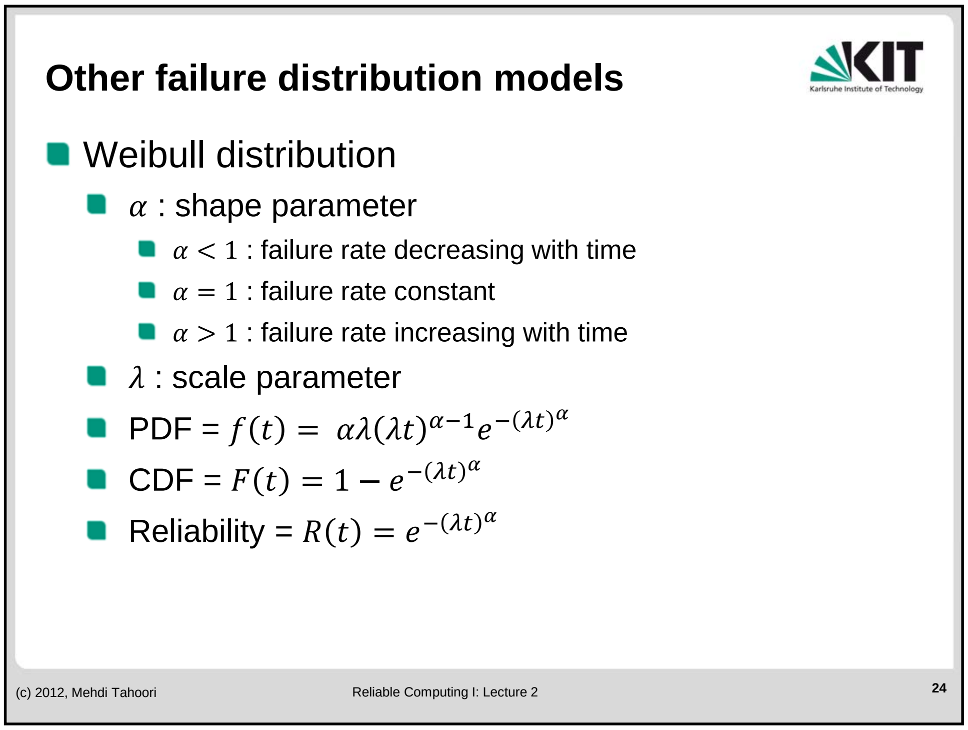

Other failure distribution models

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

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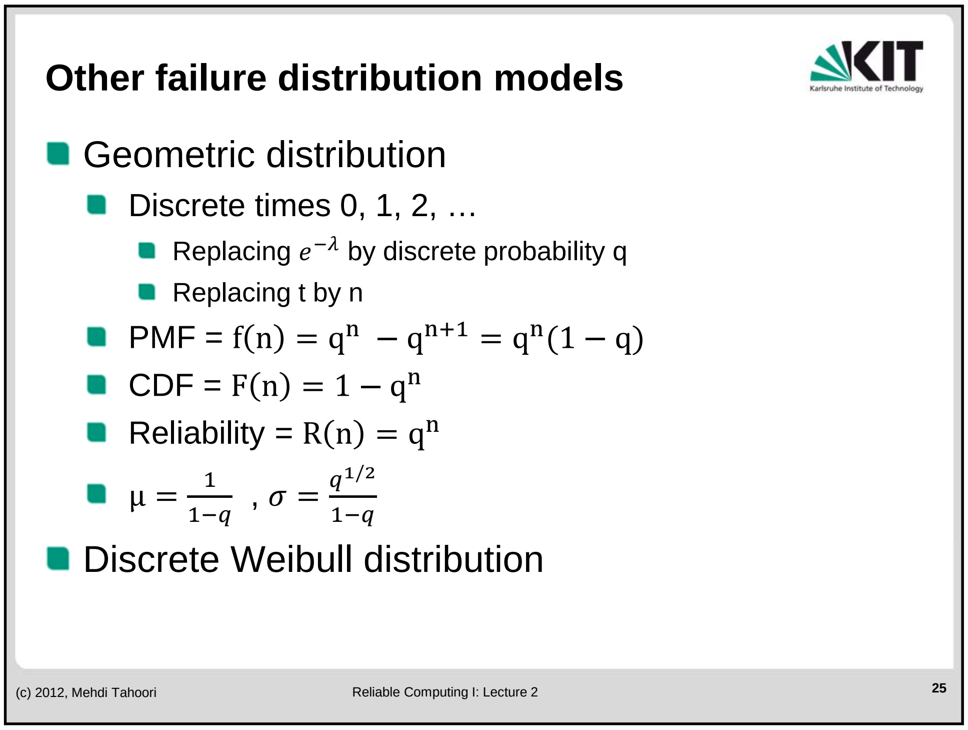

Other failure distribution models

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

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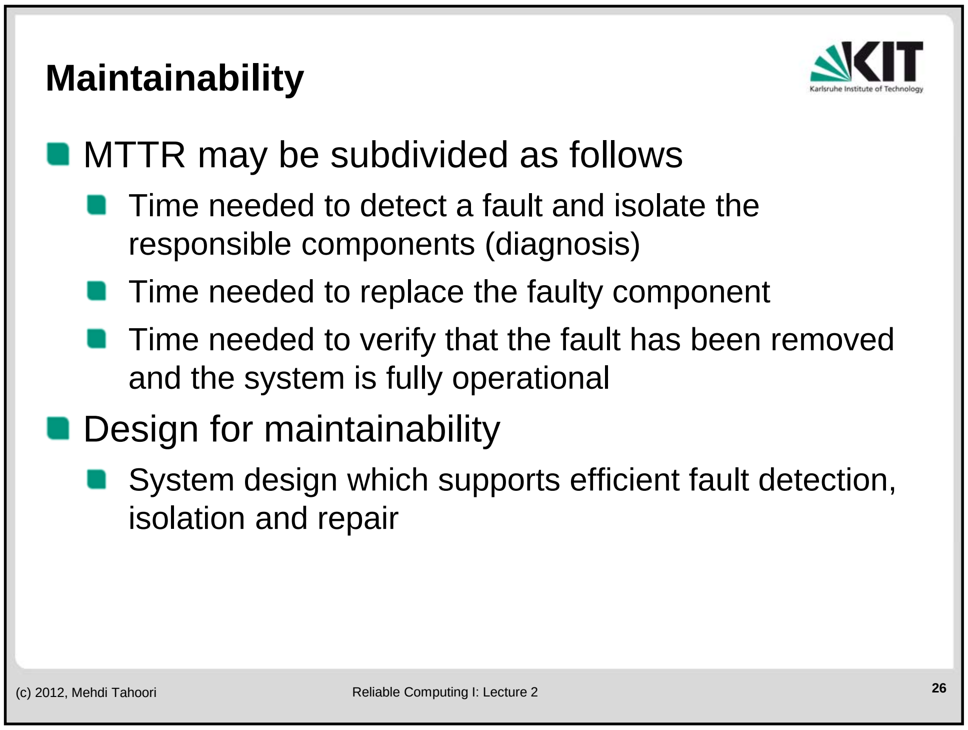

Maintainability

- 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

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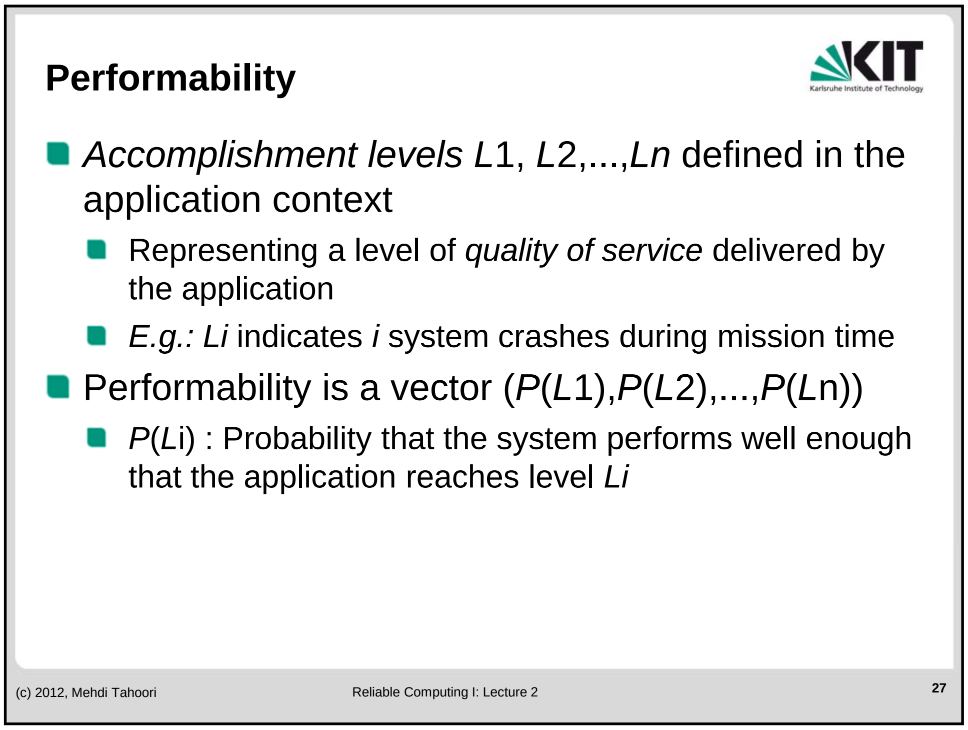

Performability

- *Accomplishment levels L*1, *L*2,...,*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*(*L*1),*P*(*L*2),...,*P*(*L*n))
  - *P*(*L*i) : Probability that the system performs well enough that the application reaches level *Li*

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