Fault Tolerance

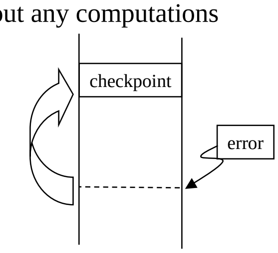
- Real-time computing systems must be *fault-tolerant*: they must be able to continue operating despite the failure of a limited subset of their hardware or software.
- They must also allow *graceful degradation:* as the size of the faulty set increases, the system must not suddenly collapse but continue executing part of its workload.

- Faults → errors → failures
  - A *fault* is a physical defect, imperfection or flaw that occurs within some hardware or software component. A fault can be caused by specification mistakes, implementation mistakes, component defects or external disturbance (environmental effects).
  - An *error* is the manifestation of a fault.
  - If the error results in the system performing its function(s) incorrectly, then a system *failure* occurs.

Dealing with Faults

- *Fault avoidance* aims at preventing the occurrence of faults at the first place: design reviews, component screening, testing.
- *Fault Tolerance* is the ability of a system to continue to perform its tasks after the occurrence of faults
  - *Fault Masking*: preventing faults from introducing errors
  - *Reconfiguration:* Fault detection, location, containment and recovery

- *forward-error recovery:* the error is masked without any computations having to be re-done.
- *backward-error recovery:* periodically take *checkpoints* to save a correct computation state. When error is detected, roll back to a previous checkpoint, restore the correct state and resume execution.



Reliability and availability

- *The reliability at time t, R(t),* is the conditional probability that the system performs correctly during the period [*0,t*], given that the system was performing correctly at time *0*.
- The *unreliability, F(t),* is equal to *1 – R(t).* Often referred to as *the probability of failure*.
- *The availability at time t, A(t)* is the probability that a system is operating correctly and is available to perform its functions at time *t*. Unlike reliability, the availability is defined at an instant of time.
- The system may incur failures but can be repaired promptly, leading to high availability.
- A system may have very low reliability, but very high availability!

Types of faults

- A *permanent* fault remains in existence indefinitely if no corrective action is taken.
- A *transient* fault disappears within a short period of time
- An *intermittent* fault may appear and disappear repeatedly.

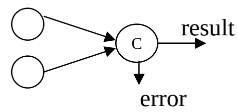
Types of Redundancy

- *Hardware Redundancy:* Based on physical replication of hardware.
- *Software Redundancy:* The system is provided with different software versions of tasks, preferably written independently by different teams.
- *Time Redundancy:* Based on multiple executions on the same hardware in different times.
- *Information Redundancy:* Based on coding data in such a way that a certain number of bit errors can be detected and/or corrected.

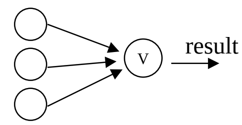
Redundant systems

- *Sparing:* Can have spares (hot or cold spares) and use a spare after a permanent fault is detected in the primary hardware.

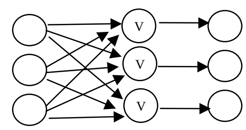
- *Duplex systems:* can detect a fault by executing twice (on separate hardware on sequentially on the same hardware) and compare the results.



- *Triple modular redundancy (TMR):* can mask an error by executing three times and taking a majority vote (may use more than one voter).



- *N modular redundancy (NMR):* can mask an error by executing *N* times and taking a majority vote. How many faults can be tolerated?



Fault-tolerant software

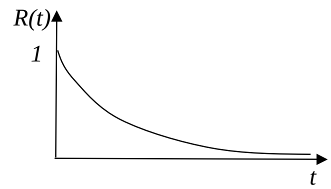
- *Consistency checks:* a software acceptance test to detect wrong results.
- *N-version programming*: Prepare N different versions and run them (in parallel or sequentially). The *voting* at the end will select the output of the majority.
- Sources of common-mode failures:
  - Ambiguities in the specification
  - Choice of the programming language
  - Choice of numerical algorithms
  - Common background of the software developers
- *Recovery block approach:*
  - Each job/task has a primary version and one or more alternatives.
  - when primary version is completed, an *acceptance test* is performed.
  - If the acceptance test fails, an alternative version can be invoked.

Mean time to failure (FTTF)

- Let *R(t)* be the reliability of a system and *F(t) = 1 - R(t).*
- *F(t)* is the probability that the system is not functioning correctly at time *t. Hence,* $\frac{dF(t)}{dt} = -\frac{dR(t)}{dt}$ is the probability that the system fails exactly at time *t (failure density function).*
- The average time to failure is

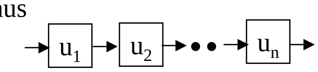
$$MTTF = \int_0^\infty t \frac{dF(t)}{dt} dt = -\int_0^\infty \frac{dR(t)}{dt} dt = [-tR(t)]_0^\infty + \int_0^\infty R(t)dt = \int_0^\infty R(t)dt$$

- Example: if *R(t) =* $e^{-\lambda t}$, then
  - MTTF = $1 / \lambda$,
  - λ is the failure rate.

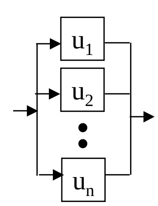


Combinatorial calculation of the reliability

- For n units connected in series, the system is functioning if all the units are functioning, thus the reliability of the system is
  $R(t) = R_1(t)\, R_2(t) \ldots R_n(t)$



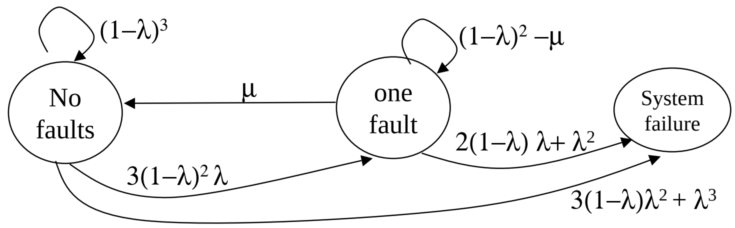
- For n units connected in parallel, the system is functioning if at least one unit is functioning, thus
  $1 - R(t) = (1 - R_1(t))\,(1 - R_2(t)) \ldots (1 - R_n(t))$,
  and the system reliability is
  $R(t) = 1 - (1 - R_1(t))\,(1 - R_2(t)) \ldots (1 - R_n(t))$



- Example: Reliability of a TMR system is
  $(3R_{unit}^2(1 - R_{unit}) + R_{unit}^3)R_{voter}$

Markov processes

- Is a process that can be represented by states and probabilistic state transitions, such that the probability of moving from a state s_i to another state s_j , does not depend on the way the process reached state s_i.
- Example: a TMR system with unit MTTF = $1/\lambda$, and mean time to repair equal to = $1/\mu$.



- Note that the failure state is an absorbing state.
- For discrete time processes, one transition occurs in every time unit.

Discrete Markov processes

- A Markov process with *n* states can be represented by an *nxn* probability matrix $A = [a_{i,j}]$, where $a_{i,j}$ is the probability of moving from state *i* to state *j* in one time unit.
- The sum of the elements in each row of *A* is equal to 1.
- If $p(t) = [p_i(t)]$ is a vector such that $p_i(t)$ is the probabilities of being in state *i* at time *t*, then, $p(t+k) = B^k\, p(t)$, where *B* is the transpose of *A*.
- Can use *the first step analysis* to find
  - the average number of transitions before absorption, and
  - the average time of being in a certain state.

Average # of transitions before absorption

- Consider an n state Markov process in which state n is an absorption state, and let v_i be the average number of steps to absorption if we start at state i.
- Hence, for every $i=1, \dots , n-1$ we have

$$v_i = a_{i,1} (1+v_1) + \dots + a_{i,n-1} (1+v_{n-1}) + a_{i,n}$$

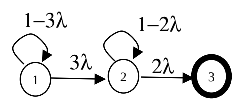
- Solve the above $n-1$ equations and find the values of $v_1 , \dots , v_{n-1}$
- Given an initial probability distribution $p(0)$, the average time to absorption is $p_1 v_1 + \dots + p_{n-1} v_{n-1} + 0 . p_n$

- Example: The TMR system without repair ($\mu = 0$) and ignoring λ^2 terms

$v_1 = (1-3\lambda) (v_1 +1) + 3\lambda (v_2 +1)$

$v_2 = (1-2\lambda) (v_2 +1) + 2\lambda$

Which gives $v_2 = 1 / 2\lambda$ and $v_1 = 5 / 6\lambda$



Another example of the first step analysis

- Consider an $n+2$ state Markov process in which states $n+1$ and $n+2$ are absorption states, we want to find out what is the probability that the process will end up in state $n+2$ (as opposed to $n+1$).
- Let u_i be the probability that the process will eventually end up in state $n+2$ assuming that the process starts at state i.
- Hence, for every $i=1, \dots , n$ we have

$$u_i = a_{i,1} u_1 + \dots + a_{i,n} u_n + a_{i,n+2}$$

- Solve the above n equations and find the values of $u_1 , \dots , u_n$
- Given an initial probability distribution $p(0)$, the probability of absorption to state $n+2$ is $p_1 u_1 + \dots + p_n u_n$
- Example: The TMR system with a voter and voter failure rate λ_v

$u_1 = (1 - 3\lambda - \lambda_v) u_1 + 3\lambda u_2 + \lambda_v$

$u_2 = (1 - 2\lambda - \lambda_v) u_2 + \lambda_v$

Which gives $u_1 = \lambda_v (5\lambda + \lambda_v) / (2\lambda + \lambda_v) (3\lambda + \lambda_v)$