IAF0530 (MSc)
IAF9530 (PhD)

Dependability and fault tolerance

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Course Format

- Grading
  - Case Study: 60%
    - Presentation: 30%
    - Written report: 70%
  - Active participation: 10%
  - Oral exam: 30%
- Presentation:
  - 20 min for MSc students
  - 30 min for PhD students
- Written report:
  - IEEE standard two-column template
    - 6 pages for MSc students
    - 10 pages for PhD students

Lecture Outline

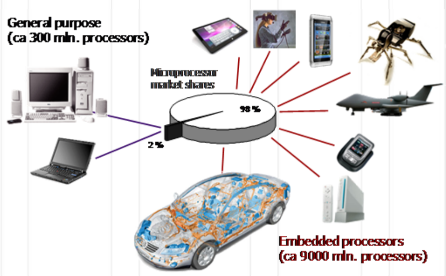
✓ **Historical perspective and famous incidents/accidents**

- **Basic terminology**

Embedded Systems

- Computing systems are everywhere
- Most of us think of "desktop" computers
  - PC's
  - Laptops
  - Mainframes
  - Servers
- But there's another type of computing system
  - Far more common...

General-Purpose vs. Embedded



Embedded Systems, cont.

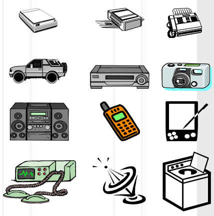
- Embedded computing systems
  - Computing systems embedded within electronic devices
  - Hard to define. Nearly any computing system other than a desktop computer
  - Billions of units produced yearly, versus millions of desktop units
  - Perhaps 50 per household and per automobile
  - „Internet of things"
  - SmartX (buildings, homes, communities, ...)

A "Short List" of Embedded Systems

Anti-lock brakes
Auto-focus cameras
Automatic teller machin
Automatic
transmission
vionic systems
Battery charger
Cam
Cell
Cell-phone base stations
Cordless phones
side check-in systems
Digital cameras
Disk drives
El readers
Electronic instruments
Electronic toys/ga
Fa
Fa
Fingerprint identifiers
Home security
Life-sup
Medical testing systems

Modems
MP
ds
Network switches/routers
On-board navi n
Pa
otocopiers
Point-of-sale systems
Portable vi
ellite phones
Scanners
Smart ers
ecognizers
Stereo systems
Teleconferencing ems
T
Temperature controllers
Theft tracking systems
TV set-top s
players
Video game consoles
Video phones
Washers and dryers

Ambient Intelligence
Medical Systems
Telecommunications
Transport systems
Security & Military
Entertainment



Our ~~daily~~ lives depend on embedded systems

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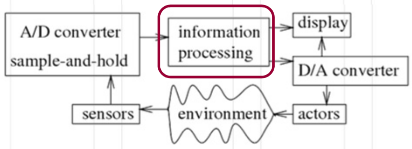
What is an Embedded System?

- Definition
  - an **embedded system** special-purpose computer system, part of a larger system which it controls.
- Notes
  - A computer is used in such devices primarily as a means to simplify the system design and to provide flexibility.
  - Often the user of the device is not even aware that a computer is present.



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Characteristics of Embedded Systems

- Single-functioned
  - Dedicated to perform a single function
- Complex functionality

Many new challenges that all have effect on dependability

At the same time all these devices are around us, maybe even inside us

  - environment
  - Must compute certain results in real-time without delay
- Safety-critical
  - Must not endanger human life and the environment

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Real-Time Systems

- **Time**
  - The correctness of the system behavior depends not only on the logical results of the computations, but also on the *time* at which these results are produced.
- **Real**
  - The reaction to the outside events must occur *during* their evolution. The system time must be measured using the same time scale used for measuring the time in the controlled environment.

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Hard vs. Soft Real-Time

- Definitions
  - A real-time task is said to be **hard** if missing its deadline may cause catastrophic consequences on the environment under control.
  - A real-time task is said to be **soft** if meeting its deadline is desirable for performance reasons, but missing its deadline does not cause serious damage to the environment and does not jeopardize correct system behaviour.
- Definition
  - A real-time system that is able to handle hard real-time tasks is called a **hard real-time system**.

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Hard vs. soft, cont.

- Examples of hard activities
  - Sensory data acquisition
  - Detection of critical conditions
  - Actuator serving
  - Low-level control of critical system components
  - Planning sensory-motor actions that tightly interact with the environment
- Examples of soft activities
  - The command interpreter of the user interface
  - Handling input data from the keyboard
  - Displaying messages on the screen
  - Representation of system state variables
  - Graphical activities
  - Saving report data

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Functional vs. Non-Functional Requirements

- Functional requirements
  - output as a function of input
- Non-functional requirements:
  - Time required to compute output
  - Reliability, availability, integrity, maintainability, dependability
  - Size, weight, power consumption, etc.

Fault Tolerance

- A fault-tolerant system is one that can continue to correctly perform its specified tasks in the presence of failures:
  - hardware
  - software
  - user errors
  - environmental, input, ...
- Fault tolerance is the attribute that enables a system to achieve fault tolerant operation.

Basic Concepts

- *Fault Tolerance* is closely related to the notion of "Dependability". This is characterized under a number of headings:
  - *Reliability* – the system can run continuously without failure.
  - *Availability* – the system is ready to be used immediately.
  - *Maintainability* – when a system fails, it can be repaired easily and quickly (and, sometimes, without its users noticing the failure).
  - *Safety* – if a system fails, nothing catastrophic will happen.

So called RAMS-studies

Faults, Errors & Failures

- Fault: a defect within the system or a situation that can lead to the failure
- Error: manifestation of the fault – an unexpected behavior
- Failure: system not performing its intended function

Fault → Error → Failure

Measuring

- Failures are measured in FITs
  - 1 FIT (failures in time), is the number of failures in 1 billion device-operation hours. A measurement of 1000 FITs corresponds to a MTTF (mean time to failure) of approximately 114 years.
- Example: Bit flips in hardware due to cosmic radiation
  - A person on an airplane over the Atlantic at 35,000 ft working on a laptop with 256 Mbytes (2 Gbits) of memory. At this altitude, the soft error rate (SER) of 600 FITs per megabit becomes 100,000 FITs per megabit, resulting in a potential error every five hours.

Fault Examples

- Year 2000 bug
- Loose wire
- Aircraft retracting its landing gear while on ground

- Effects in time:
  - Permanent
  - Transient
  - Intermittent

Permanent

- A permanent fault or failure is one which is stable and continuous.
- Permanent hardware failures require some component to be replaced or repaired.
- An example of a permanent fault would be a VLSI chip with a manufacturing defect, causing one input pin to be stuck high (stuck-at-1).

Transient

- A transient fault is one which results from a temporary environmental condition.
- For example, a voltage spike might cause a sensor to report an incorrect value for a few milliseconds before reporting correctly.

Transient faults

- Happen for a short time
- **Corruptions of data, miscalculation in logic**
- Do not cause a permanent damage of circuits
- Causes are outside system boundaries


Electromagnetic interference (EMI)

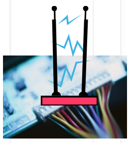

Radiation


Lightning storms

Intermittent

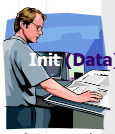
- An intermittent fault is one which only manifests occasionally, due to unstable hardware or certain system states.
- A loose contact on a connector will often cause an intermittent fault.
- Intermittent electrical faults, as a rule, are notoriously difficult to detect. Typically, whenever the fault doctor shows up, the system works fine.

Intermittent faults


Crosstalk

- Manifest similar as transient faults
- Happen repeatedly
- Causes are inside system boundaries

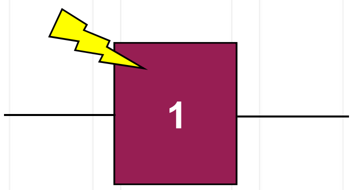
Internal EMI



Software errors (Heisenbugs)


Power supply fluctuations

Soft Errors



- Transient bit-flip (soft memory error)
  - Random event
  - Corrupts the value but not the cell
  - Can be corrected (in contrast to hard errors caused by faults in the hardware itself)
  - Happen continuously during system lifetime (i.e., can not be screened by burn-in tests)

Sources

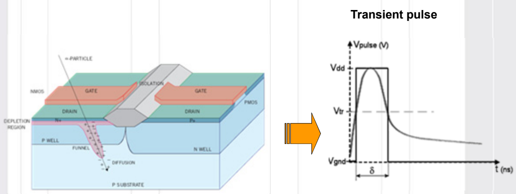
- First traced to alpha particlce emissions from chip packaging materials
  - Most sources removed (pure materials, different designs, shielding)
- Today's main problem: cosmic radiation
  - Cosmic particles from deep space (actually 5th- or 6th-hand collision particles)
    - At ground level ca 95% neutrons, 5% protons
  - Radioactive material in manufacturing process

Sources (cont.)

- Four main sources:
  - Low-energy alpha particles
  - High-energy cosmic particles
  - Thermal neutrons
  - Poor system design

SER type	Source	Mechanism	Trend
Alpha	Thorium and uranium contamination in-mold compound, silicon, or lead bumps	2- to 9-MeV alpha particle creating electron-hole funnel traveling 25 microns in silicon	Exponential increase with scaling
Cosmic	Intergalactic sources modulated by solar flares	High-energy neutrons/protons (10 MeV to 1 GeV) colliding with silicon nuclei	Decrease in failures in time per megabit
Thermal neutron	Boron present in BPSG25-meV neutrons	Collision with B10 in BPSG	Highest, always dominates if present

Soft Errors



The electric field in the depletion region directly generates electron-hole pairs in its wake, causing the charges to drift so that the transistor sees a current disturbance

Evidence of Cosmic Ray Strikes

- Documented strikes in large servers found in error logs
  - Normand, "Single Event Upset at Ground Level," IEEE Transactions on Nuclear Science, Vol. 43, No. 6, December 1996.
- Sun Microsystems, 2000 (R. Baumann, Workshop talk)
  - Cosmic ray strikes on L2 cache with defective error protection
    - caused Sun's flagship servers to suddenly and mysteriously crash!
  - Companies affected
    - Baby Bell (Atlanta), America Online, Ebay, & dozens of other corporations
    - Verisign moved to IBM Unix servers (for the most part)
- 2005 – Los Alamos 2048-CPU HP server system crashed frequently due to defective cache
- 2010 Toyota brake problem (still no agreement)
- More recently: problems with GPGPU based HPC

Current Situation

- Soft errors induced the highest failure rate of all other reliability mechanisms combined

Rober Baumann, TI

Measuring

- The rate at which SEUs (single-event-upsets) occure is given as SER, measured in FITs (failures in time)
- 1 FIT = 1 failure in 1 billion device-operation hours
- 1000 FIT ≈ MTTF 114 years

Failure Classification

- Domain/Nature
  - Value failure
  - Timing failure
- Perception
  - Consistent failure
  - Inconsistent failure
- Effect
  - Benign failure
  - Malign/catastrophic failure
- Frequency
  - Single failure
  - Repeated failure

Failures

- **Crash** Failure: After an error has been detected, the component stops silently.
- **Omission** Failure: Sometimes a result is missing; when result is available, it is correct.
- **Consistent** Failure: If there are multiple receivers, all see the same erroneous result.
- **Byzantine** (Malicious, Asymmetric) Failure: Different receivers see differing results.

Failures (cont.)

- **Timing** Failure: A server's response lies outside the specified time interval.
- **Response** Failure: The server's response is incorrect (value of the response is wrong, server deviates from the correct flow of control).
- **Arbitrary** Failure: A server may produce arbitrary responses at arbitrary times.

Fault Handling

- 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

- Fault tolerance: add redundancy to mask effect
  - Additional resources needed (more later)
  - Examples:
    - Error correction coding, voting and masking, checksums, ...
    - Backup storage, replication, ...
    - Spare tire, etc

Fault Tolerance

- **Fault detection** is the process of recognizing that a fault has occurred. Fault detection is often required before any recovery procedure can be initiated. The techniques include error detection codes, self-checking/failsafe logic, watchdog timers, and others.
- **Fault location** is the process of determining where a fault has occurred so that an appropriate recovery can be initiated.

Fault Tolerance (cont.)

- **Fault containment** is the process of isolating a fault and preventing the effects of that fault from propagating throughout the system.
- **Fault recovery** is the process of remaining operational or regaining operational status via reconfiguration even in the presence of faults. A few basic approaches are fault masking, retry, and rollback.

Definitions

- Failure rate (λ):
  - Average frequency with which something fails.

$$\frac{6\ failures}{7502\ hrs} = 0.0007998\ failures/hr = 799.8 \times 10^{-6}\ failures/hr$$

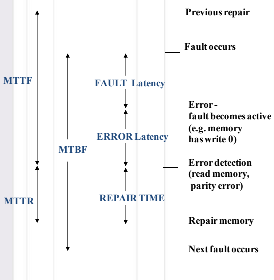
- Mean time to failure (MTTF):
  - Average time between failures

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

Dependability

- Property of a computing system which allows reliance to be justifiably placed on the service it delivers
- Dependability = reliability + availability + safety + security + ...
- Reliability → continuity of correct service
- Availability → readiness of usage
- Safety → no catastrophic consequences
- Security → prevention of unauthorized access

Dependability Concepts



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)*

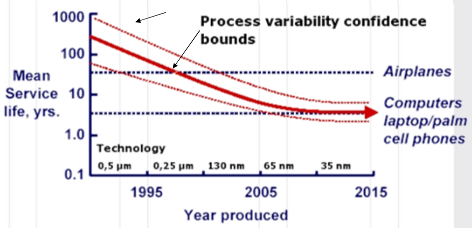
Availability:
a measure of the service delivery with respect to the alternation of the delivery and interruptions
A(t) is the probability that the system delivers a proper (conforming to specification)service at a given time t.
expected value: *EA = MTTF / (MTTF + MTTR)*

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)

Reliability

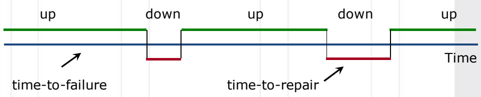
- A measure of an it performing its intended function satisfactorily for a prescribed time and under given environment conditions.
- Probability that system will survive to time t
  - In aerospace industry the requirement is that failure probability is 10-9 (one failure over 109 hours (114 000 years) of operation)
- Time To Failure (TTF)
- Mean Time To Failure (MTTF)

Commercial Chip Reliability Estimation



*Extrapolated from ITRS roadmap, MRQW-2002, Bernstein

Availability



$$Availability = \frac{MTTF}{MTTF + MTTR}$$

- Availability:
  - Probability that system is operational at time *t*
- High availability:
  - MTTF → infinity (high reliability)
  - MTTR → zero (fast recovery)

Maintainability

- *M(t)* is the probability that a failed system will be restored within a specified period of time *t*.
- Restoration process:
  - locating problem, e.g. via diagnostics
  - physically repairing system
  - bringing system back to its operational condition

Graceful Degradation

- The ability of system to automatically decrease its level of performance to compensate for hardware failure and software errors.

The Myth of the Nines

Nines	Availability	Downtime per year	Downtime per week	Example
2 nines	99%	3.65 days	1.7 hours	General web site
3 nines	99.9%	8.75 hours	10.1 min	E-commerce site
4 nines	99.99%	52.5 min	1.0 min	Enterprise mail server
5 nines	99.999%	5.25 min	6.0 s	Telephone system
6 nines	99.9999%	31.5 s	0.6 s	Carrier-grade network switch

Historical Evaluation

- Mean Time Between Failures:

$$MTBF = MTTR + MTTF$$

  - ENIAC. MTBF: 7 minutes (18000 vacum tubes)
    - ENIAC → TX-2 interactive computer (MIT) → web
  - F-8 Crusader – first fly-by-wire, 375 hours → 750 hours (IBM AP-101)
    - MD-11
    - A320 family
  - Patriot missile defence system
    - 1/3 sec in 100 hours, targeting error: 600 m
    - Needed reboot after 8 hours, was learned in hard way…

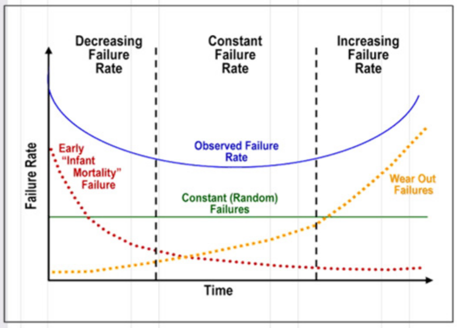
Ultra-Reliable Systems

- Airbus A320 family fly-by-wire system:
  - computer controls all actuators
  - no control rods, cables in the middle
  - 7 central flight control computers
    - 3 Motorola 68000
    - 2 Intel 80C86
    - 2 Intel 80C286
  - software for hardware written by different software houses (C, ASM, dedicated one, specifically developed)
  - all error checking & debugging performed separately
  - computer allows pilot to fly craft up to certain limits (flight envelope)
    - beyond: computer takes over

Hardware and Environment Failures

- Moving parts, high speed, low tolerance, high complexity: disks, tape drives/libraries
- Lowest MTBF found in fans and power supplies
- Often fans fail gradually → subtle, sporadic failures in CPU, memory, backplane
- Environment: power, cooling, dehumidifying, cables, fire, collapsing racks, ventilation, earthquakes, …

Bathtub Curve



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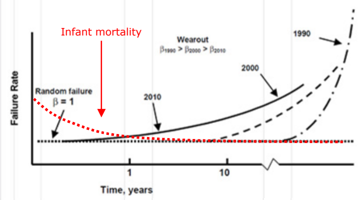
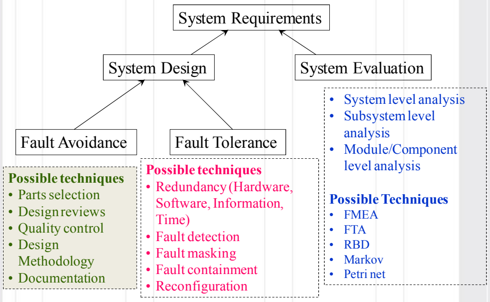
Device Reliability Trends

- As technology progresses, wearout failures become statistically indistinguishable from infant mortality failures with the same wearout drivers.



System Design & Evaluation Top-Level View



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Safety

- Attribute of a system which either operates correctly or fails in a safe manner
- Freedom from expose to danger, or exemption from hurt, injury or loss.
- "Fail-safe": traffic lights start to blink yellow
- Degrees of safety
- Closely related to risk

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Risk

- A combination of the likelihood af an accident and the severity of the potential consequences
- The harm that can result if a threat is actualised
- Acceptable/tolerable risk: The Ford Pinto case (1968)

BENEFITS
Savings: 180 burn deaths, 180 serious burn injuries, 2,100 burned vehicles.
Unit Cost: $200,000 per death, $67,000 per injury, $700 per vehicle.
Total Benefit: 180 X ($200,000) + 180 X ($67,000) + $2,100 X ($700) = $49.5 million.

COSTS
Sales: 11 million cars, 1.5 million light trucks.
Unit Cost: $11 per car, $11 per truck.
Total Cost: 11,000,000 X ($11) + 1,500,000 X ($11) = $137 million.

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System Safety & Hazards

- Safety:
  - achieved by anticipating accidents and eliminating their causes
- Hazards are potential causes of accidents
  - Conditions in a system which together with other factors in the environment inevitably cause accidents

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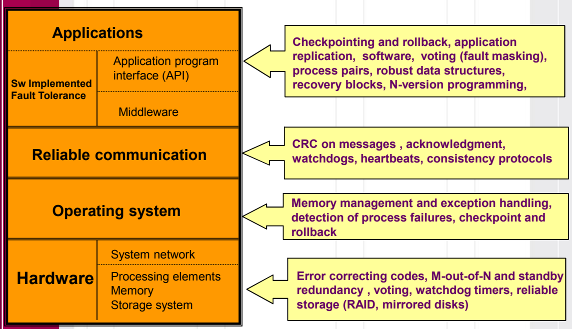
Reliability is a System Issue



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Questions?

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Administrative issues

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- Case Studies
  - Presentation + report
- Exam

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