Distributed Algorithms and Fault Tolerance

Introduction to Fault Tolerance

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Agenda

- Part 1: Introduction to fault tolerance
- Part 2: Error detection
- Part 3: Error recovery
- Part 4: Fault tolerance for distributed systems

Murphy's law

Whatever can go wrong will go wrong at the worst possible time and in the worst possible way.

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Motivations

Definitions

Faults, Errors, Failures

Availability, Reliability and MTBF

Means to attain dependability

Large scale computing systems

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Computing systems are everywhere

Usage of computing systems

- Flight controls in airplanes
- Car braking system
- Financial transactions
- Weather forecasting
- Store photos from last vacation
- Make this presentation

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How much can we rely on computing systems?

Computing systems can fail

Some failure causes

- The running environment (heat, humidity, unstable power supply)
- The users (do users know how to properly operate the system?)
- The manufacturing (in many contexts, computing systems are based on cheap components)
- The scale (very large scale systems have a higher probability to fail)
- Software bugs

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Dependability

Avizienis, Laprie and Randell (2001)

Definition

Dependability of a computing system is the ability to deliver service that can justifiably be trusted

- The service delivered by a system is its behavior as it is perceived by its user(s)
- A user is another system (physical, human) that interacts with the former at the service interface

Dependability

Avizienis, Laprie and Randell (2001)

- The function of a system is what the system is intended for, and is described by the system specification
- Correct service is delivered when the service implements the system function
- A system failure is an event that occurs when the delivered service deviates from correct service

Alternative definition of dependability

The ability of a system to avoid failures that are more frequent or more severe than is acceptable to the user(s).

System failures

System failures types

- Value failure: The output of the system is not acceptable for the given set of inputs
- Timing failure: The output of the system is not available within some expected time bounds

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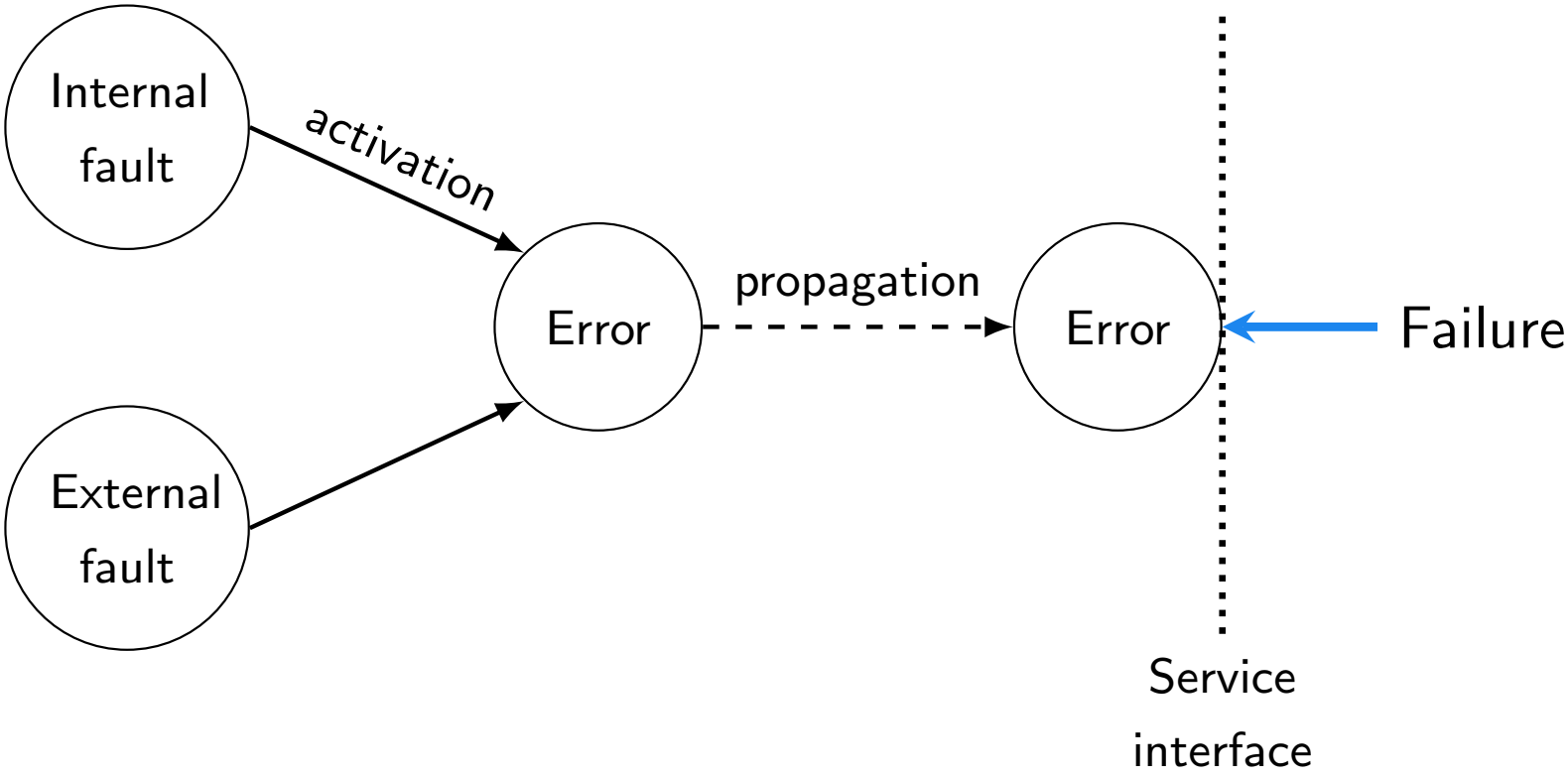
Faults, Errors, Failures

Avizienis, Laprie and Randell (2001)

An error is the part of the system state that may cause a subsequent failure: a failure occurs when an error reaches the service interface and alters the service

A fault is the adjudged or hypothesized cause of an error



Fault-Error-Failure example

- Fault: High energy particle disrupts charge on DRAM transistor.
- Error: Bit flip in a memory world
- Failure: Computation produce incorrect result

Faults

Three major fault classes

- Design faults
- Physical faults
- Interaction faults

Faults

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  - Software flaws
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Faults

Three major fault classes

- Design faults
  - Software flaws
  - Hardware flaws
- Physical faults
  - Physical deterioration
  - Physical interference
- Interaction faults
  - Input mistakes
  - Attacks

Characterization of Faults

- Domain
  - Hardware faults
  - Software faults
- Intent
  - Non-malicious
  - Malicious

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There can be non-malicious deliberate faults:

- Ex: During development, correctness might have to be traded for performance or simplicity

Characterization of Faults: Persistence

Transient (soft) faults/errors

- Occurs once and disappears
- Eg, bit-flip due to high-energy particles
- Tend to be due to transient physical phenomena

Intermittent faults/errors

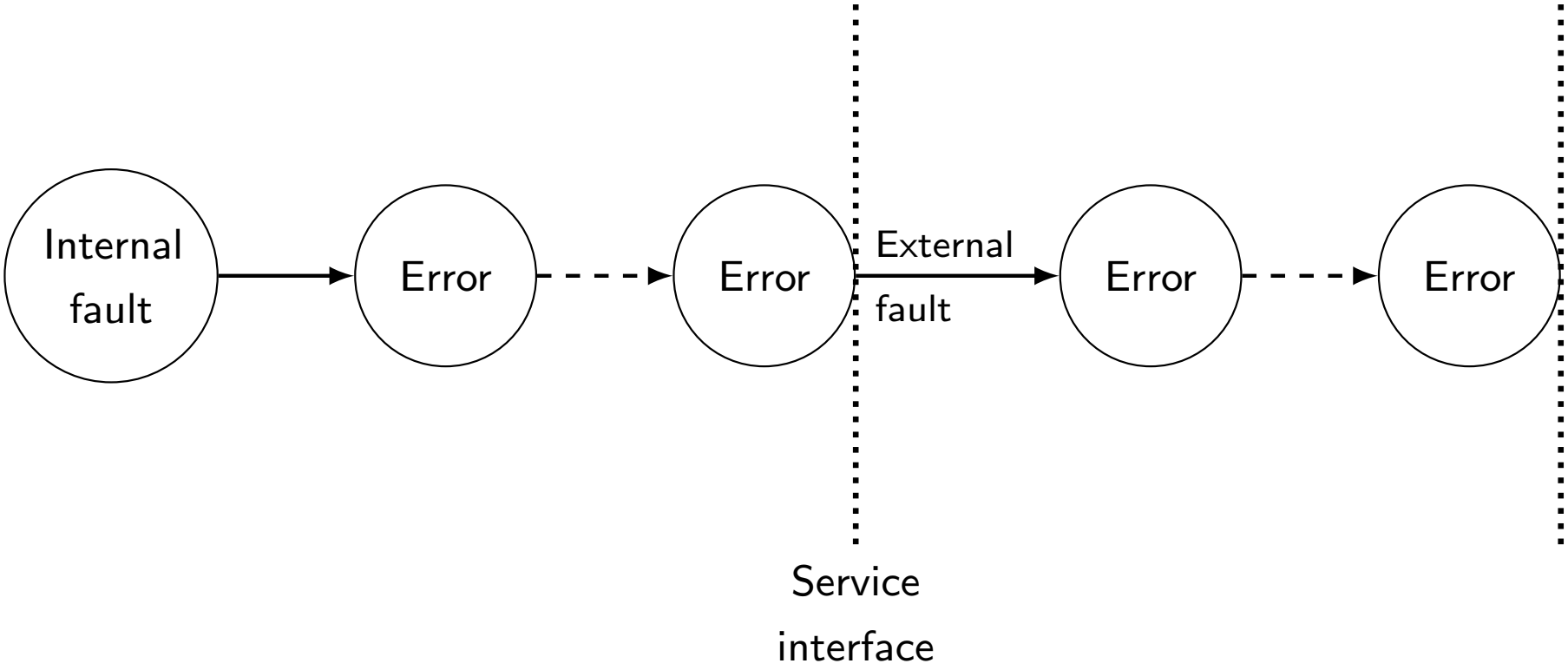
- Occurs occasionally
- Eg, a router drops some packets

Permanent (hard) faults/errors

- Occurs and doesn't go away
- Eg, a dead power supply

About faults and failures

The failure of a component is a fault from the perspective of the component using it.



Characterization of failures

- Catastrophic failures: The system is down. Large impact on the users and/or the environment.
- No response: The system does not respond anymore.
- Data failures: The output is provided but it is a wrong value.
- Timing failures: System returns a good behavior but out of the timing expectations
  - A system with timing constraints is called *real-time*.
- Random failures (Byzantines) - The system provides *random* outputs to the same inputs
  - Different users might observe different behaviors
  - Values might not be that random (malicious behavior)

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The attributes of dependability

Reliability

- The ability of a component to perform its required functions for a specified period of time

Availability

- The degree to which a component is operational and accessible when required for use

Safety

- Absence of catastrophic consequences on the user and environment

Confidentiality

- Absence of unauthorized disclosure of information

Integrity

- Absence of improper system state alteration

Maintainability

- Ease of repairing a failed system

About security

Security can be seen as a composite notion:

- Confidentiality
- Integrity: the prevention of the unauthorized modification or deletion of information
- Availability: the prevention of the unauthorized withholding of information

Reliability and MTBF

Definitions

- Reliability: A function of time $R(t)$ defined as the conditional probability that the system works properly during a time interval $[t_0, t]$ given that the system worked correctly at t_0.
- MTBF: Mean time between failures

$$R(t) = e^{-(\frac{t}{MTBF})}$$

More about MTBF

Typical MTBF of a disk range between 30 and 120 years (source: seagate)

- Does this mean that my disk can run for 30 years without failures?

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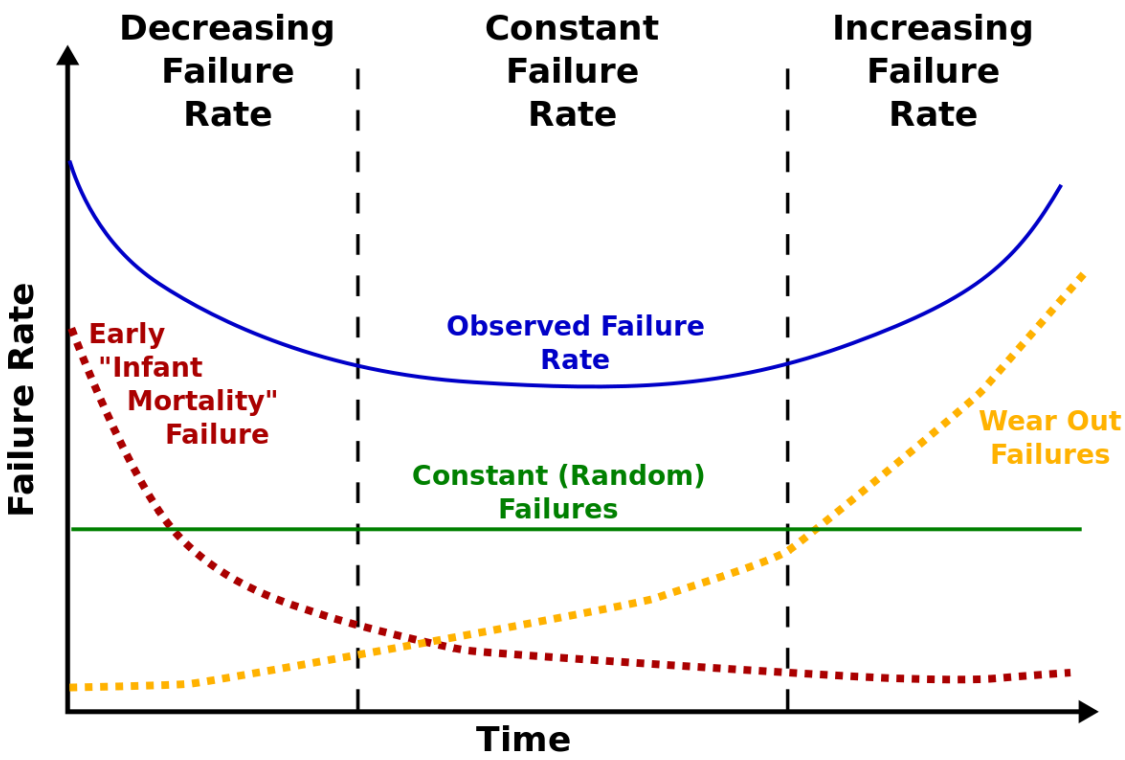
Computation

- 1000 disks run during 6 months and only 6 fail.
- Failure rate $= \frac{6}{1000 \times 0.5} = 0.012$
- MTBF $= \frac{1}{0.012} \simeq 83$ years
- But the failure rate increases with age

More about MTBF

The bathtub



- Infant mortality is due to defective products
- During normal operation, failure rate is low and almost constant

Reliability and MTBF

$$R(t) = e^{-(\frac{t}{MTBF})}$$

MTBF	Reliability in % (1 year)
120 years	99.2
30 years	96.7
5 years	81.8

Note that MTBF is very often given in number of hours. Here we use *years* as unit for the sake of readability.

MTBF of complex systems

In a system integrating many components, the failure of any of the components can result in the failure on the whole system.

We use 1000 disks to build a large storage server.

- Recall: 1000 disks run during 6 months and only 6 fail.
- Failure rate $= \frac{6}{1 \times 0.5} = 12$
- MTBF $= \frac{1}{12} = 1$ month
- Note that most data are still available when a disk fails

MTBF range of other complex systems

- A laptop/desktop
  - Typical MTBF in the order of 3 years
- A datacenter
  - Built out of 1000 *low-cost* nodes
  - MTBF $= 3/1000 \simeq 26$ hours
  - Large scale datacenters are in the scale of tens of thousands of nodes
  - Note that in this context, the failure of a node usually does not prevent the system from functioning.
- A supercomputer
  - Typical MTBF of a node $= 5$ years
  - Largest supercomputers $= 100000$ nodes
  - System MTBF $= 26$ minutes
  - Bad news: applications are usually tightly coupled

Availability

Definition

- The degree to which a component is operational and accessible when required for use.
- The proportion of time for which a component is able to perform its function

To compute availability, we need to introduce one more parameter

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To compute availability, we need to introduce one more parameter

- The mean time to repair (MTTR)

$$A = \frac{Uptime}{Uptime + Downtime} = \frac{MTBF}{MTBF + MTTR}$$

Availability: Some facts

Gray and Siewiorek (1991)

- Computer built in the late 50's
  - MTBF = 12 hours
  - MTTR = 8 hours (a dozen of fulltime engineers to repair the machine)
  - A = 60%
- Telephone switching system
  - Designed to be unavailable less than 5 minutes a year
  - A = 99.999% (*five nines availability*)
  - This is a highly available system

Availability classes

System type	Unavailability (min/year)	Availability
Managed	5256	99 %
Fault tolerant	53	99.99 %
Highly available	5	99.999 %
Ultra available	0.05	99.99999 %

- Typical online services should be made highly available
- Five-nines availability is also targeted for satellites

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Fault prevention

- How to prevent the occurrence or introduction of faults

Fault tolerance

- How to deliver correct service in the presence of faults

Fault removal

- How to reduce the number or severity of faults

Fault forecasting

- How to estimate the present number, the future incidence, and the likely consequences of faults

Fault prevention

- Act on
  - the procedures for creating and using a product
  - the technologies used for manufacturing a product
- Applied during
  - Specification (avoid incomplete/ambiguous specification)
  - Design (choice of tools)
  - Manufacturing/development (quality standard, automatic tools)
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Limit: Faults can never be completely eliminated

Fault tolerance

Intuition: Add `something` to the system to allow it to deal with faults

That's the topic of the next lectures

Fault removal

- Detecting, localizing, and removing faults
- Static techniques
  - Formal verification
  - Revision of code by experts
- Dynamic techniques
  - Mainly tests
- Maintenance
  - Corrective maintenance: Aimed at removing faults that have produced one or more errors and have been reported.
  - Preventive maintenance: Aimed to uncover and remove faults before they might cause errors during normal operation.

Fault forecasting

- Study of fault/failure relationship
  - Root cause analysis
- Collection of failure data
  - Failure models
- Failure prediction
  - Hot topic
  - If I am able to predict the failure of a node, I may be able to migrate my service to another node before the failure occurs (virtually continuous availability)
  - Making accurate predictions is not that easy

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No matter how much prevention, removal and forecasting is applied, faults will still occur. (but these techniques help reducing the number of faults)

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Failures causes

Analysis of the failures on an extreme scale supercomputer (Di Martino et al (2014))

- 75% of the (system-wide outage) are due to software
- Software includes fail-over procedures . . . that fail in a vast majority of cases
- A huge number of faults occurs in hardware. Few lead to failures.
  - 1.5 millions of memory errors in less than a year but only 0.003% failures.
- Hardware is responsible for 51% of the failures but only 23% of the total repair time.

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Lessons learned:

- Hardware fault tolerance techniques are very efficient
- Software errors can lead to *big* failures

Failures causes

Analysis of Business Data Processing cloud apps (Di Martino et al (2012))

- 34% of the failures are due to unexpected user data
- 32% of the failures are timeouts
- 95% of the failures are located in the same 5 modules (37% of LOC)

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Lessons learned:

- Exceptions need to be better handled
- A small number of errors create the vast majority of the failures $\rightarrow$ Better testing procedures are required

Failures in the cloud

Pham, Cao et al (2012)

Some examples

- Microsoft Azure (2009)
  - 1-day system slow-down (many server failures)
  - Source: Ongoing operating system update
  - Users can create a copy of their application on a different site for free
- Amazon S3 (2008)
  - 8-hour outage
  - Source: A single-bit corruption in a handful of messages

More failures in the cloud

- Amazon Web Services data center (2015)
  - 6-hour outage
  - Source: Problem with metadata management in DynamoDB (NoSQL database)
  - The failure propagated to many other services
  - The two biggest clients of AWS are Amazon.com and Netflix
    - Netflix claimed not to be impacted
    - Analyses of consumers complains show a large increase during that period

Cost of an outage

- Amazon.com experienced a 45 minutes outage in 2013
- Cost in lost sales estimated to $4 millions

References

- A. Avizienis, J. C. Laprie, and B. Randell (2001). *Fundamental concepts of dependability*.
- D. Sorin (2009). *Fault Tolerant Computer Architecture*.

- Other sources:
  - Lecture notes of N. Palix
  - Lecture notes of D. Sorin