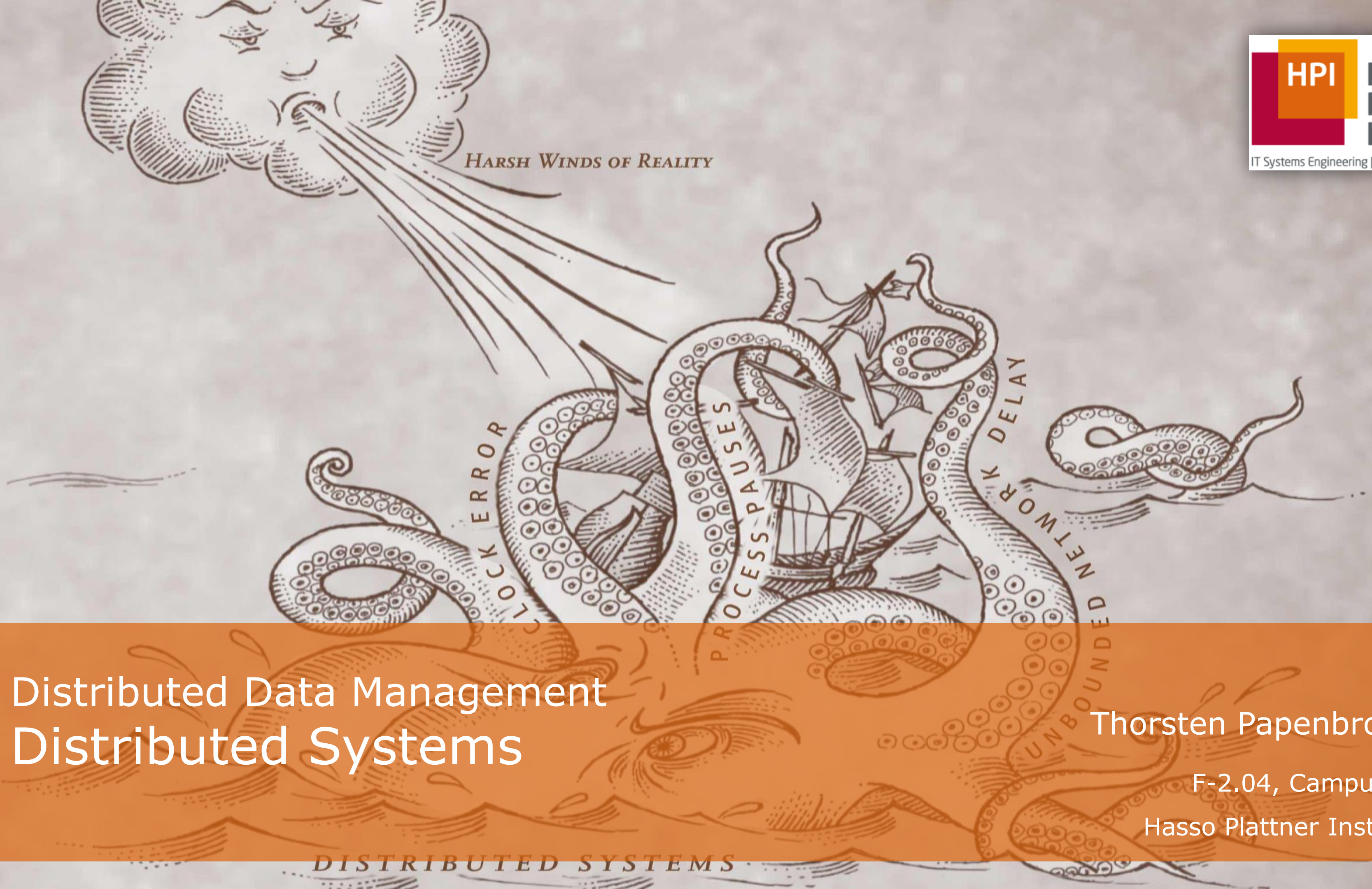
HPI Hasso Plattner Institut
IT Systems Engineering | Universität Potsdam



Distributed Data Management
Distributed Systems

Thorsten Papenbrock
F-2.04, Campus II
Hasso Plattner Institut

Introduction

Distributed Systems

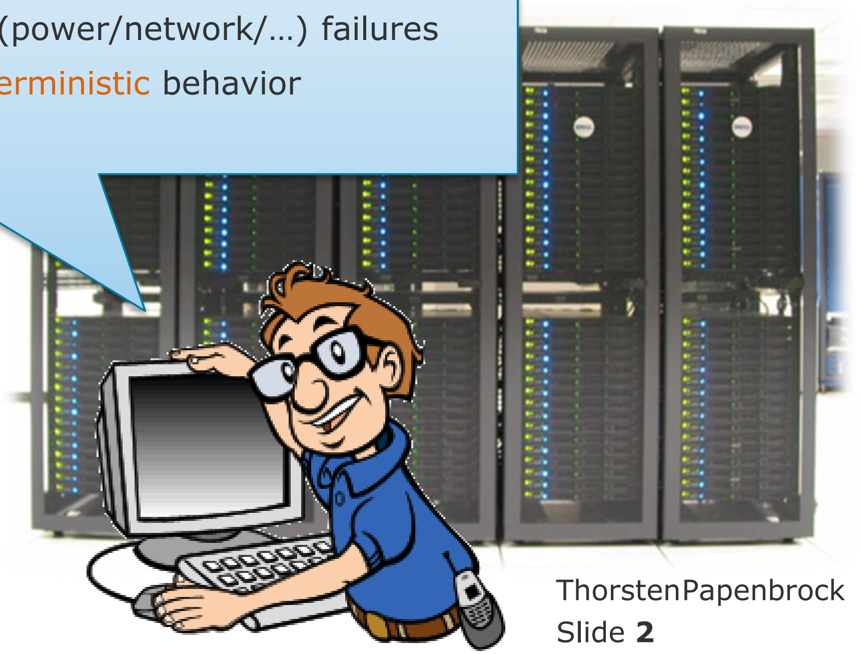
I am facing …

- software bugs
- power failures
- head crashes
- hardware aging
- …

Non-Distributed System Developer

I am facing everything he faces and …

- network faults
- clock deviation
- partial (power/network/…) failures
- nondeterministic behavior
- …



Distributed System Developer

Introduction

Distributed Systems

"My system is predictable."

"I can debug easily."

"A well operating system should not have failures."

"I use parallelism whenever necessary."

Non-Distributed System Developer

"My system is predictably unpredictable."

"Debugging is hard."

"A well operating system properly deals with its failures."

"Parallelism is my bread and butter."

Distributed System Developer

So better be prepared!

“Anything that can go wrong will go wrong”

Reliability despite Unreliable Components

Building a reliable system from unreliable components

Given: n number of nodes in the cluster

p likelihood that a node fails (in some arbitrary time interval)

Then: Probability a node failure in a cluster of size n can be calculated as …

Probability that n nodes with failure probability p did not fail

$$P(nodes\ failed) = 1 - (1-p)^n$$

Reliability despite Unreliable Components

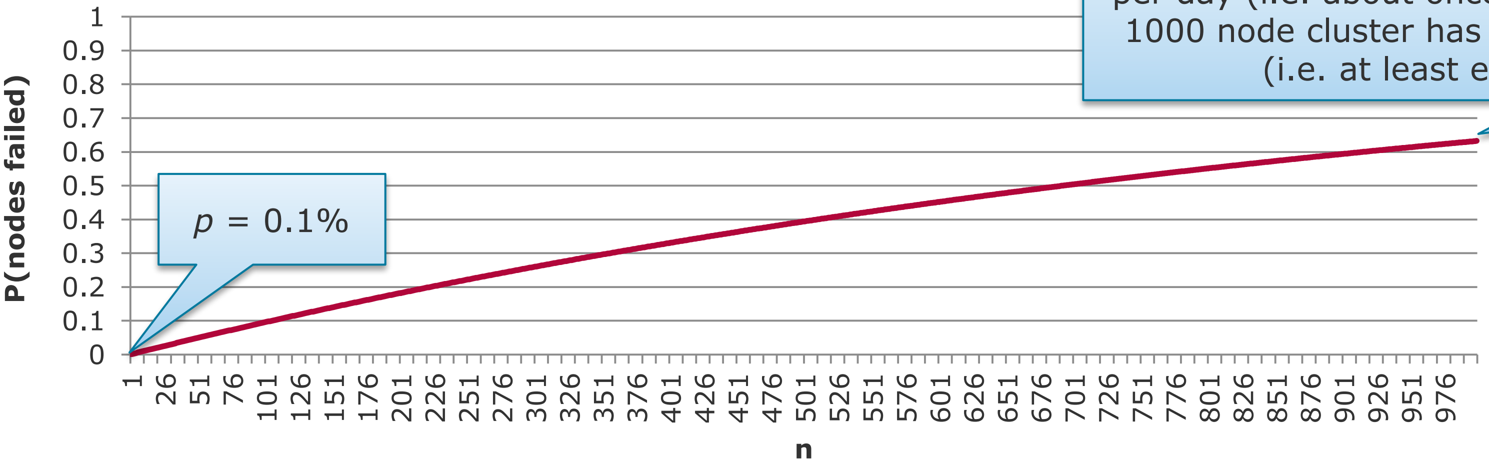
Building a reliable system from unreliable components

Given: *n* number of nodes in the cluster

p likelihood that a node fails (in some arbitrary time interval)

Then: Probability a node failure in a cluster of size *n* can be calculated as …

$$P(nodes\ failed) = 1 - (1 - p)^n$$



p = 0.1%

If one nodes fails with a probability of 0.1% per day (i.e. about once every three years) a 1000 node cluster has a disk failure of 63% (i.e. at least every 2 days)

Introduction

Reliability despite Unreliable Components

Building a reliable system from unreliable components

Given: n number of nodes in the cluster

p likelihood that a node fails (in some arbitrary time interval)

Then: Probability a node failure in a cluster of size n can be calculated as …

$$P(nodes\ failed) = 1 - (1 - p)^n$$

Without replication, this is guaranteed data loss in very short time!

So what if we use replication?

Introduction

Reliability despite Unreliable Components

Building a reliable system from unreliable components

Given: *n* number of nodes in the cluster

p likelihood that a node fails (in some arbitrary time interval)

f number of nodes that fail at the same time

Then: Probability of exactly *f* failing nodes can be calculated as (Binomial distribution) …

Number of different ways to pick *f* nodes in the *n* node cluster

Failure probability of *f* independent nodes with *p* failure likelihood

Well-being probability for the *n*-*f* other nodes

$$P(f\ nodes\ failed) = \binom{n}{f} * p^f * (1-p)^{n-f}$$

https://martin.kleppmann.com/2017/01/26/data-loss-in-large-clusters.html

Introduction

Reliability despite Unreliable Components

Building a reliable system from unreliable components

Given: n number of nodes in the cluster

p likelihood that a node fails (in some arbitrary time interval)

f number of nodes that fail at the same time

r replication factor of a distributed system

Then: Probability of unrecoverable partition loss with exactly f failing nodes can be calculated as …

All possible, entirely crashed replicas of size r in f crashed nodes

$$P(partition\ lost \mid f\ nodes\ failed) = \frac{\binom{f}{r}}{\binom{n}{r}}$$

All possible replica combinations of size r on n nodes

https://martin.kleppmann.com/2017/01/26/data-loss-in-large-clusters.html

Reliability despite Unreliable Components

Building a reliable system from unreliable components

Given: n number of nodes in the cluster

p likelihood that a node fails (in some arbitrary time interval)

f number of nodes that fail at the same time

r replication factor of a distributed system

k number of partitions in the cluster

Then: Probability of unrecoverable data loss with exactly f failing nodes can be calculated as …

Probability that all k partitions did not loose data

$$P(data\ loss \mid f\ nodes\ failed) = 1 - P(partition\ not\ lost \mid f\ nodes\ failed)^k$$

$$= 1 - (1 - P(partition\ lost \mid f\ nodes\ failed))^k$$

$$= 1 - \left(1 - \frac{\binom{f}{r}}{\binom{n}{r}}\right)^k$$

https://martin.kleppmann.com/2017/01/26/data-loss-in-large-clusters.html

Introduction
Reliability despite Unreliable Components

Building a reliable system from unreliable components

Given: *n* number of nodes in the cluster

p likelihood that a node fails (in some arbitrary time interval)

f number of nodes that fail at the same time

r replication factor of a distributed system

k number of partitions in the cluster

Then: Probability of unrecoverable data loss can be calculated as …

$$P(data\ loss) = \sum_{f=r}^{n} P(f\ nodes\ failed) * P(data\ loss \mid f\ nodes\ failed)$$

$$= \sum_{f=r}^{n} \binom{n}{f} * pf * (1-p)^{n\text{-}f} * 1 - \left(1 - \frac{\binom{f}{r}}{\binom{n}{r}}\right)^{k}$$

All numbers of failing nodes that can cause data loss (i.e. $f \geq r$)

https://martin.kleppmann.com/2017/01/26/data-loss-in-large-clusters.html

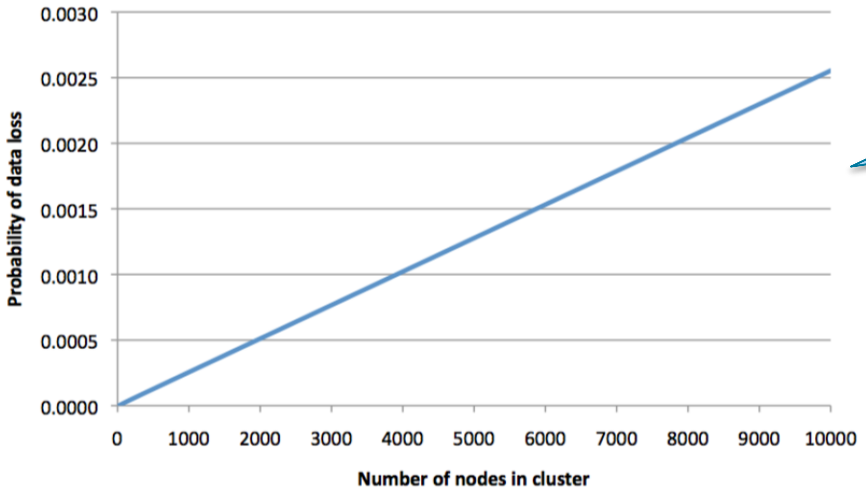
Introduction

Reliability despite Unreliable Components

Building a reliable system from unreliable components

Then: Probability of unrecoverable data loss can be calculated as …

$$P(data\ loss) = \sum_{f=r}^{n} \binom{n}{f} * pf * (1-p)^{n-f} * 1 - \left(1 - \frac{\binom{f}{r}}{\binom{n}{r}}\right)^{k}$$



Replication greatly reduces the risk of loosing data!

n = 1 → 10,000
p = 0.001
r = 3
k = 256 * n

https://martin.kleppmann.com/2017/01/26/data-loss-in-large-clusters.html

Introduction

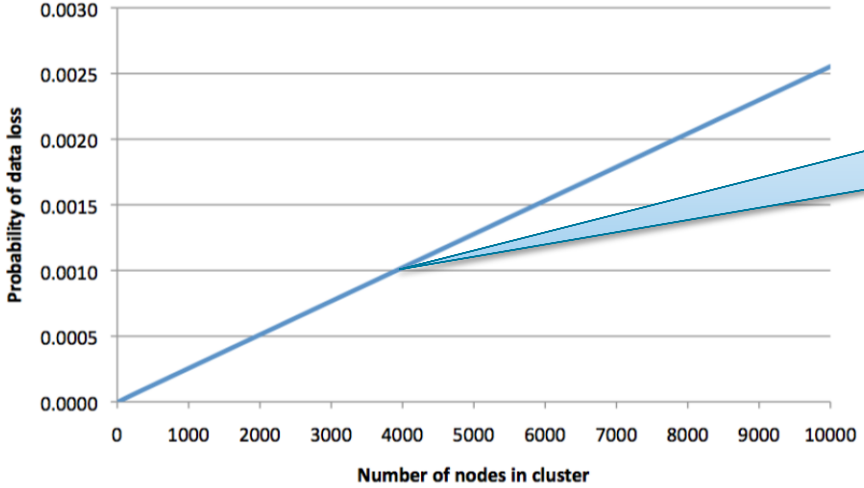
Reliability despite Unreliable Components

Building a reliable system from unreliable components

Then: Probability of unrecoverable data loss can be calculated as …

$$P(data\ loss) = \sum_{f=r}^{n} \binom{n}{f} * pf * (1-p)^{n-f} * 1 - \left(1 - \frac{\binom{f}{r}}{\binom{n}{r}}\right)^{k}$$

It looses only 1/k of the data, but that might have been the most important values!



A 4,000 node cluster has about the same probability of data loss than one single disk (with r = 3 and k = 256 * n).

n = 1 → 10,000
p = 0.001
r = 3
k = 256 * n

https://martin.kleppmann.com/2017/01/26/data-loss-in-large-clusters.html

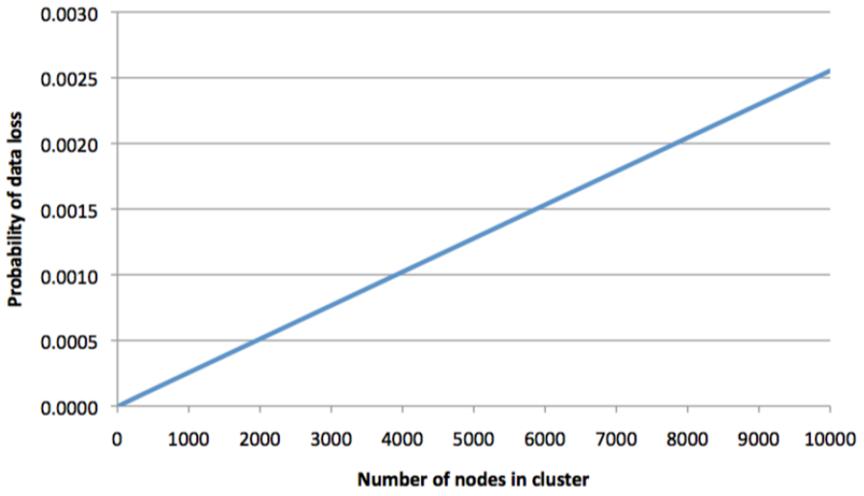
Introduction

Reliability despite Unreliable Components

Building a reliable system from unreliable components

Then: Probability of unrecoverable data loss can be calculated as …

$$P(data\ loss) = \sum_{f=r}^{n} \binom{n}{f} * pf * (1-p)^{n-f} * 1 - \left(1 - \frac{\binom{f}{r}}{\binom{n}{r}}\right)^{k}$$



Although k=3 appears to be super reliable (a failing replica always has to backups), extremely large clusters require *r*>3 (or smaller *k*).

n = 1 ,000
p = 0 001
r = 3
k = 256 * n

https://martin.kleppmann.com/2017/01/26/data-loss-in-large-clusters.html

Reliability despite Unreliable Components

Building a reliable system from unreliable components

- With no special fault handling:
  - A distributed system is only as reliable as its weakest/strongest component.
- With fault handling:
  - A distributed system is (much) more reliable as its unreliable components.

Fault handling examples

Some easily solvable faults

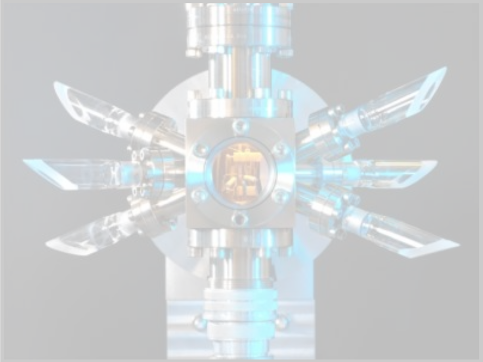
- Radio inference on wireless networks:
  - Error-correcting codes allow digital data to be transmitted accurately.
- Unreliable Internet Protocol (IP):
  - Transmission Control Protocol (TCP) retransmits missing packages, eliminates duplicates, and reassembles packets in order.

Overview
Distributed Systems

Unreliable Networks

A shark raiding an
undersea cable

Unreliable Clocks



An atomic clock with
minimum drift

Knowledge, Truth, Lies

Students communicating their knowledge

Unreliable Networks

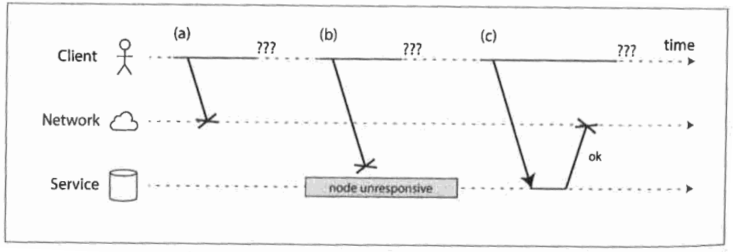
Asynchronous Messaging Issues

Network

- Physical connection between autonomous, shared-nothing computing nodes
- Asynchronous messaging via packet binary sequences
- Nodes can send messages but no guarantees as to when/whether it arrives

Sender can’t even tell if the packet was delivered …

Potential failures when sending a message



a) Request is lost on the network (e.g. cable unplugged).
b) Request is waiting in a queue and delivered later (e.g. recipient overloaded).
c) Remote node is unavailable (e.g. recipient crashed or is updating).
d) Response is delayed on the network (e.g. network overloaded).
e) Response is lost on the network (e.g. network switch misconfigured).

Detecting Faults

Using the operating system

- If a process on a node crashes, but the operating system (OS) still runs:
    - OS can close or refuse TCP connections to notify clients with an error.
    - OS can trigger failover scripts to explicitly notify certain clients.

Using the network switch

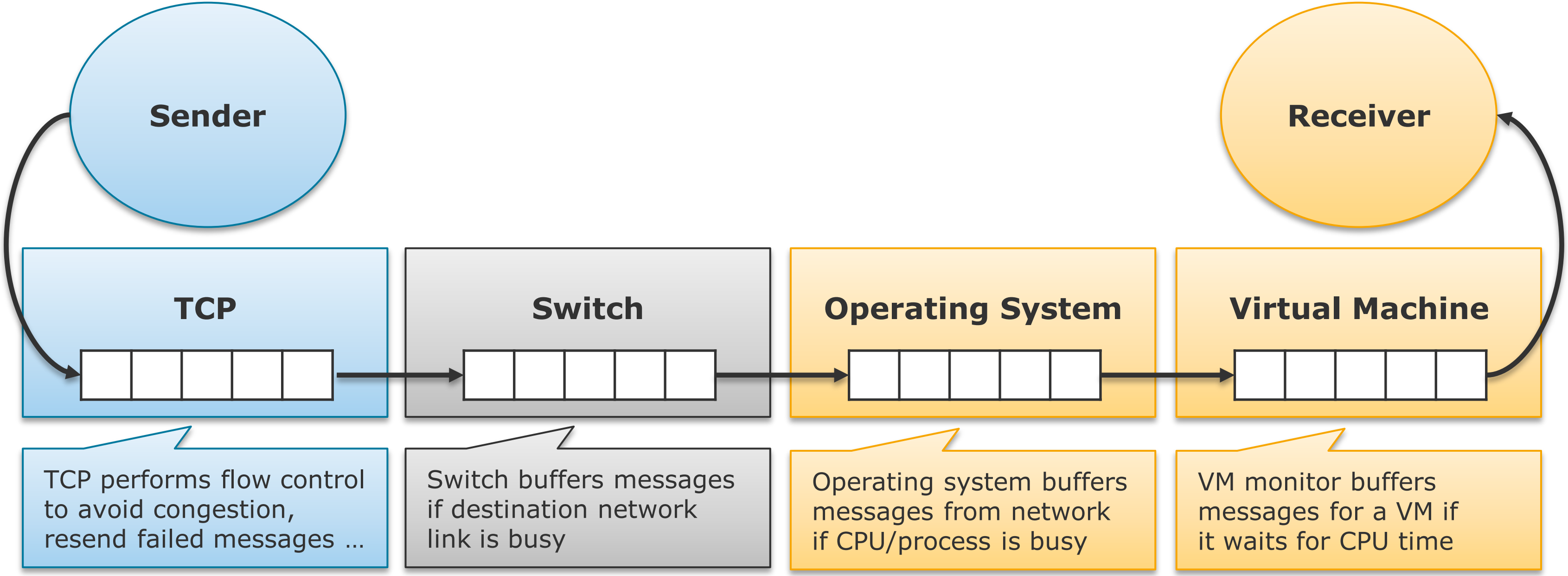
- If the client has access to the network switch:
    - Switch can detect link failures on hardware level (e.g. detect if remote is powered on).

Using timeouts

- Log the sending time for each message.
- Messages are declared lost if their recipient does not answer within a certain timeout.
    - ➢ Most universal fault detection mechanism

Unreliable Networks

Queues on the Network



TCP performs flow control to avoid congestion, resend failed messages …

Switch buffers messages if destination network link is busy

Operating system buffers messages from network if CPU/process is busy

VM monitor buffers messages for a VM if it waits for CPU time

- Many reasons for a packages being delayed (query congestion)
- Even if the receiver could guarantee a processing time for messages, the network cannot guarantee a transmission time for messages.

Unreliable Networks

Timeouts

Issues

- How to set the timeout?
  - Too long (conservative): Program waits wastefully long before triggering fault handling.
  - Too short (aggressive): More false message loss reports each triggering fault handling.
- How to handle failures?
  - Resend message
  - Reroute message
  - Escalate as system error

→ Messages might get **handled multiple times**!

→ Messages might **worsen overload** if this caused the timeout!

Note that we cannot know:

- What caused the error?
- Has a message been worked on?

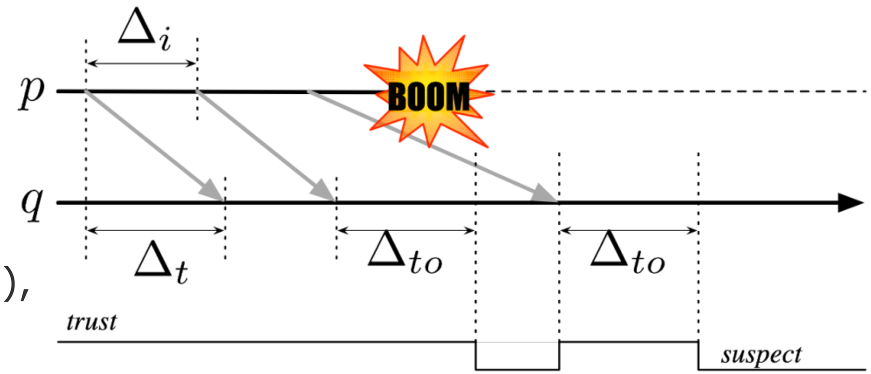
Analytical Systems

- Nodes with high CPU load due to analytical calculations
- Network with high traffic due to data-intensive nature
  - ➢ Overall high system load makes timeouts hard to predict.

Defining Timeouts Experimentally

The traditional heartbeat method

- The monitored process p sends periodical heartbeat messages to the server process q.
- Δ_i : the heartbeat send interval of p
- Δ_t : the initial wait time
- Δ_{to} : the timeout
- Upon receiving the first heartbeat (Δ_t), p measures the time to the next heartbeat (Δ_{to}), which is then set as the timeout.
- Problems:
  - Static timeout: Query congestion might naturally delay heartbeats on higher load.
  - Initialization: If the second heartbeat is delayed, Δ_{to} is set too large.
  - Binary trust: Client is either trusted or suspected.



Unreliable Networks

Defining Timeouts Experimentally

The accrual failure detector method

- Accrual failure detector:
  - German: “anwachsender Fehlererkenner”
  - Output a suspicion-level for each node instead of binary trust or fixed timeout.
- Suspicion level:
  - Measure describing the probability that node *p* has failed at time *t.*
  - Defined as a continuous function for *p* over *t* : $susp\_level_p(t) \geq 0$
  - Properties
    - Asymptotic completeness: If p is faulty, $susp\_level_p(t) \rightarrow \infty$.
    - Eventual monotony: If p is faulty, $susp\_level_p(t)$ *monotonically increases.*
    - Upper bound: If p is correct, $susp\_level_p(t)$ *has an upper bound.*
    - Reset: If p is correct, $susp\_level_p(t) = 0$ for some $t > t_0$.
  - ➢ Used to adjust load balancing and timeout expectations

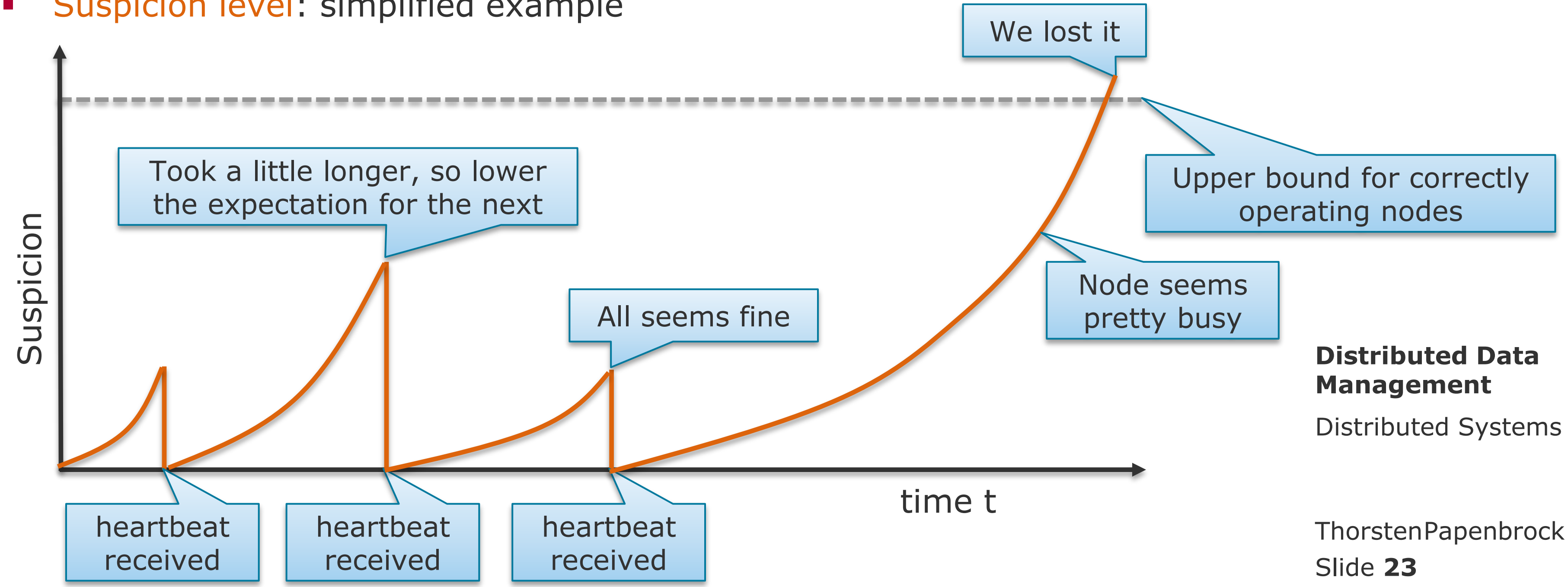
Trust is interpreted from the development of suspicion

i.e., whenever a heartbeat arrives

Defining Timeouts Experimentally

The accrual failure detector method

- Suspicion level: simplified example



Unreliable Networks

Defining Timeouts Experimentally

The accrual failure detector method

- Suspicion level interpretation:
  - Example interpretation algorithm:
    - Initialize two dynamic thresholds T_{high} and T_{low} to the same arbitrary values >0 and start trusting a node.
    - S-transition:
      - Whenever $susp\_level_p(t)$ crosses T_{high} upwards, $T_{high} = T_{high} + 1$ and suspect *p*.
    - T-transition:
      - Whenever $susp\_level_p(t)$ crosses T_{low} downwards, $T_{low} = T_{high}$ and trust *p*.
    - ➢ The longer the algorithms monitors $susp\_level_p(t)$, the better T_{high} captures real node failures.
  - Suspicion dynamically adjusts to the current latency and load.
    - ➢ T_{high} becomes a fix threshold that is robust against load changes.

Defining Timeouts

Naohiro Hayashibara, Xavier Défago, Rami Yared, and Takuya Katayama,
"The φ Accrual Failure Detector",
Japan Advanced Institute of Science and Technology, School of Information Science,
Technical Report IS-RR-2004-010, May 2004

The φ accrual failure detector

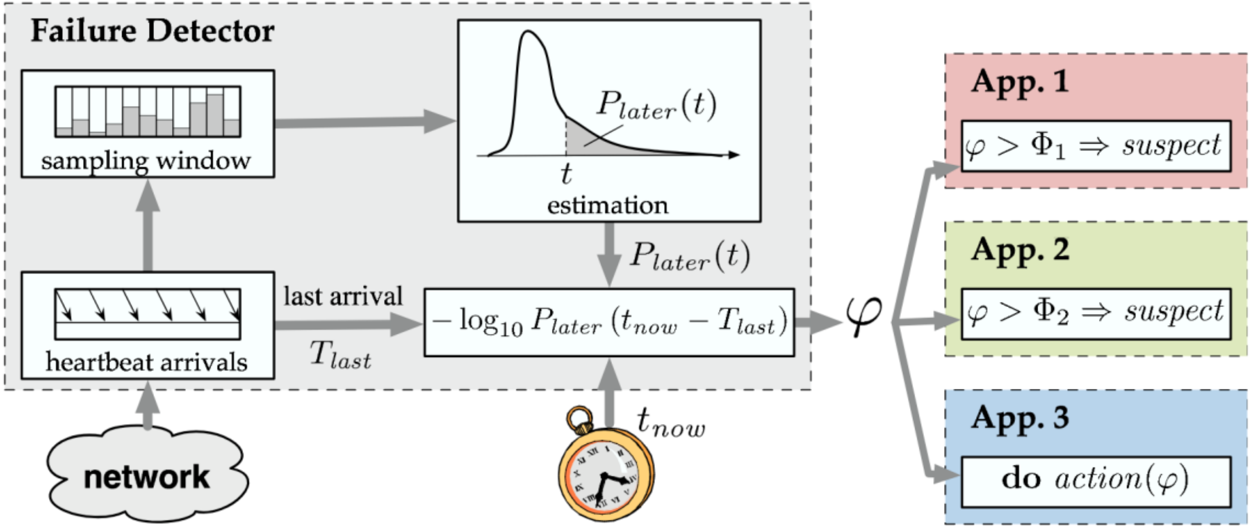
- A concrete implementation of the accrual failure detection method
- Implemented in Akka, Spark, Flink, Cassandra, Riak, ZooKeeper, …
- φ (Phi):
  - Suspicion level: $\varphi_p(t) = susp\_level_p(t)$
  - Comparable: If $\varphi_p(t) > \varphi_q(t)$, p is more likely to fail at time t than q, i.e., p differs more clearly from its usual timing than q.
    - ➢ Useful for fault detection and load balancing.
- General idea:
  - Continually measure response times (jitter) and availability of nodes via heartbeat.
  - Calculate $\varphi_p(t)$ based on p's heartbeat history.

Defining Timeouts

Naohiro Hayashibara, Xavier Défago, Rami Yared, and Takuya Katayama,
"The φ Accrual Failure Detector",
Japan Advanced Institute of Science and Technology, School of Information Science,
Technical Report IS-RR-2004-010, May 2004

The φ accrual failure detector

- Variables
  - T_{last}: Arrival time of most recent heartbeat
  - t_{now}: Current time
  - P_{later}: Probability that a heartbeat will arrive more than t time units after the previous one



- Heartbeat arrivals
  - Heartbeats arrive with a sequence number to restore their send order.
- Sampling window
  - Stores the arrival times in a fixed sized window (last x heartbeats per node).
  - Pre-calculates the arrival intervals, sum, and sum of squares of all samples.

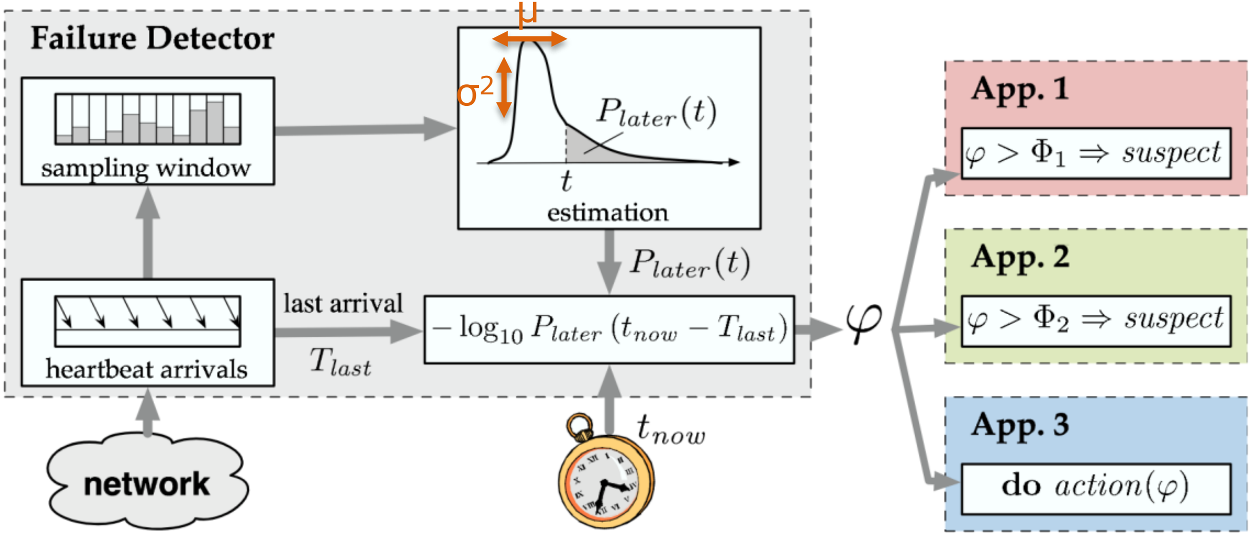
Unreliable Networks

Defining Timeouts

Naohiro Hayashibara, Xavier Défago, Rami Yared, and Takuya Katayama,
"The φ Accrual Failure Detector",
Japan Advanced Institute of Science and Technology, School of Information Science,
Technical Report IS-RR-2004-010, May 2004

The φ accrual failure detector

- Variables
  - T_{last}: Arrival time of most recent heartbeat
  - t_{now}: Current time
  - P_{later}: Probability that a heartbeat will arrive more than t time units after the previous one
- Estimation
  1. Calculate the mean μ and the variance σ² for the arrival time samples.
  2. Calculate $P_{later}(t)$:



$$P_{later}(t) = \frac{1}{\sigma\sqrt{2\pi}} \int_{t}^{+\infty} e^{-\frac{(x-\mu)^2}{2\sigma^2}} \mathrm{d}x$$

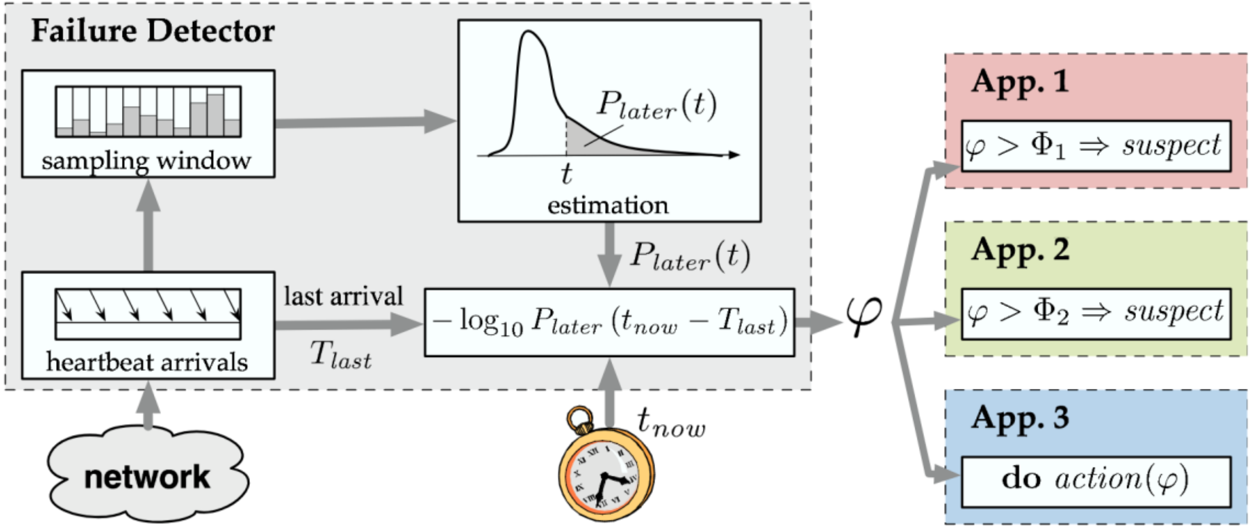
Unreliable Networks
Defining Timeouts

Naohiro Hayashibara, Xavier Défago, Rami Yared, and Takuya Katayama,
"The φ Accrual Failure Detector",
Japan Advanced Institute of Science and Technology, School of Information Science,
Technical Report IS-RR-2004-010, May 2004

The φ accrual failure detector

- Variables
  - T_{last}: Arrival time of most recent heartbeat
  - t_{now}: Current time
  - P_{later}: Probability that a heartbeat will arrive more than t time units after the previous one
- φ calculation

3. Calculate φ using P_{later} and the time since *p*'s last heartbeat:



$$\varphi(t_{now}) \overset{\text{def}}{=} -\log_{10}(P_{later}(t_{now} - T_{last}))$$

P_{later} gets increasingly smaller; $-\log_{10}$ turns small values into very large values.

Interpretation by application:

E.g. failure detection with T_{high} and T_{low} where $T_{high} = \Phi$

Unreliable Networks
Ignoring Timeouts

TCP vs. UDP

- User Datagram Protocol (UDP) does not use timeouts.
  - No guarantee of delivery, ordering, or de-duplication.
  - ➢ Preferable if outdated messages are worthless:

sensor processing

Nachrichten | heute

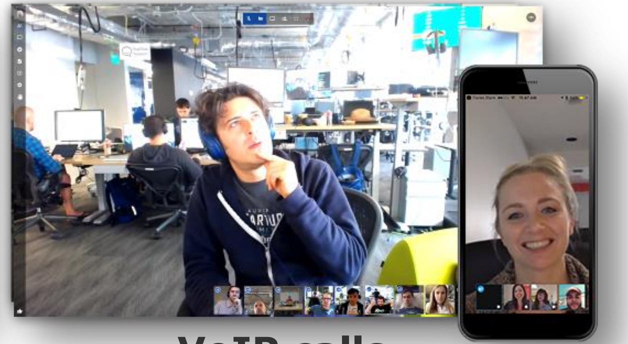
ZDF heute Sendung vom 19.09.2017

Mit folgenden Themen: Suu Kyi zur Gewalt gegen Rohingya; Wie tritt Trump bei der UNO auf?; Hurrikan "Maria" über der Karibik; Die Wirtschaft vor der Wahl; weiteren Nachrichten und dem Wetter.

10 min | 19.09.2017

video streaming

gaming

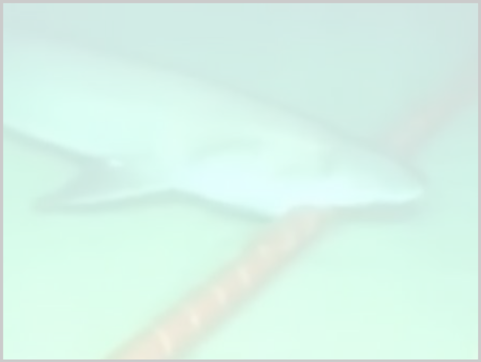


VoIP calls

- ➢ Problematic for most analytical use cases!

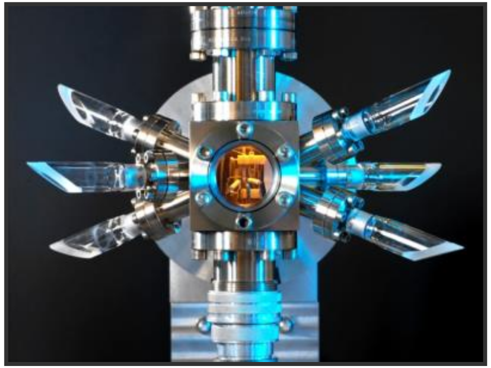
Overview
Distributed Systems

Unreliable Networks



A shark raiding an undersea cable

Unreliable Clocks



An atomic clock with minimum drift

Knowledge, Truth, Lies

Students communicating their knowledge

Unreliable Clocks

Clocks vs. Networks

Unreliable clocks

often cause
silent, creeping failures and data loss.

Unreliable networks

usually cause
noticeable crashes and failures.

Both need to be considered in application logic!

About Clocks

Computer clocks

- Actual hardware devices: quartz crystal oscillator
- Not perfectly accurate and not in sync with other clocks

Clock usage in distributed systems

1. Measure duration e.g.:
    - Has this request timed out yet?
    - What’s the 99th percentile response time of this service?
    - How long did the user spend on this page?
2. Measure points in time e.g.:
    - When was this heartbeat send?
    - When does this cache entry expire?
    - What’s the timestamp of this error message?

About Clocks

Kinds of clocks

a) Time-of-day clock:

- Returns the current time according to some calendar (e.g. millis since 01.01.1970 UTC).
- Example: `clock_gettime(CLOCK_REALTIME)` (Linux)
  `System.currentTimeMillis()` (Java)
- Can be changed completely (e.g., synchronized via NTP).
- Used to measure points in time.

b) Monotonic clock:

- A constantly forward moving clock with no reference point (specific values are meaningless).
- Example: `clock_gettime(CLOCK_MONOTONIC)` (Linux)
  `System.nanoTime()` (Java)
- Can be speeded up or slowed down (e.g., by 0.05% via NTP).
- Used to measure durations (time intervals).

Unreliability

Clock drift

- Natural deviation of mechanical clock speeds due to …
  - machine temperature;
  - gravitation;
  - aging and abrasion.
- Unavoidable even if clocks get synchronized frequently

Illusion of synchronized clocks

- Clock drift: 17 sec drift for clocks synchronized once a day (Google)
- Back-shifts: clocks being forced to sync to past times
- Network delay: no synchronization can work around network delay
- Leap seconds: necessary time adjustment due to earth rotation
- Virtualization: VMs use virtualized clocks that pause if VM has no CPU time

Unreliable Clocks

Use Libraries for Time-Calculations!

"Time [and synchronization] is so difficult to get right that you don't try to write it yourself!"

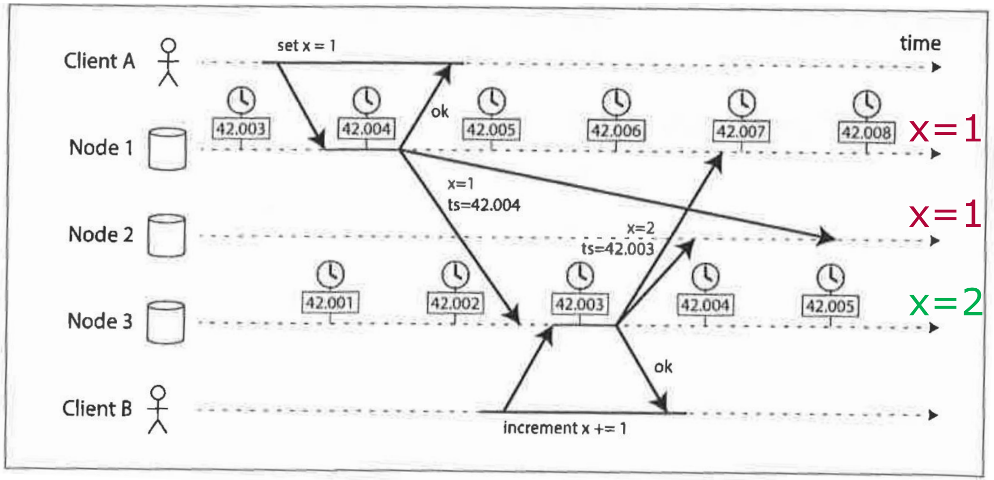
Tom Scott

The Problem with Time & Timezones - Computerphile

1,383,370 views

https://www.youtube.com/watch?v=-5wpm-gesOY

Unreliable Clocks
Risks



Synchronized clocks in distributed DBMSs

- Used often when messages require a global ordering

- Last-Write-Wins (LWW):
  - Writes get a timestamp from the first node that sees them.
  - During change propagation, newer writes overwrite older writes.
  - ➢ If clocks are out-of-sync, newer writes might get overwritten/dropped.

- Snapshot isolation:
  - Transactions get a timestamp from the node that opens them.
  - During transaction processing, transactions see only older changes.
  - ➢ If clocks are out-of-sync, snapshots might be inconsistent.

Unreliable Clocks

Risks

Synchronized clocks in distributed DBMSs

- Used often when messages require a global ordering

```
while (true) {
   request = getIncomingRequest();
   if (lease.expiryTimeMillis -
             System.currentTimeMillis < 10000) {
      lease = lease.renew();
   }
   if (lease.isValid()) {
      process(request);
   }
}
```

Better not pause here!

- Single-leader lease:
  - In single-leader replication, the leader obtains a lease with a timestamp for being leader.
  - Lease:
    - Kind of a lock with timeout that can be held by only one node.
    - If lease's timeout expires, the leader needs to renew the lease.
    - If leader fails and does not renew, another leader can be elected.
  - If clocks are out-of-sync, leader might hold lease for too long (two leader brain split).
  - If the leader **pauses and resumes** in a critical section, it might process writes without permission.

Remember:
no mutexes,
semaphores, …
in distributed
systems!

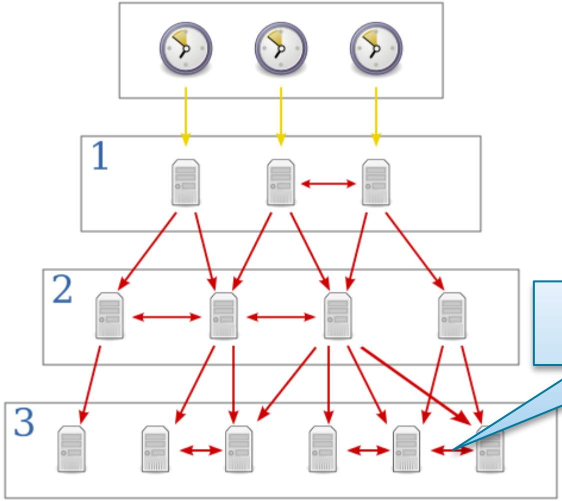
Unreliable Clocks

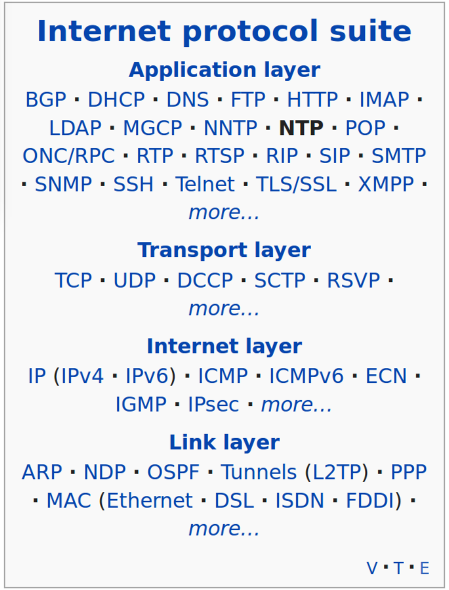
Synchronization

David
L. Mills

Network Time Protocol (NTP)

- Most popular clock synchronization protocol for packet-switched, variable-latency data networks.
- Assumption:
  - Some nodes (servers) have very precise clocks (atomic, GPS, …)
- Protocol:
  - Nodes with less precise clocks synchronize their clocks with these reference clocks directly or indirectly.
  - ➢ The closer a node is to the reference clocks, the more precise it can (potentially) sync its clock.





Internet protocol suite

Application layer

BGP · DHCP · DNS · FTP · HTTP · IMAP · LDAP · MGCP · NNTP · **NTP** · POP · ONC/RPC · RTP · RTSP · RIP · SIP · SMTP · SNMP · SSH · Telnet · TLS/SSL · XMPP · *more...*

Transport layer

TCP · UDP · DCCP · SCTP · RSVP · *more...*

Internet layer

IP (IPv4 · IPv6) · ICMP · ICMPv6 · ECN · IGMP · IPsec · *more...*

Link layer

ARP · NDP · OSPF · Tunnels (L2TP) · PPP · MAC (Ethernet · DSL · ISDN · FDDI) · *more...*

V · T · E

Unreliable Clocks

Synchronization

Network Time Protocol (NTP)

- Synchronization Algorithm:
  - Client nodes regularly poll server nodes and calculate:

1. time offset

Offset send

Offset receive

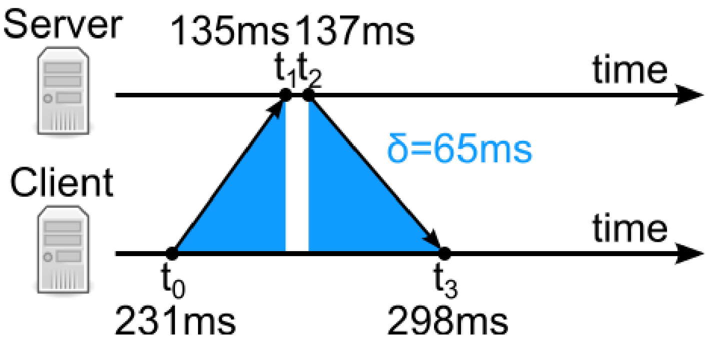
t_1 and t_3 include transmission time so it is added and deleted

$$\theta = \frac{(t_1 - t_0) + (t_2 - t_3)}{2}$$

Because we calculated the offset twice!

2. round-trip delay

$$\delta = (t_3 - t_0) - (t_2 - t_1)$$



t0, t1, t2, and t3 are timestamps attaches to the sync message.

  - θ and δ are passed through statistical analysis to remove outliers.
  - Client then gradually adjusts its local clock using θ e.g. by always adding 0.3 * θ to its local time.

Unreliable Clocks
Synchronization

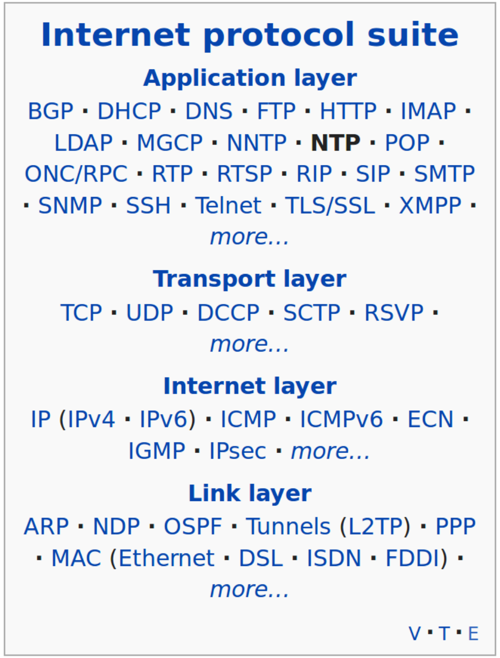
Network Time Protocol (NTP)

- Most popular clock synchronization protocol for packet-switched, variable-latency data networks.
- Computers synchronize their time with a group of servers.
- Servers get their time from more accurate time sources.

Confidence in local time t

- Estimation about the deviation between local and system time
- A client’s local time t can be expected to be t + uncertainty.
- uncertainty ≈ own expected clock drift since last NTP-sync + network round-trip time + server’s uncertainty

➢ Systems that rely on synchronized clocks try to estimate uncertainty and incorporate it in their application logic.



Internet protocol suite

Application layer

BGP · DHCP · DNS · FTP · HTTP · IMAP · LDAP · MGCP · NNTP · **NTP** · POP · ONC/RPC · RTP · RTSP · RIP · SIP · SMTP · SNMP · SSH · Telnet · TLS/SSL · XMPP · *more...*

Transport layer

TCP · UDP · DCCP · SCTP · RSVP · *more...*

Internet layer

IP (IPv4 · IPv6) · ICMP · ICMPv6 · ECN · IGMP · IPsec · *more...*

Link layer

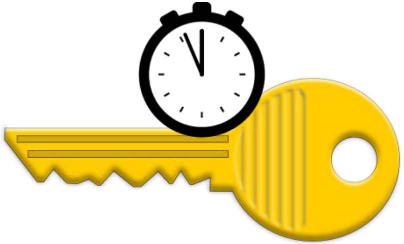
ARP · NDP · OSPF · Tunnels (L2TP) · PPP · MAC (Ethernet · DSL · ISDN · FDDI) · *more...*

V · T · E

Locking

Leases

- Leases are necessary if a system requires that there is only one of some thing:
  - One node with a certain permission for a particular resource
  - One node with a particular role in the system (e.g. leader)
- Obtaining a lease grants exclusive rights for a certain time.
- Assumption:
  - One node (lock service/server/authority) assigns locks/leases.
- If the time expires (monotonic time) …
  - the lease owner must renew it.
  - the lock service will re-assign the lease.



➢ We know that this approach alone can lead to split brain actions.

Unreliable Clocks

Locking

Leases

- If the time expires (monotonic time) …
    - the lease owner must renew it.
    - the lock service will re-assign the lease.

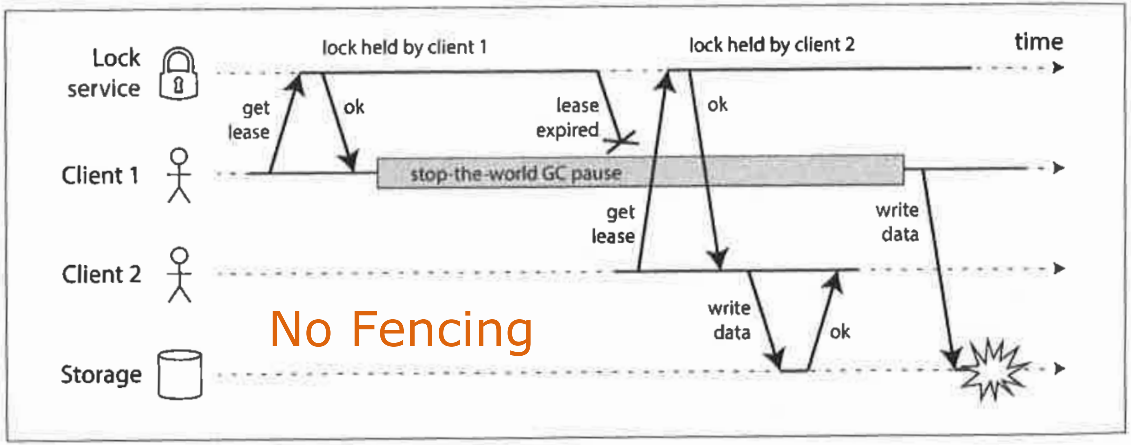
- Fencing token:
    - A number that increases every time a lock is assigned.
    - Handed to the lease owner as part of the lease.
    - Lease owner must issue the fencing token with every action.
    - Locked resource (!) checks if fence token is up-to-date (e.g. newest).
        - Reject if other node possesses newer fence token.

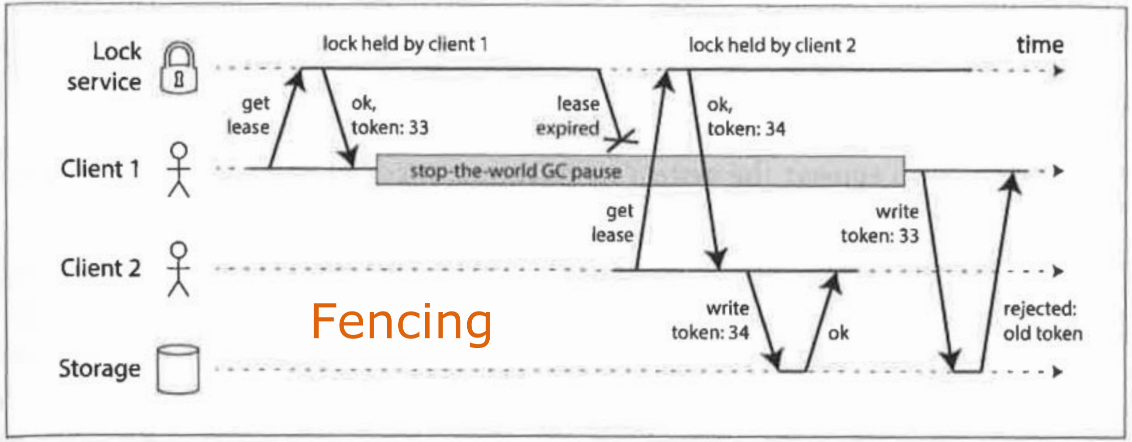
To counter the problem:
A node wrongly thinks
that it has the lock!

Locking

Leases

- Example:

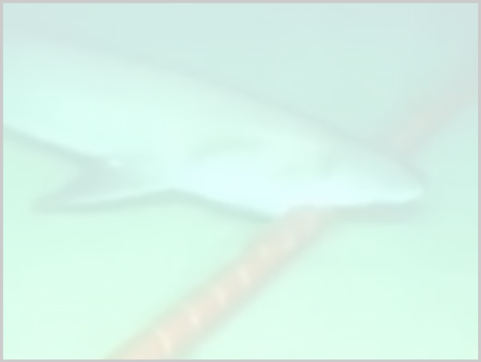




Overview

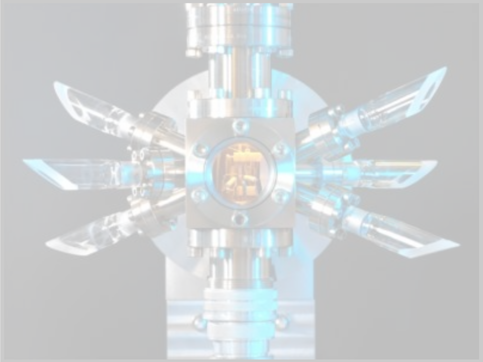
Distributed Systems

Unreliable Networks



A shark raiding an undersea cable

Unreliable Clocks



An atomic clock with minimum drift

Knowledge, Truth, Lies

Students communicating their knowledge

Knowledge and Truth

Knowledge

- A node can know nothing about other nodes for sure.
  - Can only make guesses based on received messages.

Truth

- = Statement supported by the cluster as a whole.
- Individual nodes may disagree with this statement.
- Can be defined by …
  - Property
    - A truth indicating statement property (e.g. versions or timestamps)
  - Authority
    - A representative node with a special role (e.g. master or leader)
  - Majority
    - A voting algorithm that finds a majority (e.g. via total order broadcast)

Knowledge and Truth

Property

- A truth indicating statement property (e.g. versions or timestamps)
- Determine truth:
  - Ask every node.
  - Compare the answers by their truth indicating property.
  - Consider the answer with the highest property value as truth.
- Note: Property collisions (same property value for different statements) need to be avoided.
- Examples:
  - A quorum read identifies the most recent value by its version.
    - ➢ The reader will get the most recent value from r responses (although n - w many nodes may disagree with that version).
  - Lamport timestamps clearly mark the most recent value.
    - ➢ All nodes will agree to that value (regardless of whether it is underrepresented or not).

Knowledge and Truth

Authority

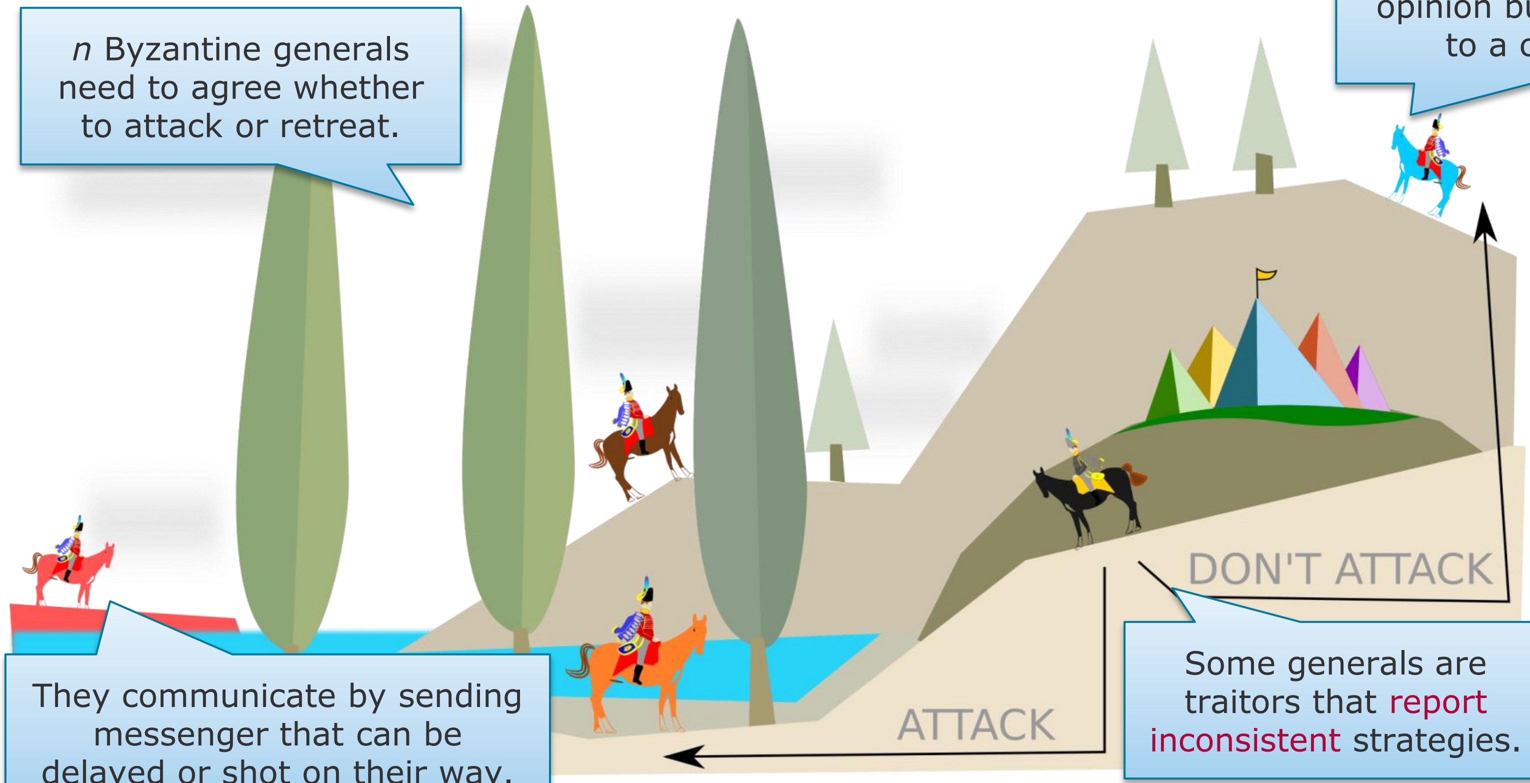
- A representative node with a special role (e.g. master or leader)
- Determine truth:
  - Ask the representative node.
  - Consider its answer as truth.
- Note: Asking any other node in the cluster does not ensure “true” statements.
- Examples:
  - A lease service hands out roles, locks and permissions.
    - ➢ The service always knows the nodes with these leases (although nodes might temporarily disagree).
  - A replication leader accepts and forwards all write operations.
    - ➢ The leader always serves the most recent version of a replica (although some changes might not have propagated yet).

Knowledge and Truth

Majority

- A voting algorithm that finds a majority (e.g. via total order broadcast)
- Determine truth:
  - Ask every node.
  - Consider the most frequent answer as truth.
- Note: Only clear majorities (>50% of the nodes) are stable; smaller majorities might have ties.
- Examples:
  - A node loses its connection to the network, but is still alive.
    - ➢ The majority sees the node disappear and will declare it dead (although the connection and not the node was faulty).
  - A change propagation message gets lost on the network.
    - ➢ The majority holds an outdated value that is declared valid (although the most recent value is on the node issuing the change).

Lies: Byzantine Problem



n Byzantine generals need to agree whether to attack or retreat.

Every general has an own opinion but would agree to a consensus.

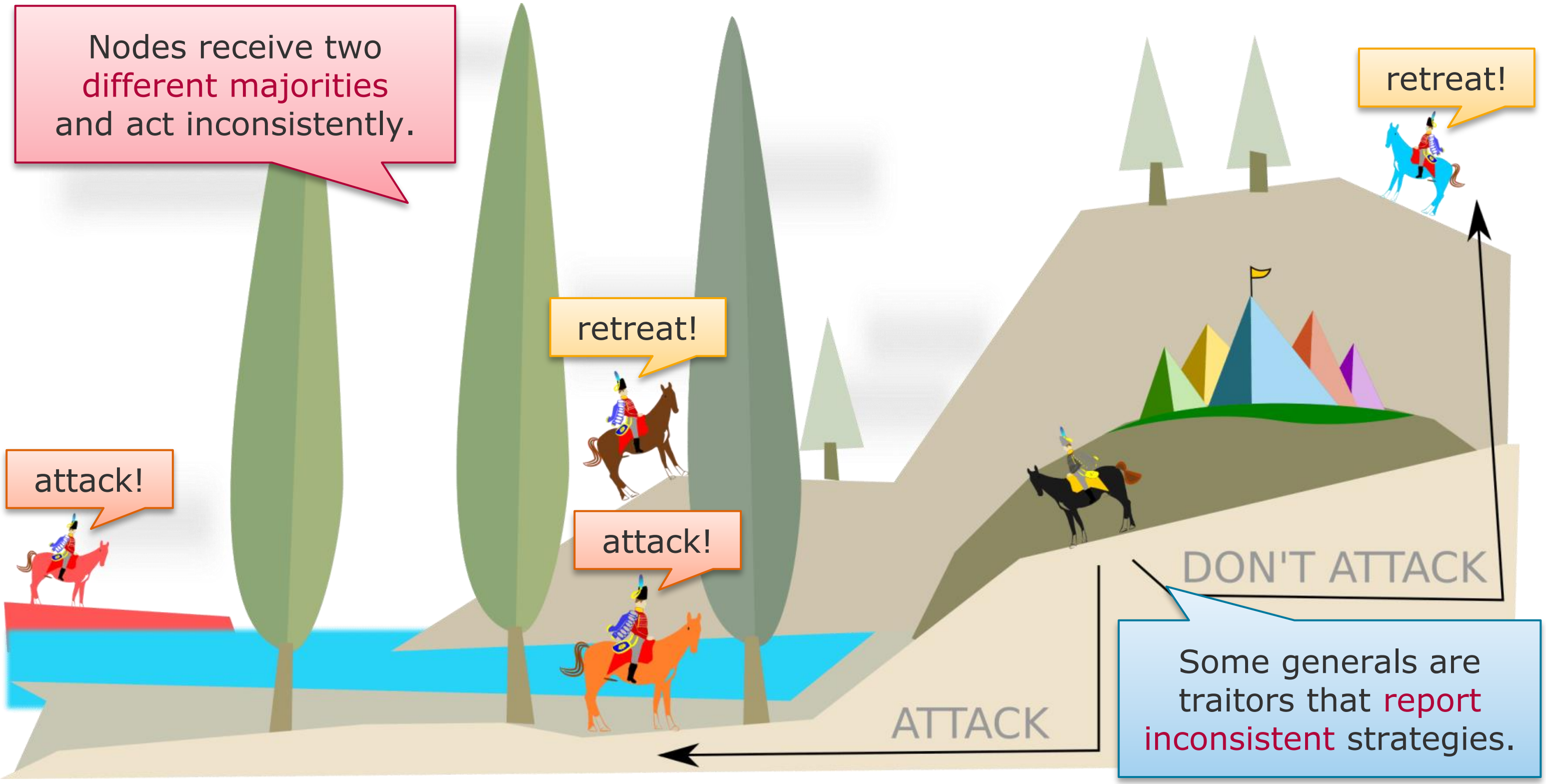
They communicate by sending messenger that can be delayed or shot on their way.

Some generals are traitors that report inconsistent strategies.

©https://blog.cdemi.io/byzantine-fault-tolerance/

Knowledge, Truth, and Lies

Lies: Byzantine Fault



Nodes receive two different majorities and act inconsistently.

Some generals are traitors that report inconsistent strategies.

©https://blog.cdemi.io/byzantine-fault-tolerance/

Lies

Weak Lies

- Nodes accidentally send invalid information (with no bad intention):
  - outdated, miss-calculated, damaged, lost, …
- Reasons:
  - software bugs, signal interference, misconfiguration, hardware faults, software update …
- Protection:
  - checksums (e.g. TCP), redundancy (e.g. NTP), quorums (e.g. Cassandra), sanity checks (application), …

Byzantine Lies

- Nodes systematically send invalid information (usually with bad intention)
- Reasons:
  - hardware faults, security compromises, malicious attacks, …
- Protection:
  - complicated, often inefficient consensus protocols
    - hardware-based, multiple-consensus-rounds, consensus-hierarchies, proof of work …

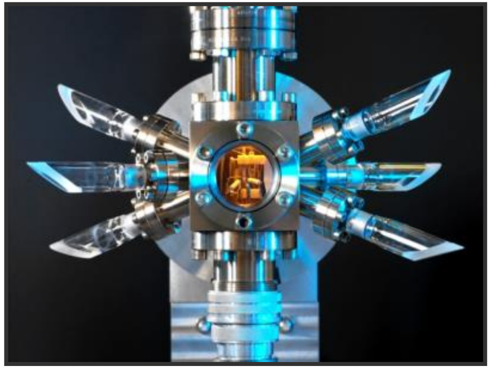
Distributed Systems

Summary

Unreliable Networks

A shark raiding an undersea cable

Unreliable Clocks



An atomic clock with minimum drift

Knowledge, Truth, Lies

Students communicating their knowledge

Unreliable Networks

- Messages can be lost, reordered, duplicated, and arbitrarily delayed

Unreliable Clocks

- Time is approximate at best, unsynchronized, and can pause

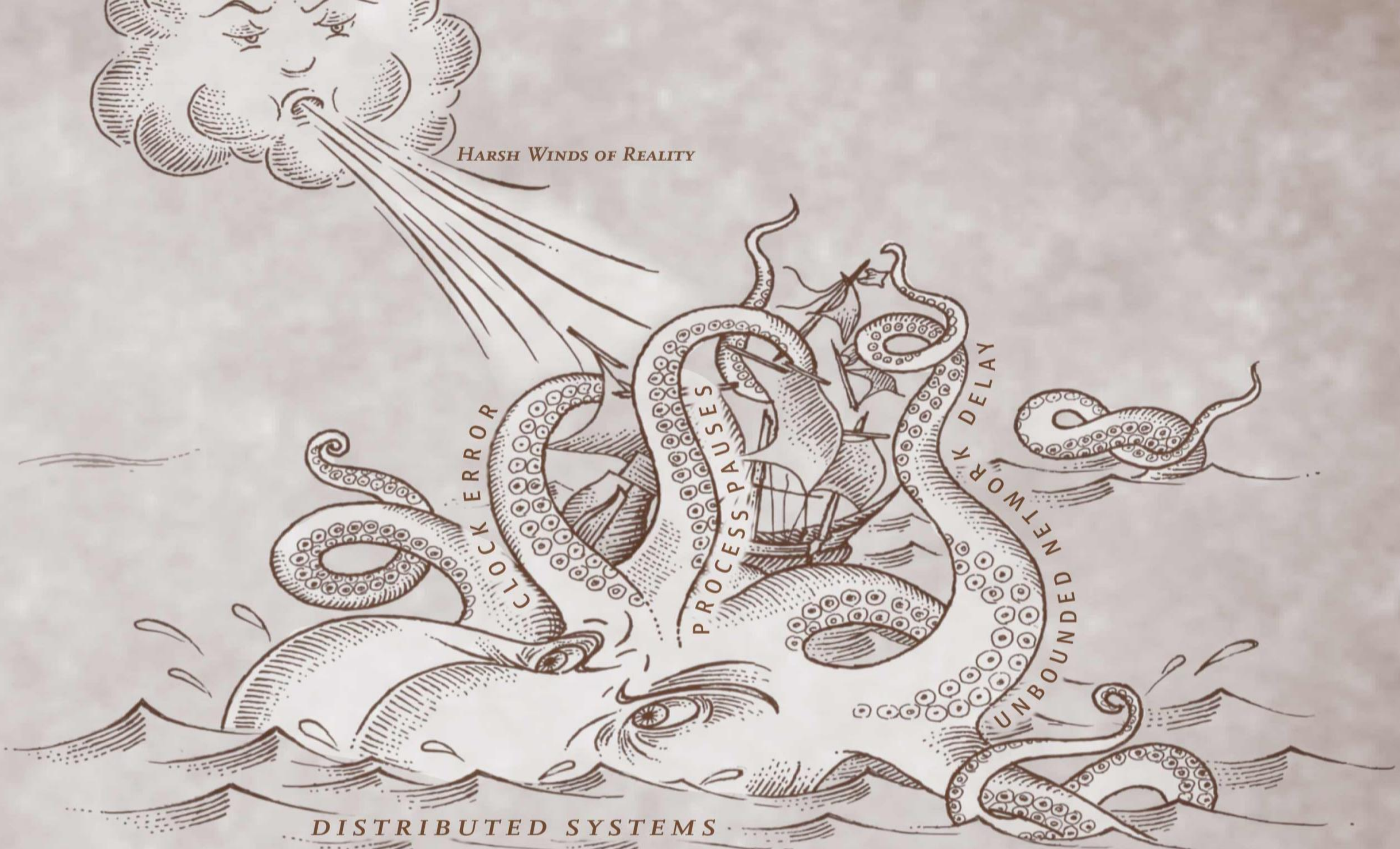
Distributed Systems

Check yourself

The φ accrual failure detector

- Suppose we observed the following heartbeat intervals (in s):
    - 14, 34, 15, 11, 17, 10, 35, 29, 28, 21
- Furthermore, assume we haven't received a heartbeat for 31s now.

- Use the φ accrual failure detector to estimate the probability P_{later} that the heartbeat will still arrive and give the value of φ.
- In reality, the heartbeat intervals follow a Gaussian distribution with the parameters mean $\mu=15.0$ and variance $\sigma^2=100.0$.
  By what factor did we misjudge the probability of P_{later}?


HARSH WINDS OF REALITY
CLOCK ERROR
PROCESS PAUSES
UNBOUNDED NETWORK DELAY
DISTRIBUTED SYSTEMS