

Lecture Notes

Distributed System

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Contents

1	Verteilte Systeme/Distributed Systems	3
1.1	Orga	3
1.1.1	Elektisches	3
1.1.2	Übungen	3
1.1.3	Material/Inhalt	3
2	Distributed Systems	5
3	Architectures of distributed Systems	7
3.1	System architectures	8
4	PeerSim	11
5	Processes	12
5.1	Virtualisation	13
5.2	Client-/Serverprocesses	14
5.3	Code Migration	16
6	Communication	18
6.1	RPC	18
6.2	Asynchronous RPC	18
6.3	Message oriented communication	
	18	
6.4	Message-passing-interface (MPI)	
	19	
6.5	Message-queuing-system, Message-oriented-middleware (MoM)	19
6.6	stream oriented communication	19
6.7	Multicast communication	19
6.8	Gossip-based-communication	20
7	Naming	21
7.1	Distributed Hash Tables	21
8	Synchronisation	22
8.1	Clock synchronisation algorithms	22
8.2	Network Time Protocol (NTP)	22
8.3	Berkeley algorithm	23
8.4	Logical Clocks - YEAH ALP5! :-	23

9	Vector Clocks	24
10	Mutual Exclusion	25
11	Leader Election algorithms	27
11.1	leader election in a synchronnous ring	27
11.1.1	LCR algorithm	27
11.1.2	Algorithm of Hirschberg and Sinclair (HS-Alg)	28
11.1.3	Time slice algorithm	29
11.1.4	Variable speeds algorithm	29
11.2	Leader election in a wireless environment	29
11.3	The Bully Algorithm(flooding) (Garcia-Mdina, 1982)	30

Chapter 1

Verteilte Systeme/Distributed Systems

1.1 Orga

VL Di 10-12 (nicht am 23.04.)
Ue Do 10-12

1.1.1 Elektisches

- (kvv)
- Website AG
- Sakai

1.1.2 Übungen

- ca. 5 Übungsblätter, 14-tägig
- Vorträge in Gruppen über „verteilte Systeme“

1.1.3 Material/Inhalt

1. Hälfte Distributed Systems (Tanenbaum, van Steen)
 - Architektur
 - Prozesse
 - Kommunikation
 - Namen
 - Synchronisation
 - Konsistenz
 - Replikation
 - Fehlertoleranz
2. Hälfte Distributed Algorithms (Nancy Lynch)
 - synchronous network algorithms

- network models (leader election, shortest path, distributed consensus, byzantine agreement)
- asynchronous network algorithms (shared memory, mutual exclusion, resource allocation, consensus)
- timing
- network resource allocation
- failure detectors

Chapter 2

Distributed Systems

Def: A distributed System is a collection of independent computers that appears to it's users as a single coherent system.

Characteristics:

- autonomous components
- appears as single system
- communication is hidden
- organisation is hidden
(could be high-performance mainframe or sensor net)
- heterogenous system offers homogenous look/interface

Objectives:

- provide resources (printer, storage, computing)
 - share in a controlled, efficient way
 - grant access
- ⇒ connect users and resources

Transparency:

hide the fact that processes and resources are physically distributed.

Types of transparency:

access hide differences in representation and how a resource is accessed

location

migration move ressources

relocation move ressources while using

replication

concurrency

failure

transparency is desirable, but not always perfectly possible

tradeoff between transparency and complexity, maintainability and performance

Open System

- service interfaces specified using Interface Definition Language (IDL)
- service specification as text

Scalability is an important property

- scalable in size (number of nodes)

- scalable in geographic spread
- scalable in administration

Problems

- centralized services
- centralized data
- centralized algorithms

Scaling techniques

- use only asynchronous communication
- distribution, split components
- replication of components

pitfalls

1. reliable network
2. secure network
3. homogenous network
4. constant topology
5. zero latency
6. infinite bandwidth
7. zero transport cost
8. one administrator!

Types of distributed systems

- computing systems
 - cluster computing

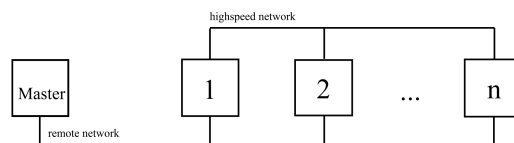


Figure 2.1: cluster computing

- grid computing(virtual organisation, geographically distributed and heterogenous))
- distributed information systems
 - transaction processing systems (database)
 - ACID (atomicity, consistency, isolated, durable)
 - enterprise systems
- Distributed pervasive systems
 - small, wireless, adhoc, no administration
 - home automation, health systems, sensor networks

Why do we need distributed systems?

- performance
- distribution inherent
- reliability
- incremental growth (scalability)
- sharing resources

Chapter 3

Architectures of distributed Systems

- how to split software into components
⇒ Softwarearchitecture
 - how to build a system out of the components
⇒ Systemarchitecture
- Middleware can help to create distribution transparency

Architecturestyles:

- Layered architecture
⇒ network stack, messages or data flow up and down
 - control flow between layers
 - requests down
 - reply up
- Object-based architectures
 - interaction between components
 - e.g. remote procedure calls
 - can be client-server system
- data-centered architectures
 - data is key element
 - communication over data, distributed database
 - web-systems mostly data-centric
- event-based architecture
 - publish-subscribe systems
 - processes communicates through events
 - publisher announces events at broker
⇒ loose coupling (publisher and subscriber need not to know each other), decoupled in space
⇒ scalability better than client-server, parallel processing, caching

Event-based and data-based can be combined

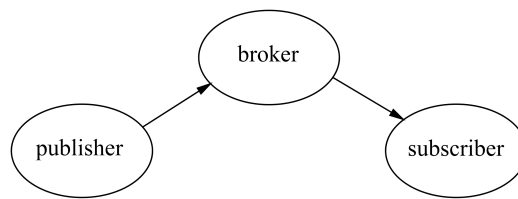


Figure 3.1: publish subscribe system

⇒ shared Data space

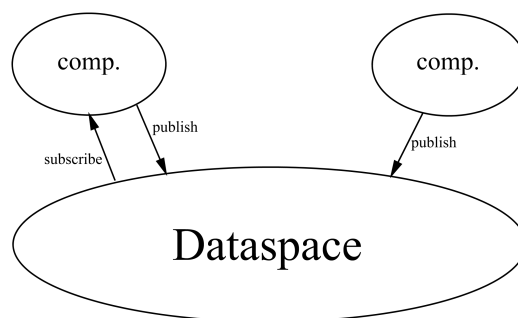


Figure 3.2: shared data space

3.1 System architectures

1. centralized architectures

client - server

- (i) single point of failure
- (ii) performance (server is bottleneck)

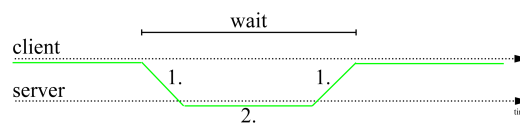


Figure 3.3: client server simple waiting situation

- (a) communication problems
- (b) server problems

can request be repeated without harm?

⇒ request is idempotent

(iii) application layering

Layers:

- 1.) User interface
- 2.) processing
- 3.) data level

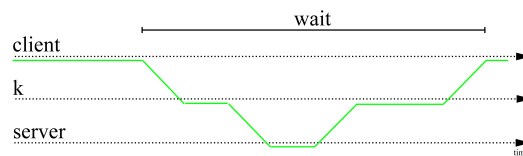


Figure 3.4: application layer

⇒ a lot of waiting

⇒ does not scale

2. Decentralized architectures

- vertical distribution (layering)
different logic on different machines
- horizontal distribution
replicated client/server operating on different data
⇒ overlay-underlay hides physical structure by adding logical structure

Structured P2P architectures

- most popular technique is distributed hash tables (DHT)
- randomly 128 bit or 160 bit ke for data and nodes. Two or more keys are very unlikely
- Chord system arranges items in a ring
- data item k is assigned to node with smallest identifier $id \geq k$

ie item 1 belongs to node 1

item 2 belongs to node 2

for each item k_i $\text{succ}(k)=id$

returns the name of the node k is assigned to

to find data item k the function $\text{LOOKUP}(k)$ returns the adress of $\text{succ}(k)$ in $O(\log(N))$ (later!)

membership management

join:

create SHA1 identifier

$\text{LOOKUP}(id) = \text{succ}(id)$

contact $\text{succ}(id)$ and $\text{pred}(id)$ to join ring

leave:

node id informs $\text{succ}(id)$ and $\text{pred}(id)$ and assigns it's data to $\text{succ}(id)$

Content adressable network (CAN)

- d-dimensional cartesian space
- every node draws random number
- space is divided among nodes
- every data draws identifier (coordinates) which assigns a node
- join
 - select random point
 - half the square in which id falls
 - assign item to centers
- leave
 - one node takes the rectangle
 - ⇒ reassign rectangles periodically

Unstructured P2P Network

- random graph
 - each node maintains a list of c neighbours
 - partial view or neighbourhood list with age
 - nodes exchange neighbour information
- active thread
select peer

PUSH

select c/2 youngest entries+myself
send to peer

PULL

receive peer buffer
construct new partial view
increment age

passive thread
recieve buffer from peer

PULL:

select c/2
send to peer
construct new partial view increment age

Chapter 4

PeerSim

Chapter 5

Processes

processes

- execution of program
- processor creates virtual processor
- for each program everything is stored in process table
- transparent sharing of resources,(processor, memory) separation
- each virtual processor has it's own independent adress space
- process switch is expensive, (save cpu context, pointers, translation lookaside buffer (TLB), memory management unit (MMU))
- perhaps even swaps to disk, if memory exhausted

2 possible solutions:

1. scheduler activation, upcall to achieve process switch
2. light-weight processes (LWP)
user level thread package

threads

- several threads share CPU
- thread context has little memory information, perhaps mutex lock
- threads avoid blocking application (e.g. spreadsheet,computation of dependent cells, intermediate backup)
- thread switch is fast
- user level threads allow parallel computation of program sections
- I/O or other blocking system calls block all threads, but thread creation/deletion is kernel task = expensive
- advantages of threads over processes vanishes

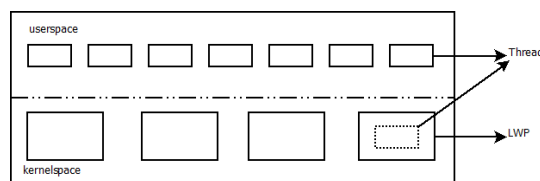


Figure 5.1: light-weight processes can run threads

execute scheduler and run thread of parent
may block on systemcall, then other LWP may run
triggered from userspace

Advantages of LWP and user-level thread package:

1. creation, deletion etc is easy, no kernel intervention
2. blocking syscall does not suspend process if enough LWPs are available
3. applications do not see LWP. They only see user-level threads
4. LWP can run on different processors in multiprocessor systems

Disadvantages:

1. LWP creation as expensive as creation of kernel-level thread

Advantages:

- a blocking systemcall blocks only thread, not process ⇒ system call for communication in distributed systems

Multiple threads in clients and servers

Clients:

- multiple thread may hide communication delay (distribution transparency)
- web browser opens several connections to load parts of a document/page
- web server may be replicated in same or different location
⇒ truly parallel access to items and parallel download

Servers:

- single threaded, e.g. file server
thread serves incoming request, waits for disk, returns file
serves next
- multithreaded
dispatcher thread receives request
hands over to worker thread
waits for disk etc.
dispatcher takes next request
- finite state machine
only one thread
examines request, either read from ... or from disk
during wait stores requests in table
serves next request
manage control either new request or reply from disk
act accordingly
process acts as finite state machine that receives messages and acts/changes state

summary:

model	characteristics
single thread	no parallelism, blocking syscalls
multi thread	parallelism, blocking syscalls
finite state machine	parallelism, non-blocking syscalls

5.1 Virtualisation

V pretends there are more resources than available.

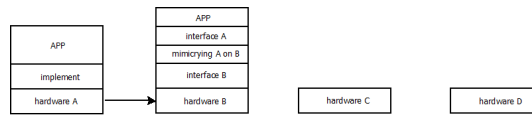


Figure 5.2: virtualisation

Reasons for the need for V.

- hardware changes much faster than SW
- ⇒ improves portability
- networks consist of different hardware
- ⇒ enables portability of programs for all usage (distributed applications, network protocols)

2 Types of Architectures for Virtualisation:

1. Runtime system providing instruction set
 - interpreted as Java
 - emulated as for Windows applications on UNIX-platform processes VM
2. Virtualisation shields hardware and offers instruction set of the same or other hardware
 - can host different OS that run simultaneously
 - ⇒ VMM such as VMware, Xen

5.2 Client-/Serverprocesses

Clients:

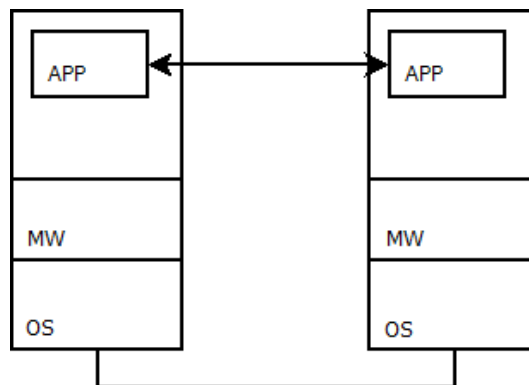


Figure 5.3: app specific communication

- b) allows to store data at the server
- **thin client** e.g. X-windows
- thin client should separate application logic from user interaction

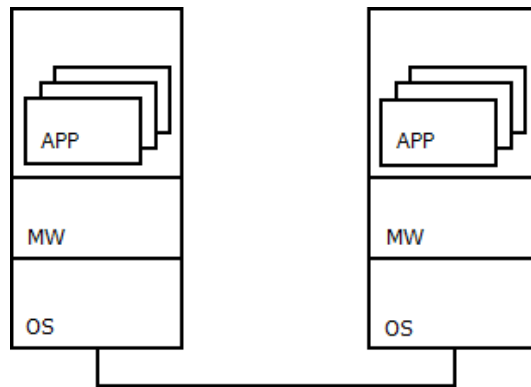


Figure 5.4: machine only communication

- often not implemented \Rightarrow poor performance
- compression of interaction commands as solution
- compound documents where user interaction triggers several processing steps on the server. must be implemented (e.g. rotation of picture changes placement in texts)

Servers:

- serves requests on behalf of the client
- Types of servers
 - **iterative Server** handles requests itself
 - **concurrent server** passes requests to worker, e.g. multithreaded server
- server listens to port, endpoint to the client; some ports are reserved for special services

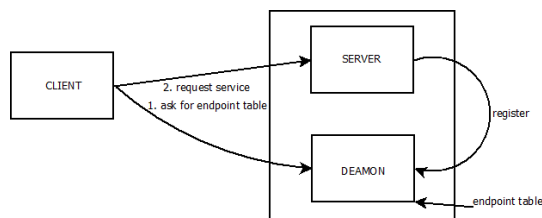


Figure 5.5: listener server

- superserver listens to several ports, replacing several (mostly idle) servers

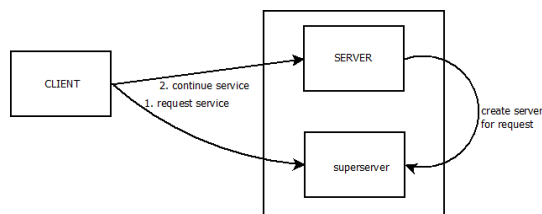


Figure 5.6: superserver

- stateless servers, keep no information on state of client → change state without informing the client, e.g. web server

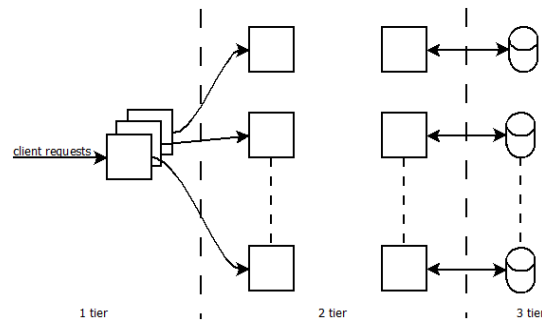


Figure 5.7: stateless server

- soft state server, maintains client state for limited time, e.g. servers informing about updates
- stateful server keeps information about client (file server keeps (client, file) table), often better performance, fault-tolerance poorer
- cookies allow to share information for server upon next visit client sends it's cookies, allows state information for stateless server

Distributed Servers

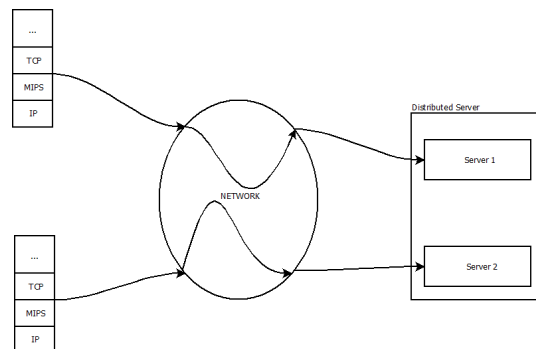


Figure 5.8: distributed server

- servers in different locations that have different ip-adresses in DNS under the same name
- MIPv6: mobility support for IPv6
- mobile node has home network with stable home address (HoA)
- special router is home agent and takes care of traffic to the mobile node
- mobile node receives care-of-adress (CoA), never seen by client
- route optimisation avoids routing through home agent

5.3 Code Migration

- Code migration on (running) process - Why?
- service placement in distributed system ⇒ minimize communication cost

- load balancing in multiprocessor machine or cluster ⇒ performance
- (security)

Models of Migration

- or process model
 1. code segment, instructions
 2. resource segment, references to external resources, i.e. file, printer, devices
 3. execution segment, execution state process, stack, private data, program counter
- **Migration types**
 - weak mobility, transfer code, (1), make 3)), which executes from beginning (i.e. java applets)
 - strong mobility, transfer 1)3), stop executions, transfer, resume

Migrating resource segment 2) is difficult

Consider process to resource binding

1. binding by identifier, URL, ftp-server-name
2. binding by value, libraries for programming
3. binding by type, local device, monitor

Resource-machine-binding

1. unattached
2. fastened
3. fixed

pass tp resource binding	unattached	fastened	fixed
by identifier	MV	GR(or MV)	GR
by value	CP	GR(or CP)	GR
by type	RB	RB(or GR,CP)	RB(or GR)

MV:move, GR, global refer-

ence, CP: copy value, RB: rebind to locally available resource

Chapter 6

Communication

we skip networking → Telematik

Consider:

- Remote procedure call
- Message-oriented communication
- Stream-oriented communication
- Multicast communication

6.1 RPC

Remote procedure call uses stubs to pack parameters in message
value parameters

⇒ value packed in messages, transfer byte-by-byte ⇒ problem can be little endian vs big endian systems

reference parameters are: extremely difficult; create array and pass by value; how to handle graphs, linked lists...

Remote procedure calls

6.2 Asynchronous RPC

- hide communication, communication transparency

6.3 Message oriented communication

- avoids synchronous communication which blocks sender Berkeley sockets UNIX TCP/IP
server |socket|→|bind|→|listen|→|accept|→|read|←→|write|→|close|

client |socket|—————->|connect|->|read|<->|write|->|close|

6.4 Message-passing-interface (MPI)

- standard for communication
- communication within group of processes
- each group/member has identifier

6.5 Message-queuing-system, Message-oriented-middleware (MoM)

- asynchronous persistent communication
- store messages
- transfer may take minutes, not milliseconds
- applications communicate by inserting messages into queues
- messages are inserted into local queue
- message carries destination address
- queue manager may act as relays, router
- message broker transform type A into type B, using a set of rules
- applications are email, workflow, batch processing, queries accross several databases

6.6 stream oriented communication

- temporal relationship between items important
- multimedia data is compressed
- QoS is important
 - bit rate
 - max delay for session setup
 - max end-to-end delay
 - max delay variance (jitter)
 - max round trip delay
- networking solution such as differentiated services
- synchronisation of streams

6.7 Multicast communication

- application level multicast uses overlay
- tree, unique path between each pair of nodes
- mesh, more robust, fault-tolerant

Example: Construct overlay tree for chord

- node that wants to start multicast generates key 128bit/160bit (nid) randomly
- lookup of succ(nid) finds node responsible for key mid
⇒ succ(nid) becomes root of tree
- join: lookup (nid) creates lookup message with join request routed from P to succ(nid)
- request is forwarded Q (first time forward), Q becomes forwarder
⇒ P child of Q
- request is first time forwarded by R, R becomes forwarder
⇒ Q becomes child of R
- multicast: lookup(nid) sends message to the root
multicast from root

Efficiency?

Quality of application level tree

1. Link stress, number of traversals of same link per packet
2. stretch, relative delay penalty (RDP)
 $\frac{\text{transmission time in overlay}}{\text{transmission time in delay/network}} \Rightarrow \text{minimize aggregated stretch, average RDP over all node pairs}$
3. tree cost, minimize aggregated link cost, link cost = cost between end points
⇒ find minimal spanning tree

6.8 Gossip-based-communication

- epidemic behaviour
- a node does not have new data (susceptible), it has the data (infected) or is unwilling to spread (removed)

Anti-entropy-model

P chooses randomly Q

1. P pushes its data to Q
 2. P pulls Q's data
 3. P and Q exchange data
- if many nodes are infected probability for selecting susceptible node is low
⇒ low probability of data dissemination
 - pull works when many nodes are infected. Susceptible node determines spread. They have a high probability to contact infected nodes
 - if only one node is infected push/pull is best
 - Round is period in which each node at least once selects a neighbor
number of rounds needed to spread $\approx \mathcal{O}(\log(N))$, N is number of nodes

Rumor spreading, gossiping:

function of nodes that never obtain data: $s = e^{\mathbb{W}((k \wedge 1)(1 \mathbb{W} s))}$

e.g. $k = 4, \ln(s) = 4,97$

⇒ $s = 0,007$

less than 0,7 remain without data

removing data is difficult : delete message is send via gossiping

Chapter 7

Naming

Flat naming

7.1 Distributed Hash Tables

- m-bit identifier (128 or 160 Bit)
- entity with key k is under jurisdiction of node with smallest identifier $id \geq k$
 $\Rightarrow \text{succ}(k)$
- resolve key k to address of $\text{succ}(k)$
- option 1: each node p keeps $\text{succ}(p)$, $\text{pred}(p)$ node forwards request for key k to a neighbor
if $\text{pred}(p) \leq k \leq p$, return(p)
 \Rightarrow not scalable
- better solution: each Chord node maintains finger table of length m
 $FT[i] = \text{succ}(p \wedge 2^{i\mathbb{W}_1}) = \text{succ}(p \wedge 1) = \text{succ}(2)$ (smallest id, such that $id \geq 2$)
 i -th entry points to $2^{i\mathbb{W}_1}$ ahead of p
- to lookup k node p forwards request to p with index j in p 's finger table:
 $q = FT_p[j] \leq k < FT_p[j+1]$
- example:
resolve $k = 26$ from node 1
 $k = 26 > FT_1[5] \Rightarrow$ forward request to node
 $18 = FT_1[5]$
 - node 18 selects node $20 = FT_{18}[2] \leq k < FT_{18}[3]$
 - node 20 selects node $21 \Rightarrow 28$ which is responsible for key 26
 - lookup generally requires $O(\log(N))$ steps, N nodes in system
 - join/leave is rather simple
 - keeping finger table up to date is expensive

Chapter 8

Synchronisation

8.1 Clock synchronisation algorithms

System model: each machine has timer that causes H interrupts per second

- clock C adds up ticks (interrupts)
- $C_p(t)$ is clock time on machine p
- perfect clock: $C_p(t) = t \forall p, t$
 $\iff C'_p(t) = \frac{dC_p(t)}{dt} = 1$
 \iff frequency of clock C_p at time t
- $C'_p(t) \setminus 1 \iff$ skew of p 's clock, difference to perfect clock.
- $C_p(t) \setminus t \iff$ offset
- real timers do not interrupt H timespers maximum drift p such
 $1 \setminus \rho \leq \frac{d(H)}{dt} \leq 1 \wedge p$
- at time δt two clocks that are drifting apart can be
 $|C_2(\Delta t) \setminus C_1(\Delta t)| \leq 2\rho\Delta t$
- if the difference should never exceed δ_i then synchronisation every $\frac{\delta}{2\rho}$ seconds is needed
- time allways moves forward.

8.2 Network Time Protocol (NTP)

- nodes contact time server that has an accurate clock
- time server pasive
 A estimates its offset to B as
 $\Theta = T_3 \setminus \frac{(T_2 \setminus T_1) \wedge (T_4 \setminus T_3)}{2}$
 assuming communication time is symmetric
 delay:
 $\delta = \frac{(T_2 \setminus T_1) \wedge (T_4 \setminus T_3)}{2}$
- A probes B, B probes A
- NTP stores 8 pairs (Θ, δ) per node pair using $\min(\delta)$ for smallest delay
- either A or B can be more stable
- reference node has strattime 1 (clock has starttime o)
- lower starttime level is better, will be used.

8.3 Berkeley algorithm

- assumes no node has 'good' time
- time server polls all nodes for their time
- takes average and adjusts speed of nodes correspondingly
- all nodes agree on time, which may not be correct

8.4 Logical Clocks - YEAH ALP5! -.-

- logical time need not correct in real time.
- needs 'happens before' relation $a \rightarrow b$
- happens before means:
 1. if a, b are events in the same process and a happens before b , then $a \rightarrow b$ is true
 2. if a denotes the event of sending a message and b the event of receiving this message by another process then $a \rightarrow b$ (Anmerk. von Tobi: is true?)
- happens before is transitive:
 $a \rightarrow b \wedge b \rightarrow c \Rightarrow a \rightarrow c$
- concurrency:
if x, y happen in different processes and neither $x \rightarrow y$ nor $y \rightarrow x$, then x, y are concurrent (which means, it is not known who comes first)
- if $a \rightarrow b$ then $C(a) \rightarrow C(b)$
- 4 properties of logical time
 1. No two events get assigned the same time.
 2. Logical times of events in each process are strictly increasing
 3. logical time of send event is strictly smaller than receive event for the same message
 4. for any $t \in T$ only finitely many events get assigned logical times smaller than t .
- Example:

Algorithm

1. Before each event P_i executes
 $C_i \leftarrow C_i \wedge 1$
2. When Process P_i sends message m to P_j it sets the timestamp of m , $ts(m)$ to the current time
 $ts(m) \leftarrow C_i$.
3. upon receipt of a message m process P_j adjust its time to $C_j \leftarrow \max(C_j, ts(m))$, then executes step 1 and delivers message

Example

Consider a bank with two data centers A and B, that need to be kept consistent. Each request uses the nearest copy. Assume a customer has \$1000,- in his bank account and decides to add \$100,- using copy A. At the same time 1% interest is added to copy B. What happens? How can we solve the problem? Totally ordered multicast

every message is sent to all receivers+itself with timestamp

- messages are stored in queues and acknowledged by timestamp
- queues are Lamports logical clocks
- eventually all queues are identical \Rightarrow total order

Chapter 9

Vector Clocks

- Lamport's logical clock causally order
- $T_{sent}(m_i) < T_{recv}(m_i)$ does $T_{recv}(m_i) < T_{sent}(m_j)$ tell something about m_i, m_j
use Vector Clocks
- each process P maintains VC
 1. $VC_i[i]$ is I of events that occurred so far at P_i VC in the logical clock of P_i
 2. $VC_i[j] = k$, P_i stores k events at P_j .
useful for causally ordered multicast

Chapter 10

Mutual Exclusion

Access to shared resources

2 types of algorithms: token-based and permission-based

- token is simple, reliability problem (lost token)
- permission difficult in distributed systems

1. Centralised algorithm

- one process is coordinator
- coordinator allows access only to one process
- fair, requests are processed in order of arrival
- no starvation
- easy to implement
- coordinator is single point of failure
- (handle message loss with ack)
- dead coordinator looks like permission denied

2. Decentralised algorithm

- Each resource is replicated n times, $rname_i$ is the name of the replica

- each replica has its own controller, the name is a hash of the $rname_i$
- if $rname$ is known, each process can generate the address of the controllers
- access to resource when $m > n/2$ controllers grant it
- Let p probability that a coordinator resets during Δt
 $P[k] = \text{prob}\{k \text{ out of } m \text{ coordinators reset during } \Delta t\} = \binom{m}{k} p^k (1-p)^{m-k}$
- at least $2m \setminus n \geq n \wedge 2 \setminus n = 2$ coordinators need to reset in order to violate the voting.

This happens with probability $\sum_{k=2m \setminus n}^n P[k]$

e.g. $\Delta t = 10s, n = 32, m = 0,75n$

Probability of violation in 10^{40}

- if a process gets less than m votes access to the resource is denied
- random backoff, retry
many requests, no one gets access
- heavy load \Rightarrow drop in utilisation

3. A distributed algorithm

- deterministic

- uses total ordering of events
- process that wants to access a resource sends out message containing (resourcename, process no, current localtime) to all other processes and itself
- process receives a message. Either:
 - (a) returns OK, if does not want a resource
 - (b) queues request, if it has resource
 - (c) compares timestamps, sends OK if timestamp is smallest, queues request and sends no reply else
- grants mutual exclusion without deadlocks or starvation

Problems:

- note failure \Rightarrow dito
- load, all processes take part in decisions (needs $2(n-1)$ messages for n processes)
- algorithm is slower, more complicated, more expensive, less robust than centralised alg.
- not a good algorithm

4. Token Ring Algorithm

- processes form a logical ring
- token circulates
- owner of token can access resource
- simple and efficient
- not fair under heavy load

Problems:

- token loss
-

	Algorithm	messages per entry/exit	Delay before access	Problems
Comparison	Centralised	3	2	coordinator crash
	Decentralised	$3mk$	$2m$	starvation, low efficiency
	Distributed	$2(n \setminus 1)$	$2(n \setminus 1)$	crash of any process
	Token Ring	1 to ∞	0 to ∞	lost token, process crash, fairness?

Chapter 11

Leader Election algorithms

11.1 leader election in a synchronnous ring

Network is a graph G consisting of n nodes connected by unidirectional links. Use $\text{mod } n$ for labels

- elected node is "leader"
- leader election is not possible for identical processes/nodes

11.1.1 LCR algorithm

(Lelan, Chang, Roberts)

- unidirectional communication
- ring size unknown
- only leader produces output
- algorithm compares UID

```
1 For each node
2   a = a UID, initially i's UID
3   send = a UID or NULL, initially i's UID
4   status = {unknown, leader} initially unknown
5
6 message generation
7   send = current value of send to node i+1
8
9 state transitions
10  send = NULL
11  if incoming message is v (a UID) then
12    v > u: send v
13    v = u: status = leader
14    v < u: do nothing
```

Correctness

Let max index of process with $\max(\text{UID})$ let u_{\max} is its UID
Show:

- (i) process max outputs "leader" after n rounds
- (ii) no other process does the same

We clarify:

(iii) After n rounds $\text{status}_{\max} = \text{leader}$
and

(iv) For $0 \leq r \leq n-1$ after r rounds

$$\text{send}_{\max} = u_{\max}$$

find UID at distance r from i_{\max} as it has to go once around.

Show (iv) for all r : Induction
then (iii)

Complexity

- time complexity is n rounds
- communication complexity $\mathcal{O}(n^2)$
- not very expensive in time many messages

11.1.2 Algorithm of Hirschberg and Sinclair (HS-Alg)

- reduces number of messages to $\mathcal{O}(n \log n)$

```

1 each process has states with components
2   u, UID: initially i's UID
3   send+ containing NULL or (UID, flag {in, out}, hopcount): initially
   (i's UID, out, 1)
4   send as send+
5   status  $\in \{\text{unknown}, \text{leader}\}$  initially unknown phase  $\in \mathbb{N}$ : initially 0
6
7 message generation
8   send current send+ to process  $i+1$ 
9   send current send as send to process  $i-1$ 
10
11 state transitions
12   send+ = NULL
13   send = NULL
14   if message from  $(i-1)$  is  $(v, \text{out}, h)$  then
15      $v > u$   $\wedge$   $h > 1$ : send+ =  $(v, \text{out}, h-1)$ 
16      $v > u$   $\wedge$   $h = 1$ : send =  $(v, \text{in}, 1)$ 
17      $v = u$  status = leader
18   if message from  $i+1$  is  $(v, \text{out}, h)$  then
19      $v > u$   $\wedge$   $h > 1$ : send =  $(v, \text{out}, h-1)$ 
20      $v > u$   $\wedge$   $h = 1$ : send+ =  $(v, \text{in}, 1)$ 
21      $v = u$  status = leader
22   if message from  $i-1$  is  $(v, \text{in}, 1)$   $\wedge$   $v \neq u$  then
23     send+ =  $(v, \text{in}, 1)$ 

```

```

24 if message from i+1 is (v,in,1) & v≠u then
25   send W=(v,in,1)
26 if both messages from iW1 and i+1 are (u,in,1) then
27   phase++
28   send+=(u,out, 2^{phase})
29   send W=(u,out, 2^{phase})

```

Complexity

Total number of phases is at most $1 \wedge \lceil \log(n) \rceil$

the total number of messages is at most $1 \wedge \lceil \log(n) \rceil \approx \mathcal{O}(n \log n)$

Total time complexity is at most $3n$ if n power of 2 otherwise is $5n$

11.1.3 Time slice algorithm

- ring size n is known
- unidirectional
- elects minimum

*

```

1 phases with n rounds
2 in phase r consisting of rounds (vW1)n+1,...,vn
3 only a token carrying UID v is permitted
4 if a process with UID v exists, then it elects itself leader and
   sends a token with it 's UID

```

Complexity: number of messages is n , time complexity $n \cdot u_{min}$

11.1.4 Variable speeds algorithm

- each process i creates a token to travel around the ring, carrying UID u of origin
- tokens travel at different speed
- token carrying UID v travels 1 message every 2^v rounds
- each process memorises smallest UID
- return to origin elects UID

Complexity

...

How many messages in total? $\sum_{k=1}^n \frac{1}{2^k W_k} (< 2n)$

Time complexity: $n \cdot 2^{u_{min}}$

11.2 Leader election in a wireless environment

- consider time needed for communication
- nodes set up a tree
- select based on information like battery lifetime
- node issues leader request to all its neighbours
- becomes parent if there is none yet

11.3 The Bully Algorithm(flooding) (Garcia-Mdina, 1982)

- process P holds election
 1. P sends ELECT message to all processes
 2. P wins if there is no response \Rightarrow P is leader
 3. if Q answers, Q takes over