D Distributed Systems

D.1 Overview

- Definition and Motivation
- Taxonomy
- Communication Models
- Selected Problems of Distributed Systems
- Object-Based Distributed Systems

D.2 References

General:

NeS98. J. Nehmer, P. Sturm: *Systemsoftware, Grundlagen moderner Betriebssysteme*. dpunkt, 1998.

Mul89. S. Mullender (Ed.): *Distributed Systems*. ACM Press, 1989.

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Tan95. A. S. Tanenbaum: *Verteilte Betriebssysteme*. Prentice Hall, 1995.

Special Problems:

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Flyn72. M. J. Flynn: “Some Computer Organizations and Their Effectiveness.” *IEEE Transactions on Computers*, **C-21**, Sept. 1992, pp. 948–960.

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Matt89. F. Mattern: *Verteilte Basisalgorithmen*. Springer, Informatik-Fachberichte Nr. 226, July 1989.

D.3 Definition and Motivation

- *“Distributed System”*
  Definition according to Tanenbaum and van Renesse
  - ◆ It looks like an ordinary centralized system.
  - ◆ It runs on multiple, independent CPUs.
  - ◆ The use of multiple processors should be invisible (transparent).
- *“Distributed System”*
  Definition according to Mullender
  - ◆ Additionally: Not any single points of failures
- Definitions are not precise
  - ◆ Sometimes it is hard to identify a centralized or a distributed system.
  - ◆ Definitions are often based on certain characteristics that are important.

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1 Advantages

- Efficiency to cost ratio
  - ◆ High performance computers are very expensive
  - ◆ Microprocessors became very cheap
  - ◆ Multiple microprocessors can easily have more computing power than a high performance computer and cost much less.
- ★ Costs
  - ◆ Distributed systems can be much cheaper at same capacity.
  - ◆ Expensive devices (e.g., color printers) can be shared by many users.
- ★ Efficiency
  - ◆ Distributed systems can be much more efficient than any available high performance computer.

1 Advantages (2)

- ■ Centralized CPU vs. personal computer
  - ◆ Response time of centralized systems is very bad at high load.
  - ◆ Personal computers are available for a single user.
  - ◆ More computing power available for a single user: better user interfaces, etc.
- ★ Load Balancing
  - ◆ Unlike individual PCs, a distributed system can grant peak performance to a single user without annoying other users.
- ★ Inherent distribution
  - ◆ People are distributed
  - ◆ Information is distributed
  - ◆ Devices are distributed
  - ◆ Distributed systems model the inherent distribution of today’s organizations.
  - ◆ People can communicate via distributed systems. Some day, a distributed system might replace the POTS (plain old telephone system).

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1 Advantages (3)

- ■ Scalability
  - ◆ “No” restriction on the maximum size of the system.
- ★ Extensibility, incremental growth
  - ◆ It is easier to add a new computer to a distributed system than to extend a high performance machine.

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1 Advantages (4)

- ★ Availability
  - ◆ Distributed systems can have redundant components (CPUs, memory, communication channels, etc.)
  - ◆ System just runs on if a component fails.
- ★ Reliability
  - ◆ Reliability needs availability.
  - ◆ Reliable systems mask failures (e.g., CPU failure, communication failures, etc.)
  - ◆ Distributed systems can be made very reliable. However, this is a difficult task.

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2 Disadvantages

- ▲ Concurrency
  - ◆ Distributed systems are inherently concurrent.
  - ◆ Controlling concurrency is complex.
  - ◆ Combining well-understood components can generate new problems not apparent to the components.
- ▲ Propagation of effect
  - ◆ One malfunctioning computer can bring down the whole system.
  - ◆ There can be unforeseen dependences between components.
- ▲ Security
  - ◆ It is harder to secure a physically distributed system.
  - ◆ Communication channels can be wire tapped and eavesdropped.
  - ◆ Data access could not be controlled on certain sites.

2 Disadvantages (2)

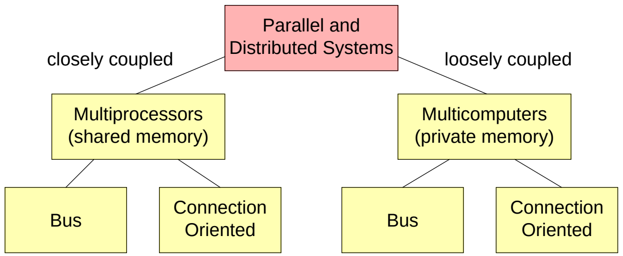
- Efficiency
    - Distributed systems can only gain efficiency for the total output of the entire system. If you cannot parallelize your application you cannot benefit from the available high performance.
- Load Balancing
    - It is hard to balance the load because the physical distribution of resources may not match the distribution of demands.
- Scalability
    - A working system with ten nodes may fail miserably when it grows to a hundred nodes.
- Complexity
    - All in all, a distributed system is much more complex than a centralized one (e.g., dealing with partial failures, concurrency, load balancing, etc.)

D.4 Taxonomy

- Classification according to Flynn (1972)
    - SISD – Single Instruction Stream, Single Data Stream
      all current single CPU computers (PCs, Mainframes)
    - SIMD – Single Instruction Stream, Multiple Data Streams
      high performance computers, vector computers
    - MISD – Multiple Instruction Streams, Single Data Stream
      no known system available that implements this category
    - MIMD – Multiple Instruction Streams, Multiple Data Streams
      systems with independent CPUs
- Distributed systems are always seen as MIMD computers

D.4 Taxonomy (2)

- Taxonomy of parallel and distributed computer systems (MIMD)



according to Tanenbaum 1995

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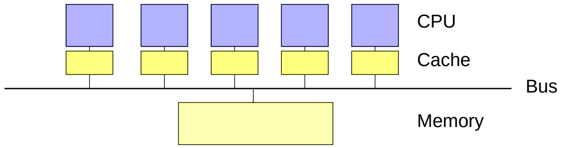
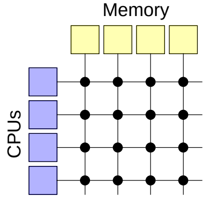
1 Multiprocessors

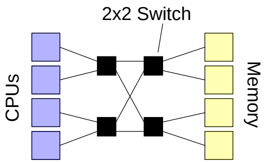
- Shared memory
    - All CPUs share the memory
    - Memory is coherent
        - Written data items are immediately visible to other CPUs
- Bus-based systems
    - CPUs access memory via a bus
    - Limited number of CPUs
    - Increased performance by CPU-side caches
    - Cache consistency achieved by bus snooping



1 Multiprocessors (2)

- Connection-oriented systems
  - ◆ For more than 64 processors bus-based systems fail
  - ◆ Cross-bar switch / Omega switching network





  - ◆ Cross-bar switches need n^2 switches
  - ◆ Omega networks need $n \cdot \log_2 n$ switches
  - ◆ Slow memory access
  - ◆ Solution: hierarchical systems (NUMA = Non uniform memory access)

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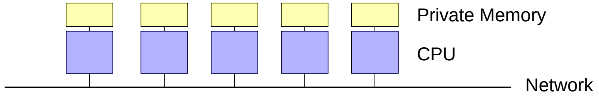
2 Multicomputers

- Each CPU has its own private memory

- Bus-based multicomputers
  - ◆ Workstations in a LAN



  - ◆ CPUs connected to a fast communication bus

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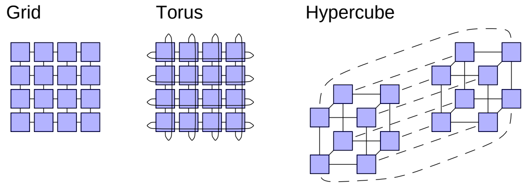
2 Multicomputers (2)

- Connection-oriented multicomputers
  - ◆ Examples of topologies:



  - ◆ Each CPU is connected to a number of other CPUs

- Computers in a wide area network?
  - ◆ Bus-based, as each CPU is virtually connected to every other
  - ◆ Connection-oriented, as there is no uniform access to other CPUs

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3 Network Operating Systems

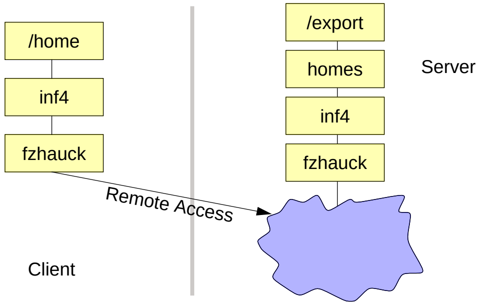
- Early distributed systems

- Loosely-coupled systems
  - ◆ Multicomputers usually in a LAN

- One (but not necessarily the same) operating system on each system
  - ◆ Users act locally
  - ◆ Users have access to remote systems
    - Remote login: **`rlogin faui04a`**
    - Remote copy: **`rcp faui04a:aFile myCopy`**
    - Shared file systems
    - Shared devices (e.g., printers)

3 Network Operating Systems (2)

- Shared file systems
  - Users can operate on remote files as on local files
  - File server provide remote access to local files
  - Local file name is not necessarily equal to remote file name



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4 True Distributed Systems

- Same operating system on each node
- System behaves like a uniprocessor
  - Users should not see any differences if they access the system from another node.
  - The identity of the local computer is not important.
  - File sharing semantics is usually well-defined.
- Transparencies
  - Location transparency — location of resources is irrelevant
  - Migration transparency — resources may move
  - Replication transparency — resources may be replicated
  - Concurrency transparency — multiple accesses to a resource at a time
  - Parallelism transparency — activities may be executed in parallel

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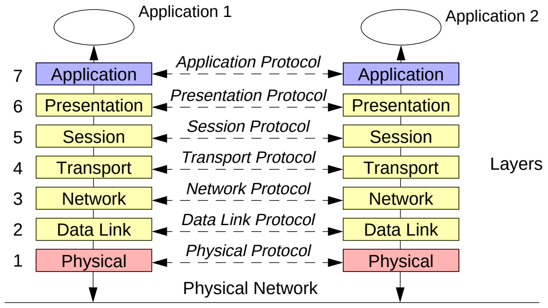
D.5 Communication Models

- Communication needs agreement
  - Protocols

1 Protocol layers according to the ISO OSI reference model



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1 Protocol Layers (2)

- Physical Layer
  - Transmission of 0s and 1s on the wire
- Data Link Layer
  - Sending bits; separating frames or packets; checking frame integrity
- Network Layer
  - Routing of messages in larger networks
- Transport Layer
  - Implementation of reliable connections
  - Fragmentation and reassembling
- Session Layer
  - Dialog control; synchronization

1 Protocol Layers (3)

- Presentation Layer
  - ◆ Transparency of different internal representations of data
- Application Layer
  - ◆ Set of application protocols
    - Electronic mail protocol
    - File transfer protocol
    - etc.

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2 Classification

- Synchronicity
  - ◆ Is the sender blocked until the receiver gets a message, or not?
- Pattern of Interaction
  - ◆ Message Passing — a message is sent from one party to the other
  - ◆ Request-Reply (Client-Server) Interaction — there is a message to the receiver and a message back to the original sender
- Addressees
  - ◆ One receiver
  - ◆ Multiple receivers (group communication, multicast, broadcast)

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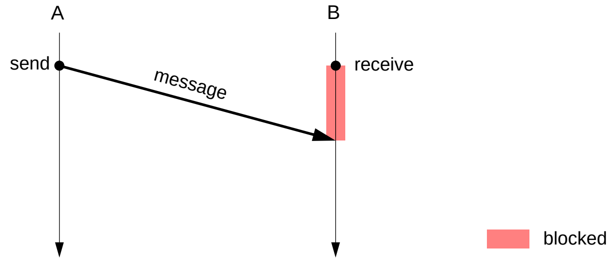
2 Datagram Message

- Message passing; asynchronous send



- ◆ Sender can proceed immediately
- ◆ Receiver may be blocked until a message arrives
- ◆ Needs buffer space for not yet received messages

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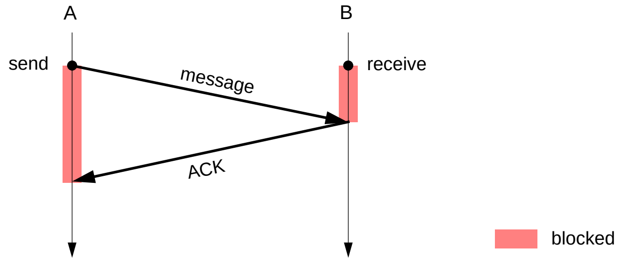
3 Rendezvous Model

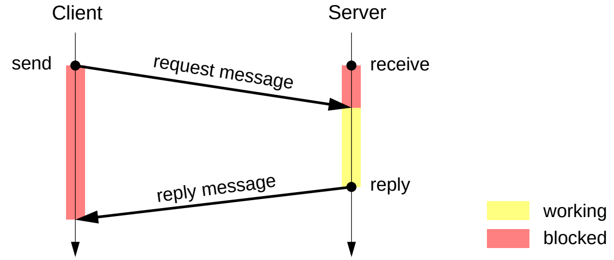
- Message passing; synchronous send



- ◆ Sender waits until message is received
- ◆ Receiver may be blocked until a message arrives
- ◆ Needs no buffer space

4 Synchronous Request-Reply Model

- Request-reply interaction; synchronous send



- ◆ Client waits until reply message is received
- ◆ Server may be blocked until a request message arrives
- ◆ Client and server do not work concurrently
- ◆ Well known representative is the RPC (remote procedure call)

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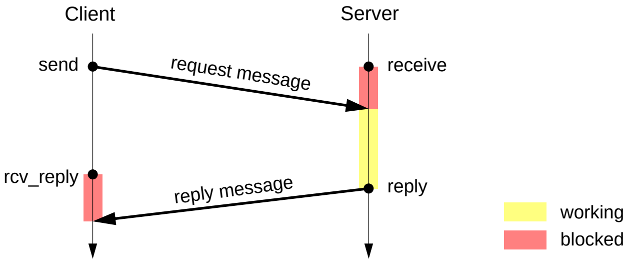
5 Asynchronous Request-Reply Model

- Request-reply interaction; asynchronous send



- ◆ Client and server can work concurrently
- ◆ Basis for group communication

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6 Reliability

- It is possible that messages get lost if we do not use a reliable connection
  - ◆ Reliable connections introduce acknowledge messages (ACK)
  - ◆ For simple message passing this means a lot of overhead

★ Combining reliability with the request-reply interaction model

- Possible errors
  - ◆ Server crash
    failure model is: total amnesia
    (server looses all knowledge of former requests)
  - ◆ Request message gets lost
  - ◆ Reply message gets lost
- Ideal semantics
  - ◆ *exactly-once*
    The request is processed exactly once at the server side.

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6 Reliability (2)

- **At-Least-Once Semantics**
  - ◆ Request is processed once or more times
  - ◆ Client will never notice an error message, but it may notice that the request was processed multiple times: operations need to be *idempotent*.
- Implementation
  - ◆ If the client does not get a reply message after some time (time-out), it resends the request.
    - There is no additional functionality needed at the server side.
    - However, the server can ignore resent requests if it can detect them.

6 Reliability (3)

- **At-Most-Once Semantics**
  - ◆ The request is processed once or not at all.
- Simple implementation (at the client side only)
  - ◆ If the reply message does not arrive within a certain period of time an error is returned to the caller (at-most-once semantics).
  - ◆ Otherwise, the result is returned (exactly-once semantics).
- More complex implementation
  - ◆ Client repeats request message after time-out (hides message losses on the wire).
  - ◆ Client has to identify server crashes (error code to the caller, at-most-once semantics).
  - ◆ Server keeps reply messages (enables resending if message gets lost)
  - ◆ Server has to identify and ignore old requests after server crash.
  - ◆ If the result is returned we have exactly-once semantics.

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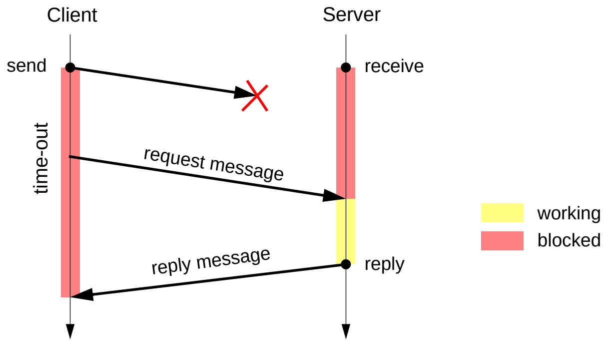
6 Reliability (4)

▲ Request message gets lost



◆ Request is repeated

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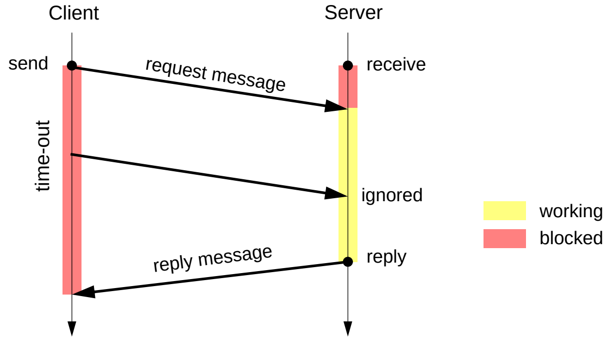
6 Reliability (5)

▲ Processing has not yet finished



◆ Repeated request is ignored

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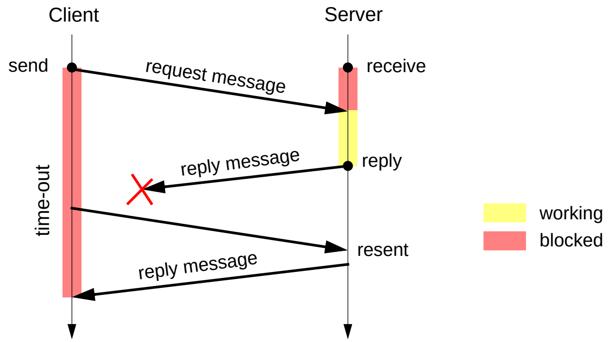
6 Reliability (6)

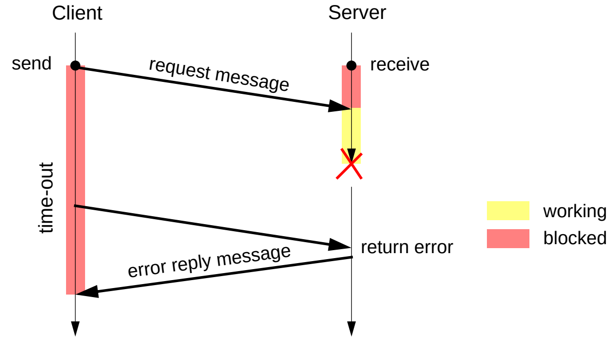
▲ Reply message gets lost



◆ Server keeps reply message and resends it

6 Reliability (7)

- Server crashes



  - Server identifies old requests (old generation number) and returns error code (at-most-once semantics)

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7 Remote Procedure Calls

- Request-reply model can be used to implement RPCs [Birrell and Nelson 1984]
  - Instead of sending a request message, we invoke a remote procedure
  - Instead of receiving a reply message, we get the results of the invocation

- ★ Invocation of a procedure is location-transparent
  - Syntax may be the same for local or remote invocation
  - Very intuitive
  - No need for explicit usage of send and receive primitives

- Implementing RPCs
  - Stub procedures on client and server side

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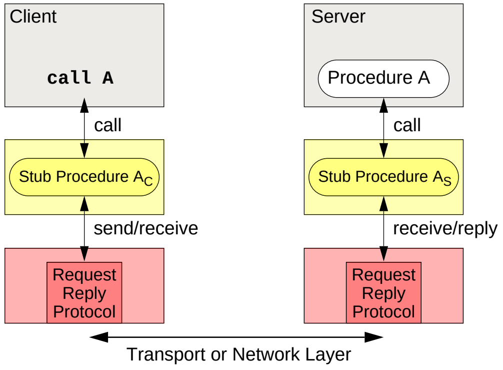
7 Remote Procedure Calls (2)

- Implementing RPCs using stub procedures



acc. to Nehmer 1995

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7 Remote Procedure Calls (3)

- Client stub procedure
  - Marshalling of parameters (composing a request message)
  - Sending request message
  - Waiting for reply message
  - Unmarshalling of the result
  - Implementing delivery semantics

- Server stub procedure
  - Receiving request message
  - Unmarshalling of parameters
  - Invoking server procedure
  - Marshalling of the result
  - Sending reply message
  - Implementing delivery semantics

7 Remote Procedure Calls (4)

- Problems with RPCs
  - Marshalling of parameters
    - Number and types must be known
      (cmp. with C: `printf( "Count %d\n", count )`)
  - Parameter passing semantics
    - *Call-by-value:* no problem
    - *Call-by-reference:* How to implement?
  - No global variables
  - Semantics
    - Server crashes; no exactly-once semantics
  - Performance
    - No concurrency
    - Large parameter data
    - Short procedures

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7 Remote Procedure Calls (5)

- Automatic generation of stub procedures
  - Tools generate code for:
    - parameter marshalling
    - client stub procedure
    - server stub procedure
    - server loop waiting for request messages

- Binding client stubs to server stubs
  - Server stub has a network address that must be known to the client stub
  - Problem: How does the client know its server?

- Name server
  - Symbolic names are converted to network addresses

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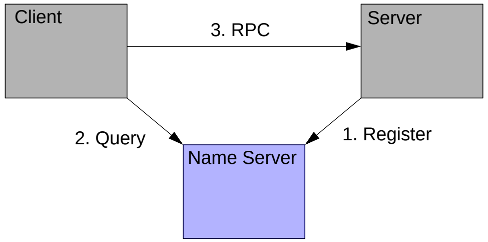
8 Name Server and Binding

- Well known name server converts names to addresses
  - Client knows a unique name for its server and the address of a name server
  - Name server converts this name to a dynamic network address

  - Client can always bind to the server
  - Server has to register its dynamic network address with the name server



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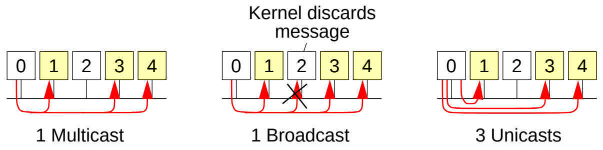
9 Group Communication

- Motivation
  - Often more than one server needs to be informed
    - multiple servers administrate a resource
    - multiple redundant servers (no “single point of failure”)

- Terminology
  - Unicast
    - One receiver (1:1)
  - Anycast
    - One receiver of many (1:1 of n)
  - Multicast
    - Multiple receivers (1:n)
  - Broadcast
    - All receivers of a special group (1:n)

9 Group Communication (2)

- Implementation of multicast
  - Using a hardware-based multicast
    - e.g., Ethernet multicast
  - Using a hardware-based broadcast
    - e.g., Ethernet broadcast
    - filtering of not addressed parties at receiver side
  - Using unicast messages
    - sending an individual message to each party



1 Multicast

1 Broadcast

3 Unicasts

acc. to Tanenbaum 1995

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9 Group Communication (3)

- Primitives for group communication
  - Message passing
    - Same primitives as for unicasts (**`send`**, **`receive`**) and multiple addressees for **`send`**
    - Different primitives: **`group_send`**, **`group_receive`**
  - Request-reply interaction
    - Multiple **`rcv_reply`** invocations to get all reply messages
- Variants of group communication semantics
  - *Reliability:* none, k-reliable, atomic/reliable
  - *Message ordering:* none, FIFO order, causal order, total order

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9 Group Communication (4)

- Reliability
  - **None:** messages may arrive or may not arrive at a receiver
  - **K-reliable:** at least k members of the group receive the message
  - **Atomic/reliable:** all members or none of them receive the message
- Message ordering
  - **None:** messages arrive in arbitrary order at a receiver
  - **FIFO order:** messages arrive in the order sent by the sender
  - **Causal order:** causality of messages is reflected in the order of arrival
    - If a member of the group receives a message A and then sends a message B to the group, each group member will first receive A and then message B.
  - **Total order:** as causal order, but additionally not causally dependent messages arrive in the same order at each receiver

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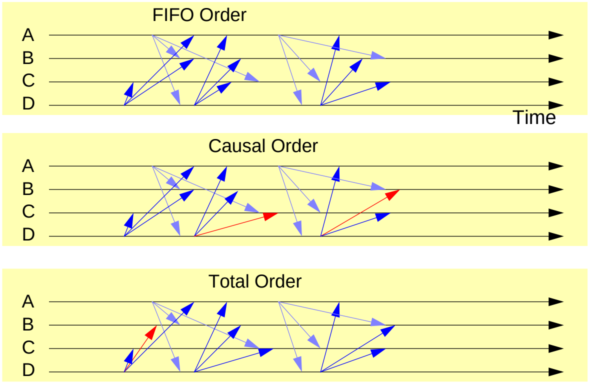
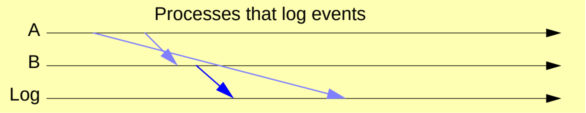
9 Group Communication (5)

- Examples for different message ordering



D.6 Selected Problems of Distributed Systems

- Causality
  - ◆ Simple message passing may violate causality (Log file example)



Log entries are not causally ordered

- Synchronization of processes
  - ◆ Semaphores and monitors depend on coherent shared memory
  - ◆ No shared memory on multicomputer systems
- Synchronization of clocks
  - ◆ System clocks are never exactly synchronized in distributed systems

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D.6 Selected Problems of Distributed Systems (2)

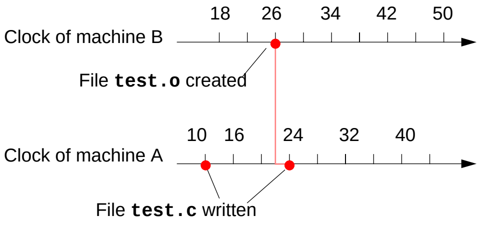
- Example: UNIX *make* command

Makefile

```
test.o: test.c

test: test.o
```

- ◆ Editor runs on machine A
- ◆ Compiler runs on machine B



➜ *Make* command will not notice necessary update!!

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1 Logical Clocks

- Usually the precise absolute time is not necessary
  - ◆ We only need to know when one event causally depends on another
  - ◆ a → b is read “b is causally dependent on a”
  - ◆ If a → b and b → c then a → c (transitivity)
  - ◆ If neither a → b nor b → a is true then a and b are said to be **concurrent**
- Clock condition:
  - ◆ If an event b causally depends on an event a then timestamp of a must be less than the timestamp of b
  - ◆ a → b ⇒ T(a) < T(b)
- Algorithm of Lamport (1978)
  - ◆ Messages as the only means for communication
  - ◆ Fulfills clock condition

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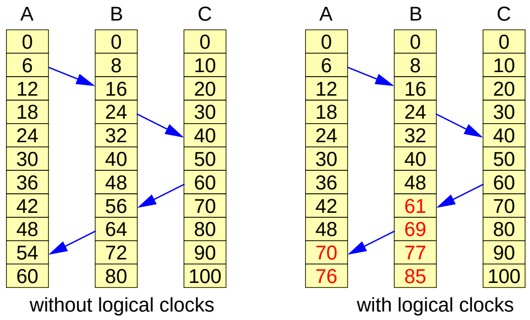
1 Logical Clocks (2)

- Example



A	B	C
0	0	0
6	8	10
12	16	20
18	24	30
24	32	40
30	40	50
36	48	60
42	56	70
48	64	80
54	72	90
60	80	100

without logical clocks

A	B	C
0	0	0
6	8	10
12	16	20
18	24	30
24	32	40
30	40	50
36	48	60
42	61	70
48	69	80
70	77	90
76	85	100

with logical clocks

- ◆ Send event happens before arrival: send time must be less than arrival time!
- ◆ Solution: adjust local clock

1 Logical Clocks (3)

- Lamport's algorithm
  - Each process has its own logical clock
    (a counter LC that is used for timestamping of events)
  - Logical clock ticks for each local event
    - *Local event:* LC := LC + 1
    - *Send event:* LC := LC + 1; send(message, LC)
    - *Receive event:* receive(message, LC_S); LC := max(LC, LC_S) + 1
  - Fulfills clock condition
  - Reverse clock condition is **not** fulfilled!
    - $T(a) < T(b) \not\Rightarrow a \rightarrow b$

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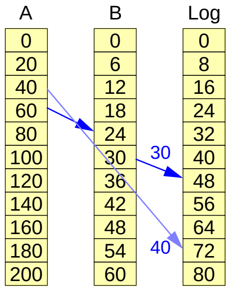
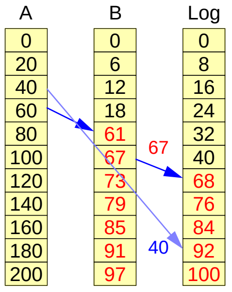
1 Logical Clocks (4)

- How does it help?
  - Logging processes: timestamp log messages with local clock



A	B	Log
0	0	0
20	6	8
40	12	16
60	18	24
80	24	32
100	30	40
120	36	48
140	42	56
160	48	64
180	54	72
200	60	80

without logical clocks



A	B	Log
0	0	0
20	6	8
40	12	16
60	18	24
80	61	32
100	67	40
120	73	68
140	79	76
160	85	84
180	91	92
200	97	100

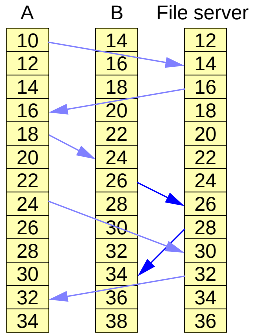
with logical clocks

  - Logical clocks help to figure out the order of the log entries that reflects causality

---

1 Logical Clocks (5)

- Does it help for the "make" example?



A	B	File server
10	14	12
12	16	14
14	18	16
16	20	18
18	22	20
20	24	22
22	26	24
24	28	26
26	30	28
28	32	30
30	34	32
32	36	34
34	38	36

A: write `test.c` (timestamp 10)

FS: `test.c` written

A: make starts compiler

B: write `test.o` (timestamp 26)
A: write `test.c` (timestamp 24)
FS: `test.o` written

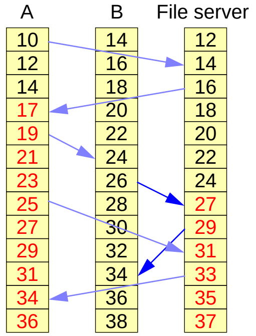
FS: `test.c` written

without logical clocks

---

1 Logical Clocks (6)

- Does it help for the "make" example?



A	B	File server
10	14	12
12	16	14
14	18	16
17	20	18
19	22	20
21	24	22
23	26	24
25	28	27
27	30	29
29	32	31
31	34	33
34	36	35
36	38	37

A: write `test.c` (timestamp 10)

FS: `test.c` written

A: make starts compiler

B: write `test.o` (timestamp 26)
A: write `test.c` (timestamp 25)
FS: `test.o` written

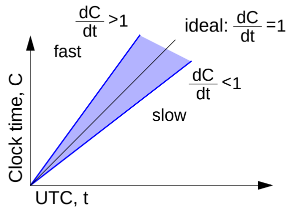
FS: `test.c` written

with logical clocks

  - NO!!

2 Clock Synchronization

- Local clocks are realized in software
  - ◆ Time chip signals interrupt that counts clock ticks
  - ◆ Local clock has a drift to UTC (Universal Coordinated Time)



  - ◆ Synchronize local clocks to minimize drift to UTC
  - ◆ Sources: DCF77, GEOS, GPS, Atomic clock

---

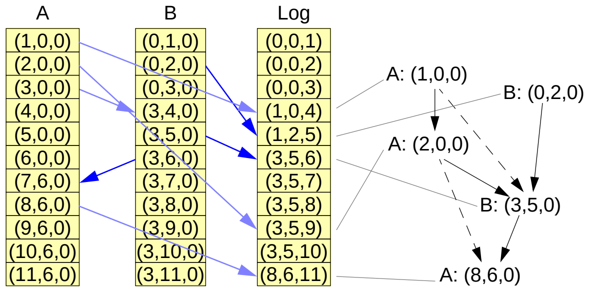
3 Vector Time

- Sometimes we would like to know whether two events are causally dependent by looking at their timestamps
  - ◆ Corresponds to reverse clock condition
  - ◆ Impossible to derive with logical clocks
- Vector time introduced by Mattern (1989)
  - ◆ Each process i of k processes maintains a clock vector V_i of k clocks
  - ◆ Local event: $V_i[i] := V_i[i] + 1$
  - ◆ Send event : $V_i[i] := V_i[i] + 1$; send(message, V_i)
  - ◆ Receive event: $V_i[i] := V_i[i] + 1$; receive(message, V_s);
    $\forall j : V_i[j] := \max(V_i[j], V_s[j])$
  - ◆ Comparing two time vectors:
    - $a \leq b :\Leftrightarrow \forall i : a[i] \leq b[i]$
    - $a < b :\Leftrightarrow (a \leq b) \wedge (a \neq b)$
    - $a \parallel b :\Leftrightarrow \neg (a < b) \wedge \neg (b < a)$

---

3 Vector Time (2)

- Example: Logging Processes



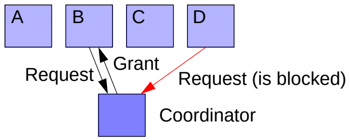
A	B	Log
(1,0,0)	(0,1,0)	(0,0,1)
(2,0,0)	(0,2,0)	(0,0,2)
(3,0,0)	(0,3,0)	(0,0,3)
(4,0,0)	(3,4,0)	(1,0,4)
(5,0,0)	(3,5,0)	(1,2,5)
(6,0,0)	(3,6,0)	(3,5,6)
(7,6,0)	(3,7,0)	(3,5,7)
(8,6,0)	(3,8,0)	(3,5,8)
(9,6,0)	(3,9,0)	(3,5,9)
(10,6,0)	(3,10,0)	(3,5,10)
(11,6,0)	(3,11,0)	(8,6,11)

  - ◆ Clocks start with concurrent timestamps
  - ◆ From the log we can identify causality of all logged events

---

4 Mutual Exclusion

- Semaphore needs coherent shared memory
  - ◆ Multicomputers cannot use a semaphore
- Centralized semaphore server and request-reply interaction
  - ◆ Centralized component (coordinator) acts like a semaphore
  - ◆ Every process has to contact the coordinator to get access to a critical region



  - ◆ Process B sends a release message to the coordinator after leaving the critical region
  - ◆ Single point of failure

4 Mutual Exclusion (2)

- Distributed algorithm
    - ◆ Lamport (1978)
    - ◆ Improved by Ricart and Agrawala (1981)
- Algorithm by Ricart and Agrawala
    - ◆ Total ordering of events
        - Lamport’s logical clock value plus process ID **`(time, pid)`**
        - The tuple makes timestamps of different events different and comparable (if time is equal process ID of different events is not)
    - ◆ Group of processes that may enter a critical region
    - ◆ Process that wants to enter the region has to send a message to all others:
        - **`group_send( LC, pid )`**
        - Send must be reliable
        - Process waits until all other group member grant permission to enter the critical region

---

4 Mutual Exclusion (3)

- ◆ If a process receives a message it does the following:
    - The receiver is not in the critical region and does not want to enter it:
      `send( OK )` to the original sender
    - The receiver is in the region:
      the message is enqueued
    - The receiver is waiting for entering the critical region:
      The receiver compares the timestamps of the incoming message with the timestamp of its own request message

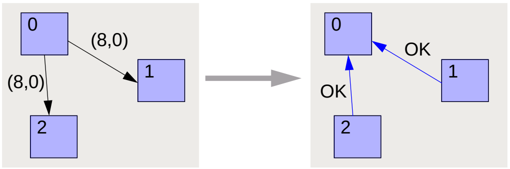
      The own timestamp is lower:
      the message is enqueued

      The own timestamp is higher:
      `send( OK )` to the original sender
- ◆ After leaving a critical region a process sends back an **`OK`** for all enqueued request messages and deletes those messages

---

4 Mutual Exclusion (3)

- No conflict: it clearly works

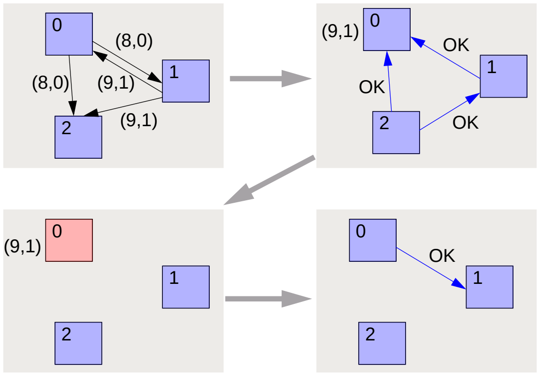


- ◆ The sender immediately gets OKs
- ◆ No further messages are sent or enqueued

---

4 Mutual Exclusion (4)

- Two processes want to enter the critical region at the same time



- ◆ The process with the lowest timestamp will win

4 Mutual Exclusion (5)

- Is it really better?
  - n points of failures
  - 2(n – 1) messages
  - Group membership must be known to all other processes
- Hardly better than the centralized version
  - Shows that it is possible to solve the problem by a distributed algorithm
  - Good example for distributed algorithms

---

5 Election Algorithms

- Problem
  - Find out a (new) coordinator, initiator, sequencer, or something similar
  - After the run of the algorithm
    - one group member should be the coordinator,
    - all other group member should know who was elected.
  - Multiple processes may start the election, but only one process will be elected.

6 Deadlock Detection

- Problem
  - Find out whether some processes are involved in a deadlock
  - Traversing the distributed dependency graph

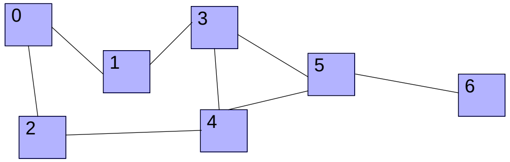
---

7 Distributed Garbage Collection

- Problem
  - Find out data object that are not referenced any more
  - Traversing the distributed reference graph

8 Echo Algorithms

- Problem
  - Distributed information to all of not fully interconnected processes and compute a function (e.g. maximum of the output of all processes)



D.7 Object-Based Distributed Systems

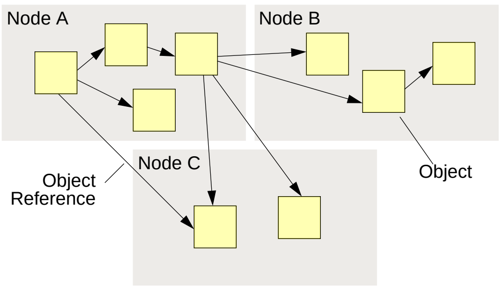
- So far: processes
  - Processes & message passing
  - Processes & remote procedure calls
- Object-based programming
  - Objects
  - Classes
  - Methods, method invocation

  - Inheritance (object-oriented programming)

★ Systems that are distributed and object-based

1 Centralized-Object Approach

- Objects as distributable entities
  - Objects are distributed on several nodes
  - Objects communicate with each other
  - Remote method invocation



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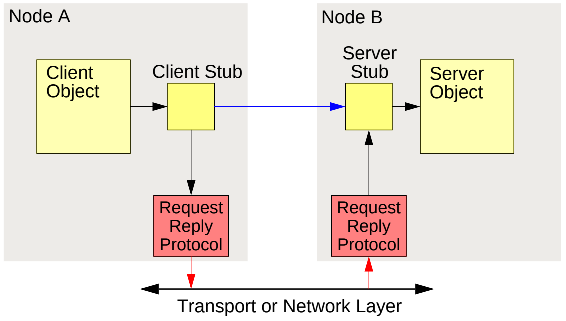
1 Centralized-Object Approach (2)

- Implementing remote method invocation
  - Stub objects similar to stub procedures



- Client-stub object represents server object at client's node

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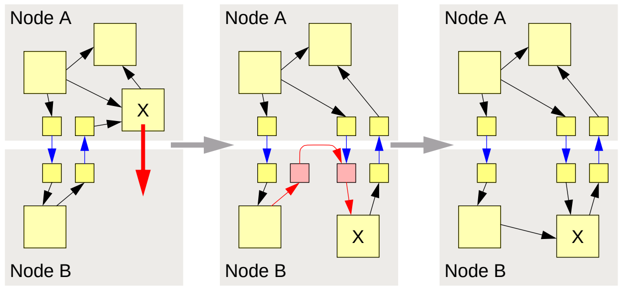
1 Centralized-Object Approach (3)

- Object mobility
  - Objects may migrate from one node to the other



  - Stubs have to be created for all references of the moved object
  - Local stub pairs can be abbreviated

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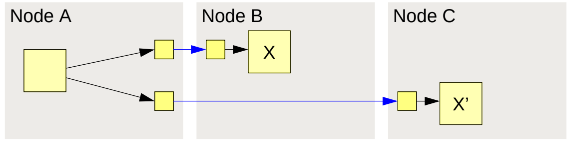
1 Centralized-Object Approach (4)

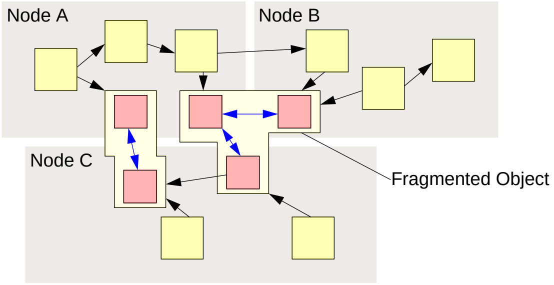
- Disadvantages
  - No transparent replication as object is a centralized entity



  - In general:
    Quality-of-service requirements often need object code at the client side!
    - Replication
    - Caching
    - Bandwidth reservation
    - etc.

2 Fragmented-Object Approach

- Distributed objects consist of fragments that can be spread over multiple nodes
    - Fragments communicate with each other
    - Method invocation is always done locally (local fragment is needed)



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2 Fragmented-Object Approach (2)

- Advantages
    - More general; includes the centralized object approach
        - one fragment is the main object
        - other fragments are stubs
    - Arbitrary communication between fragments
        - group communication for fragments replicating the object’s state
        - real-time or transactional communication
        - communication with the object is always local
    - “Intelligent stubs”
        - local fragment can replicate or cache data of the object
        - local fragment can compute methods that do need little of the object’s data

---

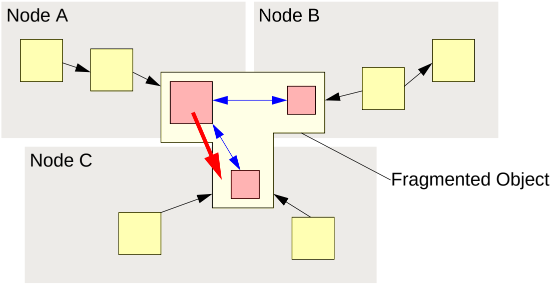
2 Fragmented-Object Approach (3)

- Disadvantages
    - Programmer has to build up the object-internal communication by his own
        - tools and libraries may help (e.g., stub fragment generator)
        - special name services may be needed
    - System does not know about stubs
        - Somehow, the system has to load the fragment code from somewhere whereas it otherwise only has to generate a stub.

---

2 Fragmented-Object Approach (4)

- Object mobility
    - Mobility is relative because the object is always accessed via a local fragment
    - Fragments may be mobile: fragments need to be replaced by one another



2 Fragmented-Object Approach (5)

- Example:
  - A new main fragment is built up at the side of stub fragment, takes over the essential data from the old main fragment, and replaces the stub.
  - The old main fragment is replaced by a new stub fragment