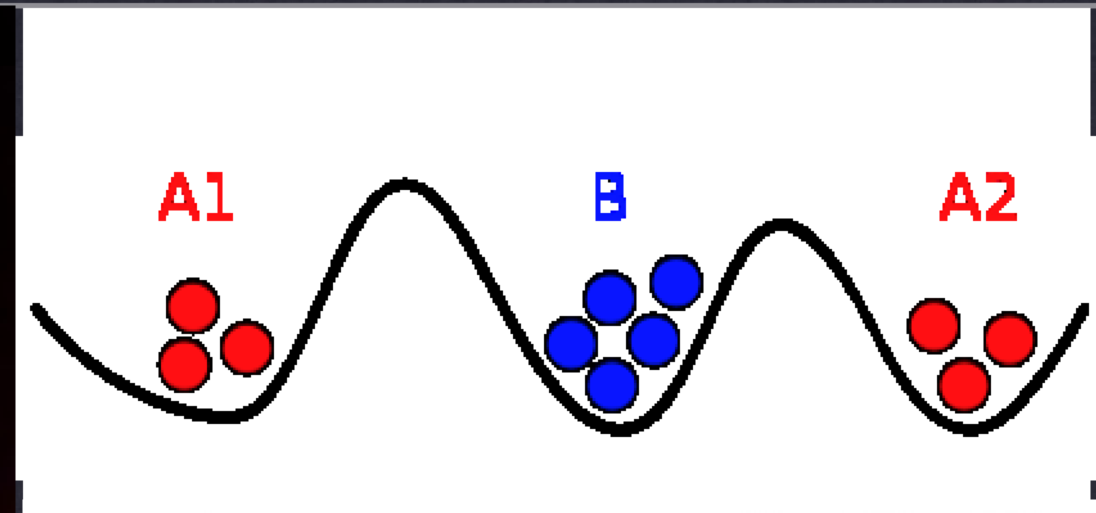
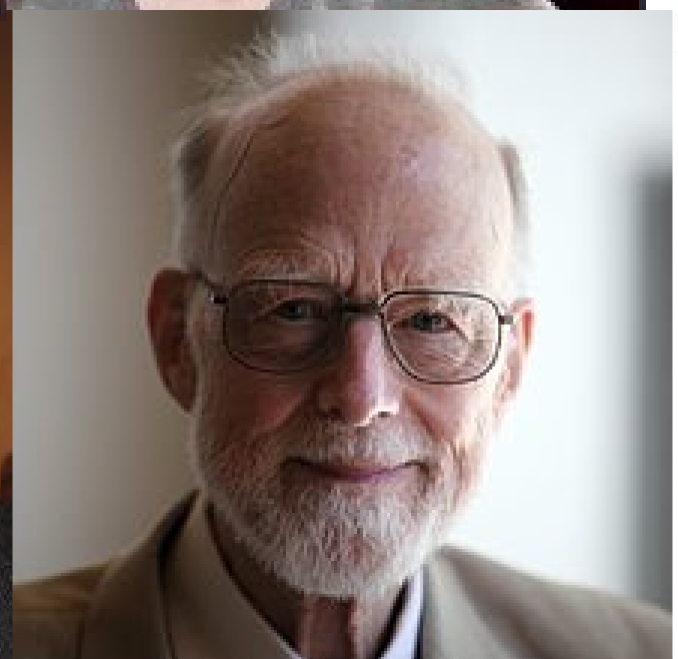
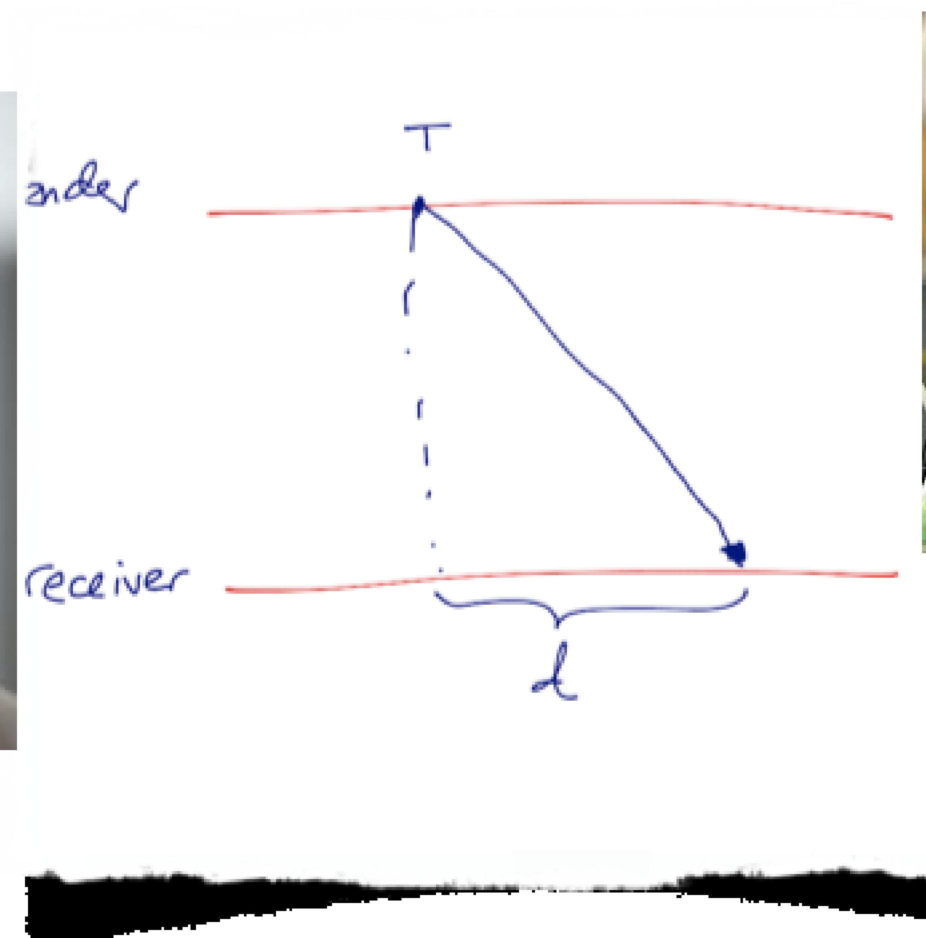
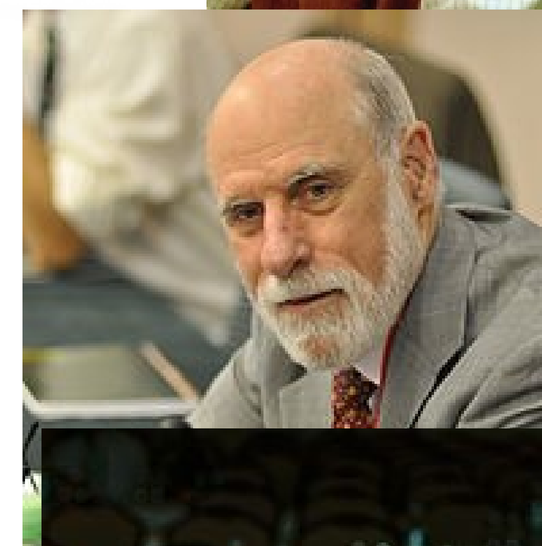
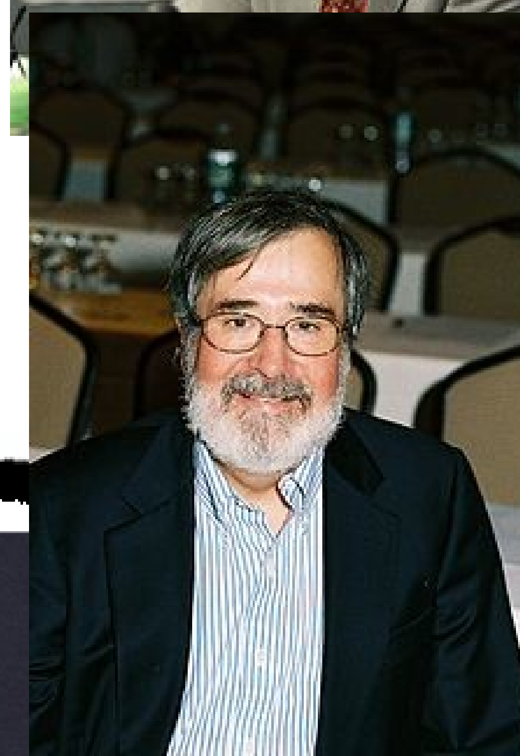






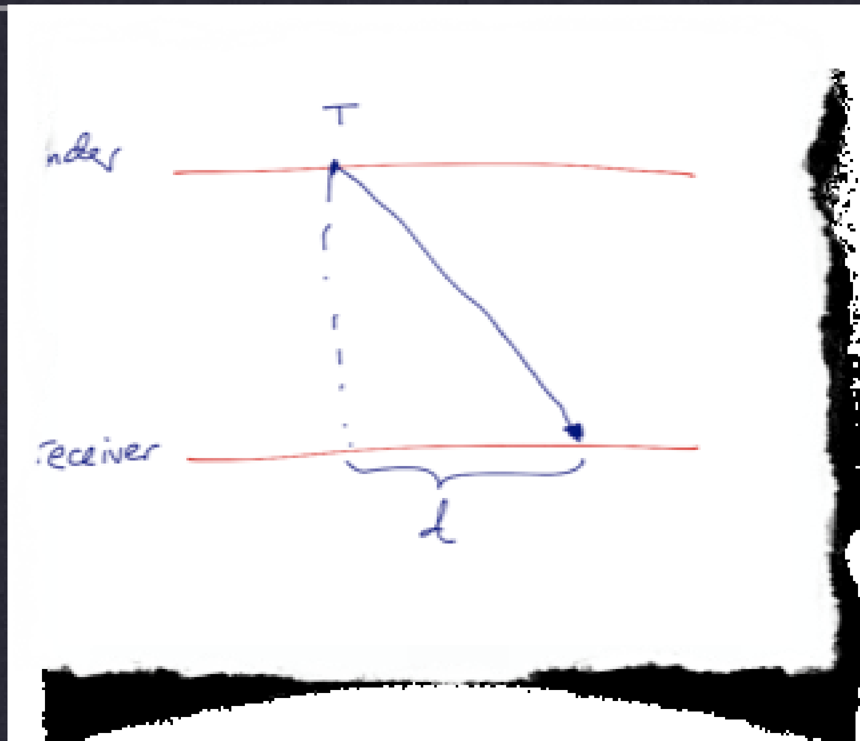



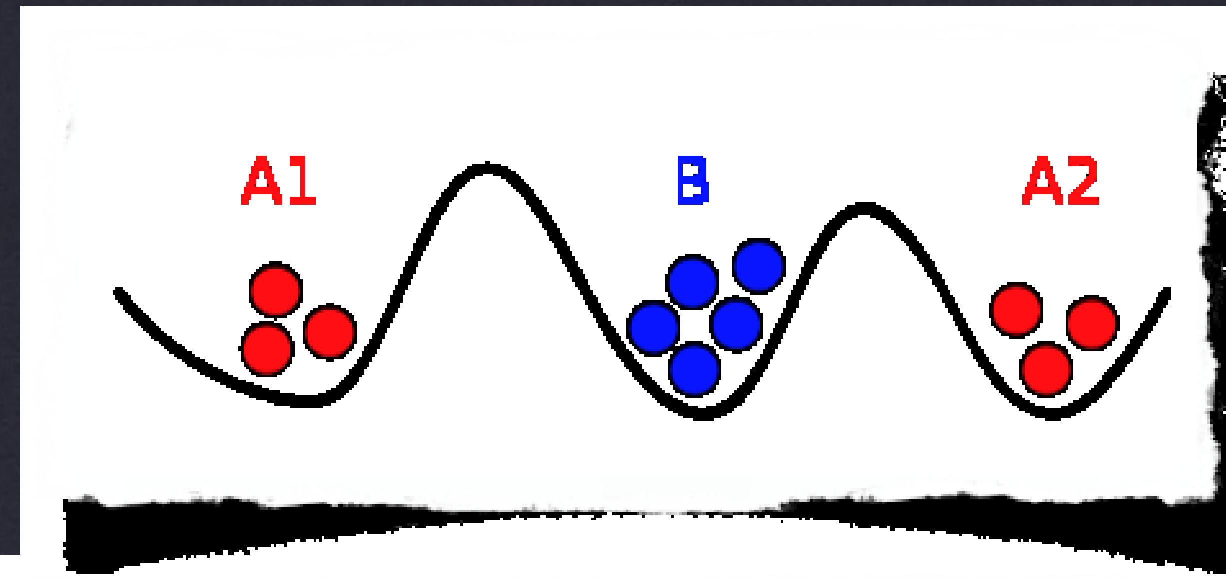



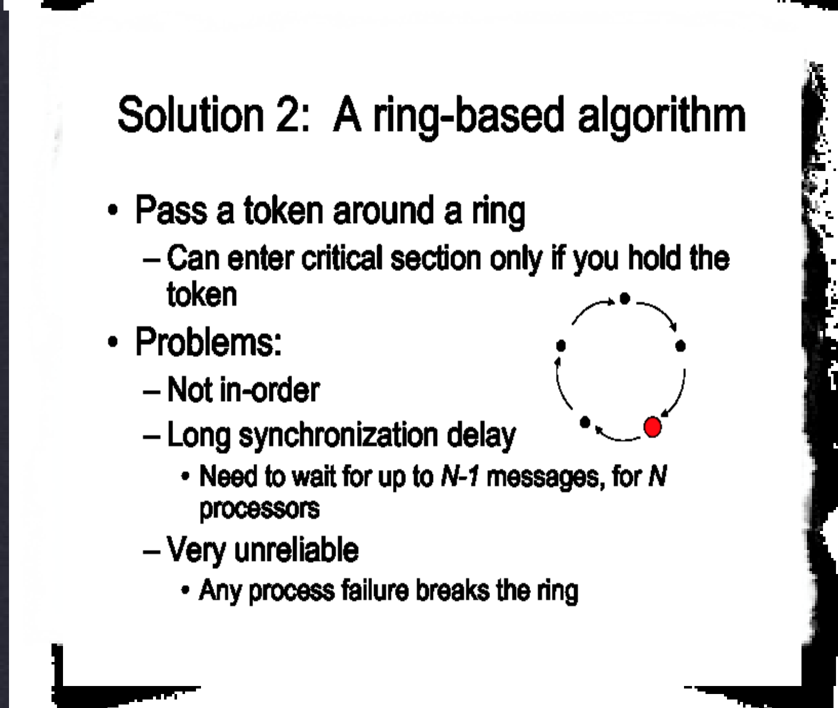
distributed systems

SEMESTER 2, 2013

LOCAL AND DISTRIBUTED COORDINATION

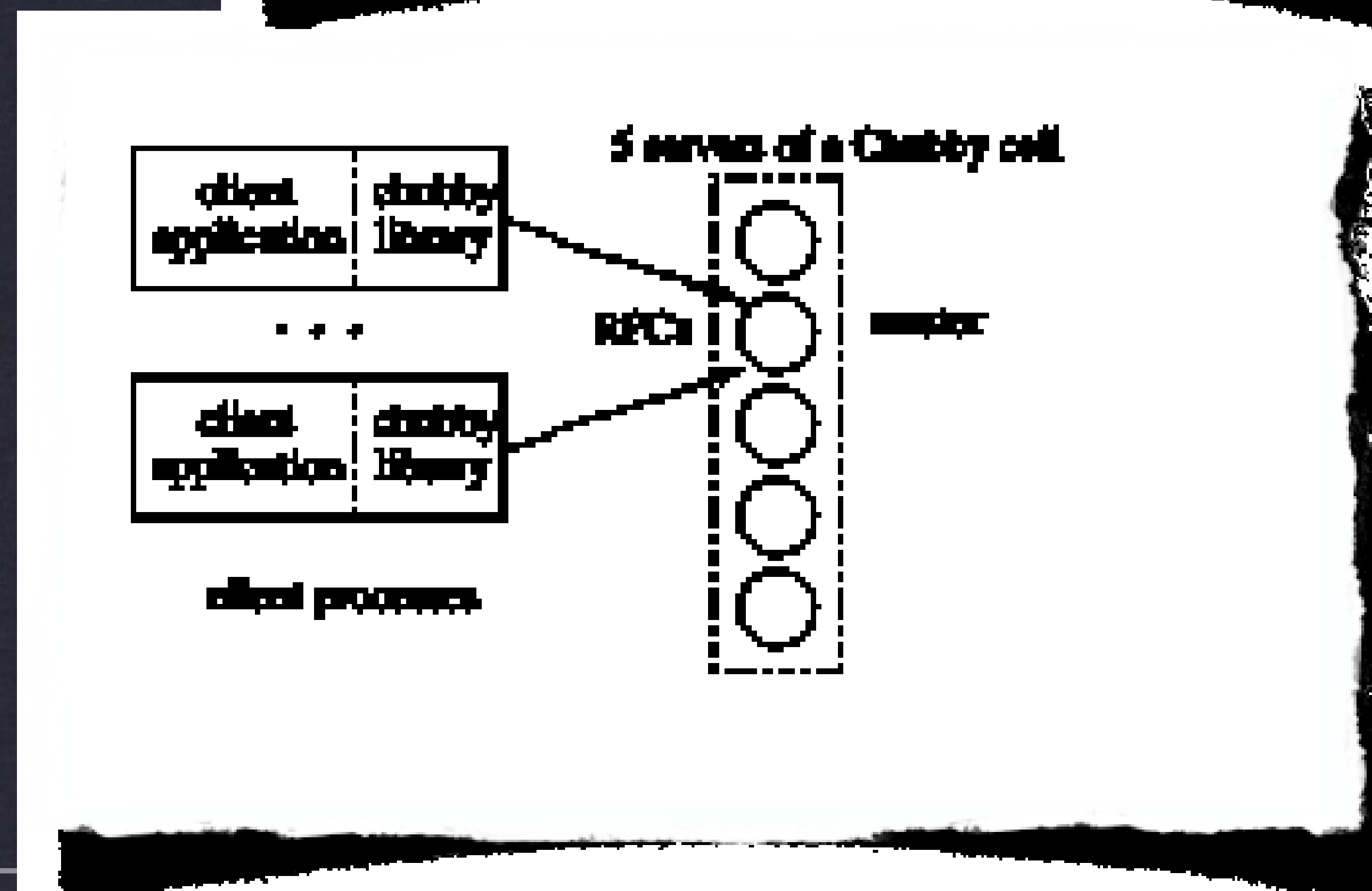






Solution 2: A ring-based algorithm

- Pass a token around a ring
  - Can enter critical section only if you hold the token
- Problems:
  - Not in-order
  - Long synchronization delay
    - Need to wait for up to *N-1* messages, for *N* processors
  - Very unreliable
    - Any process failure breaks the ring



distributed systems

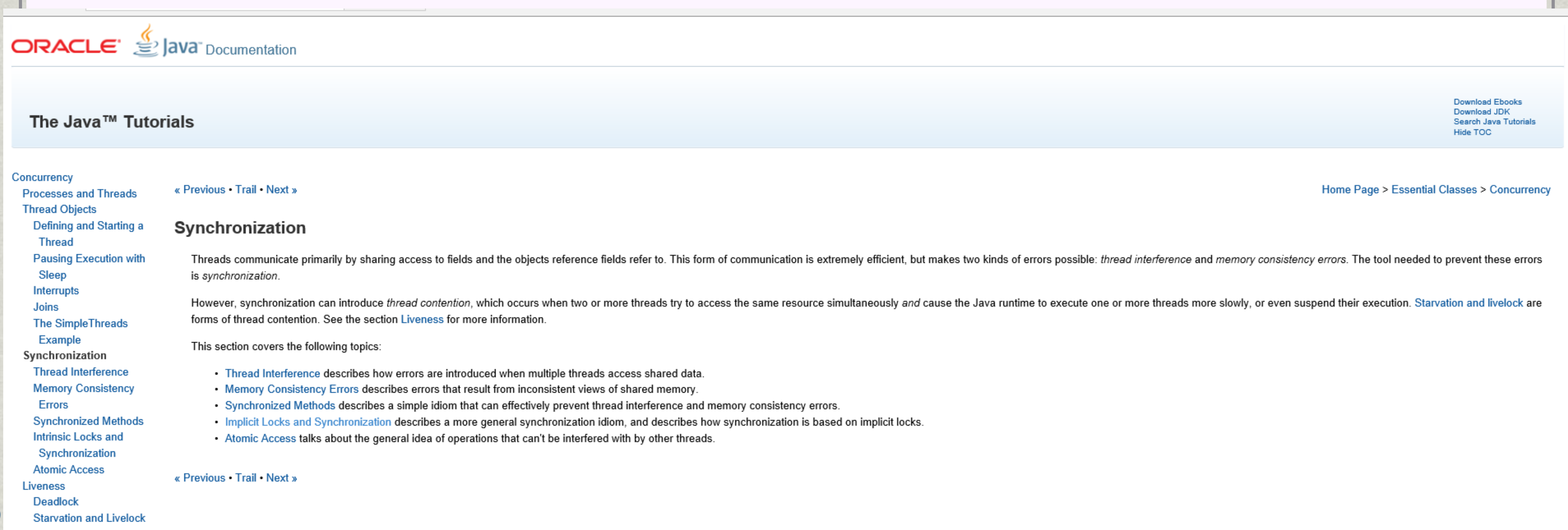
LOCAL AND DISTRIBUTED SYNCHRONIZATION

Admin issues …

- Assignment 1 – do you now the due date? Have you started this?
- Collaborative session this week
  - report due by 5pm the next day!

Last week ...

- Processes vs threads
- Threads and local synchronization
- The three heads of Cerberus



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Synchronization

Threads communicate primarily by sharing access to fields and the objects reference fields refer to. This form of communication is extremely efficient, but makes two kinds of errors possible: *thread interference* and *memory consistency errors*. The tool needed to prevent these errors is *synchronization*.

However, synchronization can introduce *thread contention*, which occurs when two or more threads try to access the same resource simultaneously *and* cause the Java runtime to execute one or more threads more slowly, or even suspend their execution. Starvation and livelock are forms of thread contention. See the section Liveness for more information.

This section covers the following topics:

- Thread Interference describes how errors are introduced when multiple threads access shared data.
- Memory Consistency Errors describes errors that result from inconsistent views of shared memory.
- Synchronized Methods describes a simple idiom that can effectively prevent thread interference and memory consistency errors.
- Implicit Locks and Synchronization describes a more general synchronization idiom, and describes how synchronization is based on implicit locks.
- Atomic Access talks about the general idea of operations that can't be interfered with by other threads.

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Revision Quiz

Q1. What is transparency in DS?

a) Making sure that the system user is not aware of using distributed resources, including their locations and access protocols.

b) Surrounding all distributed systems with a clear, glass case.

c) Making sure that the system user is aware of using distributed resources, including their locations and access protocols.

Q2. What is openness in DS?

a) Making sure that server rooms have open doors.

b) Making sure that components and extensions can be easily added to the system.

c) The use of standards and protocols.

Q3. What are the major challenges in multi-threaded programming?

a) Deadlock, starvation, race conditions

b) Livelock, race conditions, thread pools

c) Deadlock, race conditions, signals and slots

d) Livelock, starvation, race conditions

e) Deadlock, race conditions, wait/signal

Q4. How to debug multi-threaded programs?

a) Keep thread-specific logs with time-based messages. Use debugging tool support, thread analysis support (eg. Java Pathfinder) where possible.

b) Run and analyze a single-threaded version of the program.

c) Run and analyze a two-thread version of the program.

d) Run program and analyze individual thread stacks.

e) Print at stdout the thread states. Take nurofen or other painkillers. Analyze.

Q5. Race conditions are difficult because ...

a) Threads execute in different order.

b) The result of the execution depends on the order of thread execution.

c) Running is difficult. Enuf said.

d) The hare is always faster than the turtle.

e) Thread scheduling and context switching is difficult.

Q6. The initial implementation of PageRank was tested on

a) 60 million URLs

b) 70 billion URLs

c) 65 billion URLs

d) 75 million URLs

Q7. The initial implementation of PageRank was used on ...

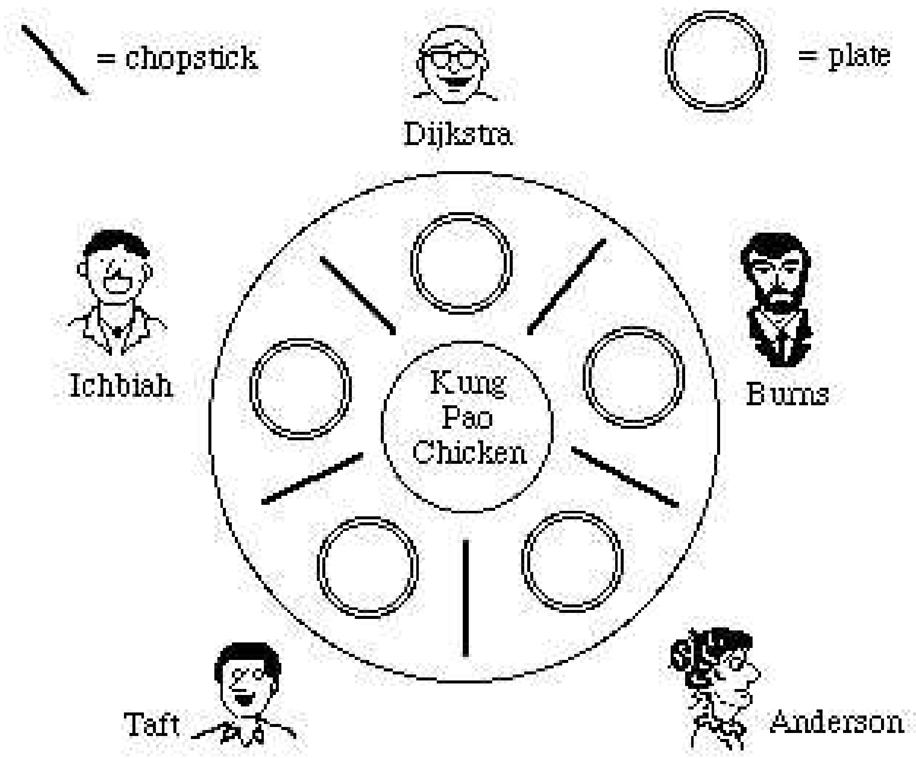
a) Content search

b) Image search

c) Title search

d) Text search

Group Activity



DINING PHILOSOPHERS

This lecture ...

- Local synchronization
  - semaphores
  - conditional variables
- Distributed synchronization
  - distributed time - an example
  - synchronizing real time
  - logical time

Recall ...

- What is a thread?
- What were the issues in multi-threaded programming?
- What was a race condition?
- How did we deal with race conditions?

Local Synchronization Mechanisms

- Locks - allows only one thread to enter a critical section and is not shared with other processes
- Mutexes – like a lock and thread acquiring owns and releases the lock
- Semaphores – like a mutex but allows more than one thread to enter a critical section and has no ownership
- Barriers
- .

Edsger W. Dijkstra

- Fundamental contributions to the development of programming languages, graph theory, distributed systems
  - Shortest path algorithm
  - Reverse polish notation
  - Banker's algorithm and semaphores, self stabilization
  - Formal verification and CSP (**communicating sequential processes)**…
- Turing Award

Semaphores

- Simple abstraction to control access to a common resource
  - signal and wait
- Variable x that allows interaction via two operations
  - `wait(x):` `while (x == 0) wait; --x;`
  - `signal(x):` `++x;`
- Both operations are done atomically

Example - Producer Consumer

- One process (the producer) generates data items and another process (the consumer) receives and uses it
- They communicate using a queue of maximum size N with the conditions
  - The consumer must wait for the producer to produce something if the queue is empty.
  - The producer must wait for the consumer to consume something if the queue is full.

Group Activity

- In groups, list examples distributed systems where producer-consumer is used
  - team with maximum number of examples wins
  - time: 3 minutes!

Example

Q: WHAT HAPPENS IF WE HAVE MORE THAN ONE PRODUCER?

```
produce:

wait(emptyCount)

putItemIntoQueue(item)

signal(fullCount)
```

```
consume:

wait(fullCount)

getItemFromQueue()

signal(emptyCount)
```

Example

```
produce:

wait(emptyCount)

wait(useQueue)


putItemIntoQueue(item)

signal(useQueue)

signal(fullCount)
```

```
consume:

wait(fullCount)

wait(useQueue)

getItemFromQueue()

signal(useQueue)

signal(emptyCount)
```

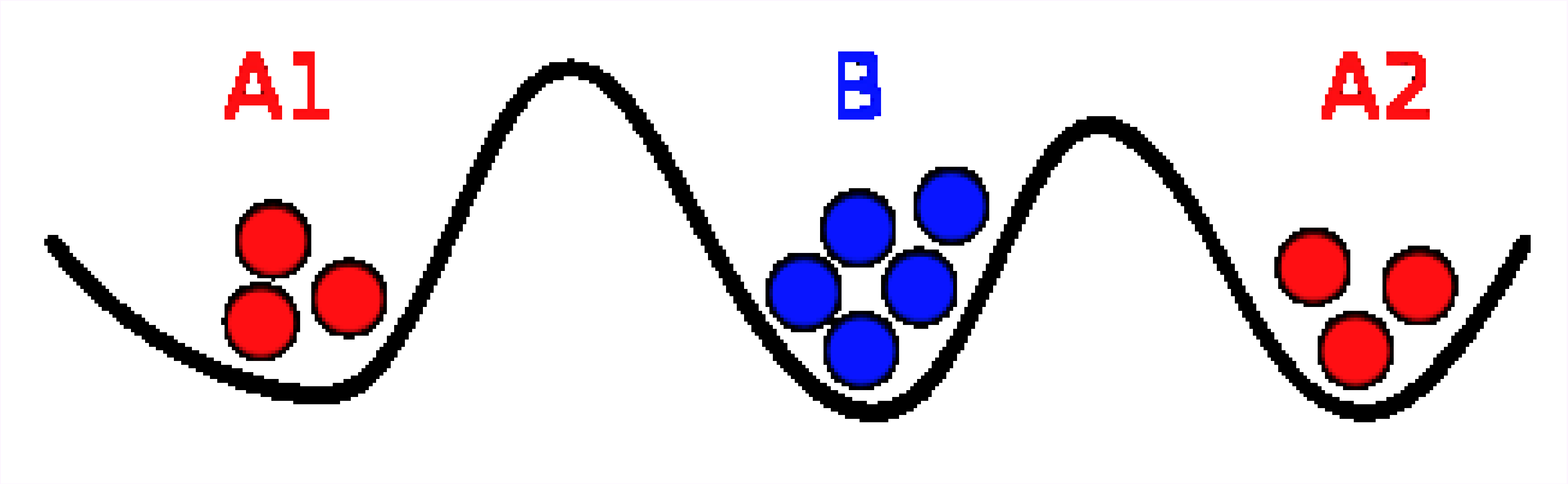
This lecture ...

- Local synchronization
  - semaphores
  - conditional variables
- Distributed synchronization
  - distributed time - an example
  - synchronizing real time
  - logical time

Distributed Synchronization

- **Multiple processes/programs on different machines** share the same resource:
  - printer, file etc
- Things are worse when you consider failures

General's problem

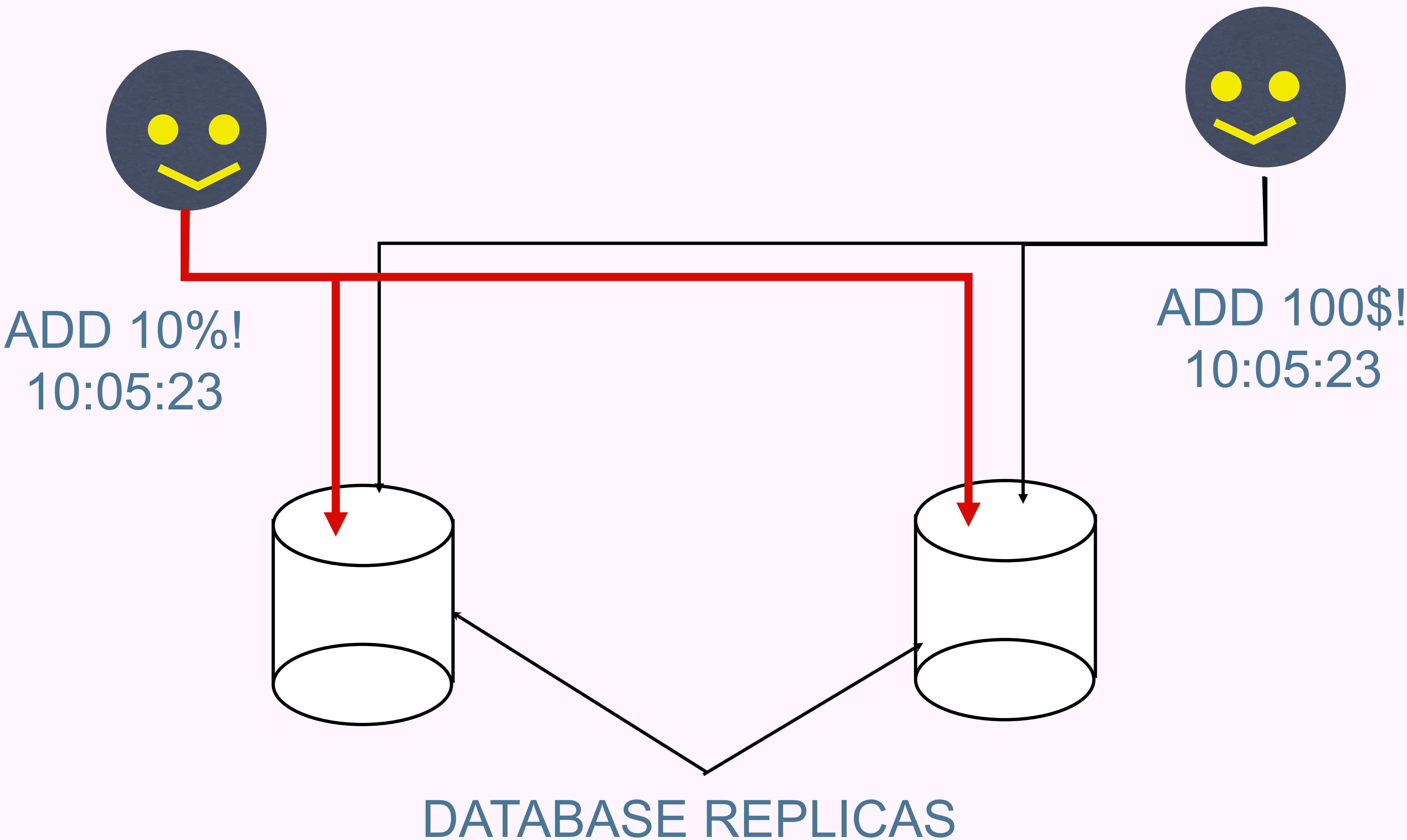


- Armies A1 and A2 need to communicate but their messengers may be captured by army B
- Clients/servers may crash, right in the middle of an RPC call
- Sent and received messages may be lost

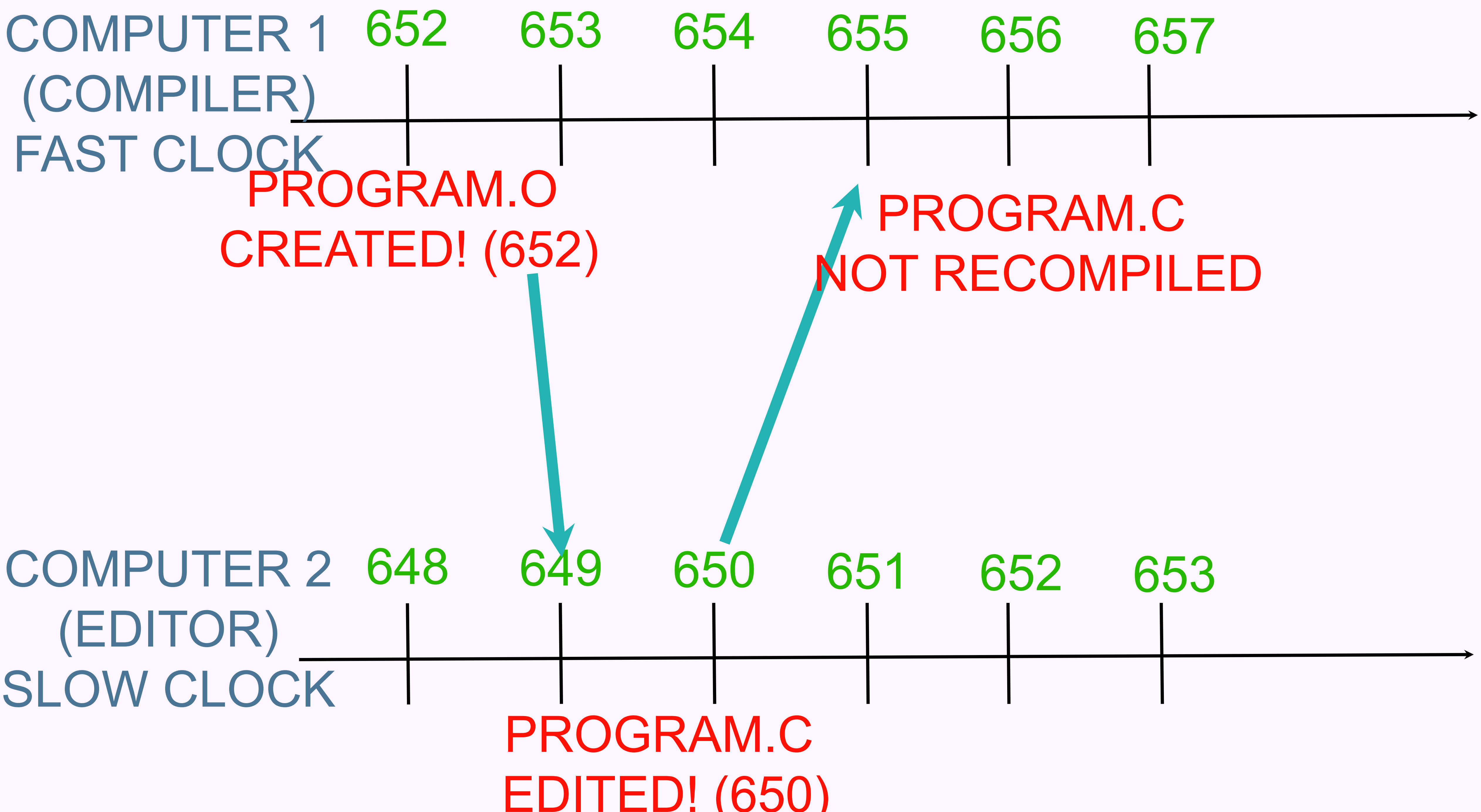
Distributed Synchronization Mechanisms

- **Logical clocks**: clock synchronization is a real issue in distributed systems, hence they often maintain logical clocks, which count operations on the shared resource
- **Consensus:** multiple machines reach majority agreement over the operations they should perform and their ordering
- **Data consistency protocols:** replicas evolve their states in pre- defined ways so as to reach a common state despite different views of the input
- **Distributed locking services:** machines grab locks from a centralized, but still distributed, locking service, so as to coordinate their accesses to shared resources (e.g., files)
- **Distributed transactions:** an operation that involves multiple services either succeeds or fails at all of them

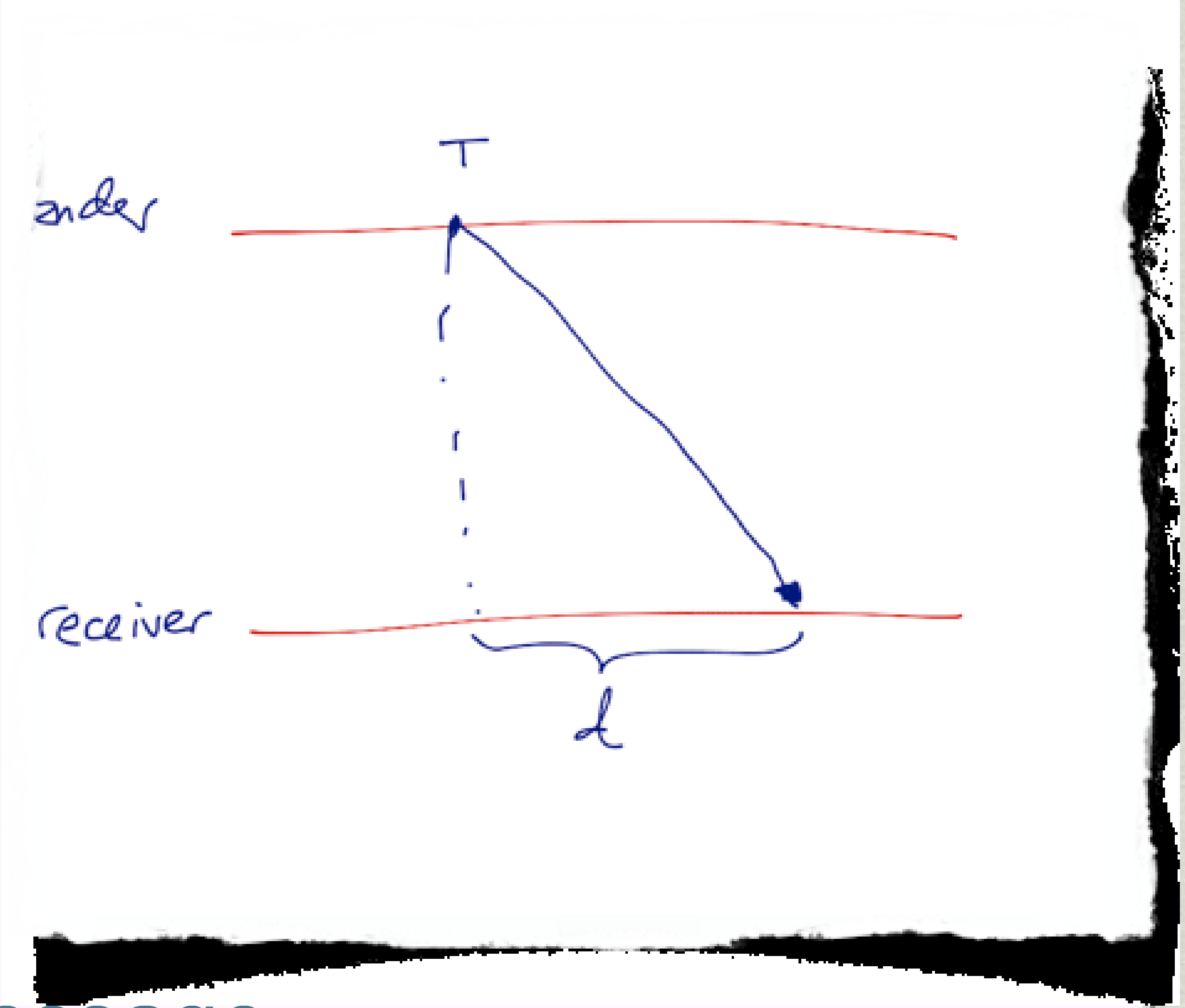
Distributed Synchronization Example I



Distributed Synchronization Example II - Distributed Make



In a perfect world ...



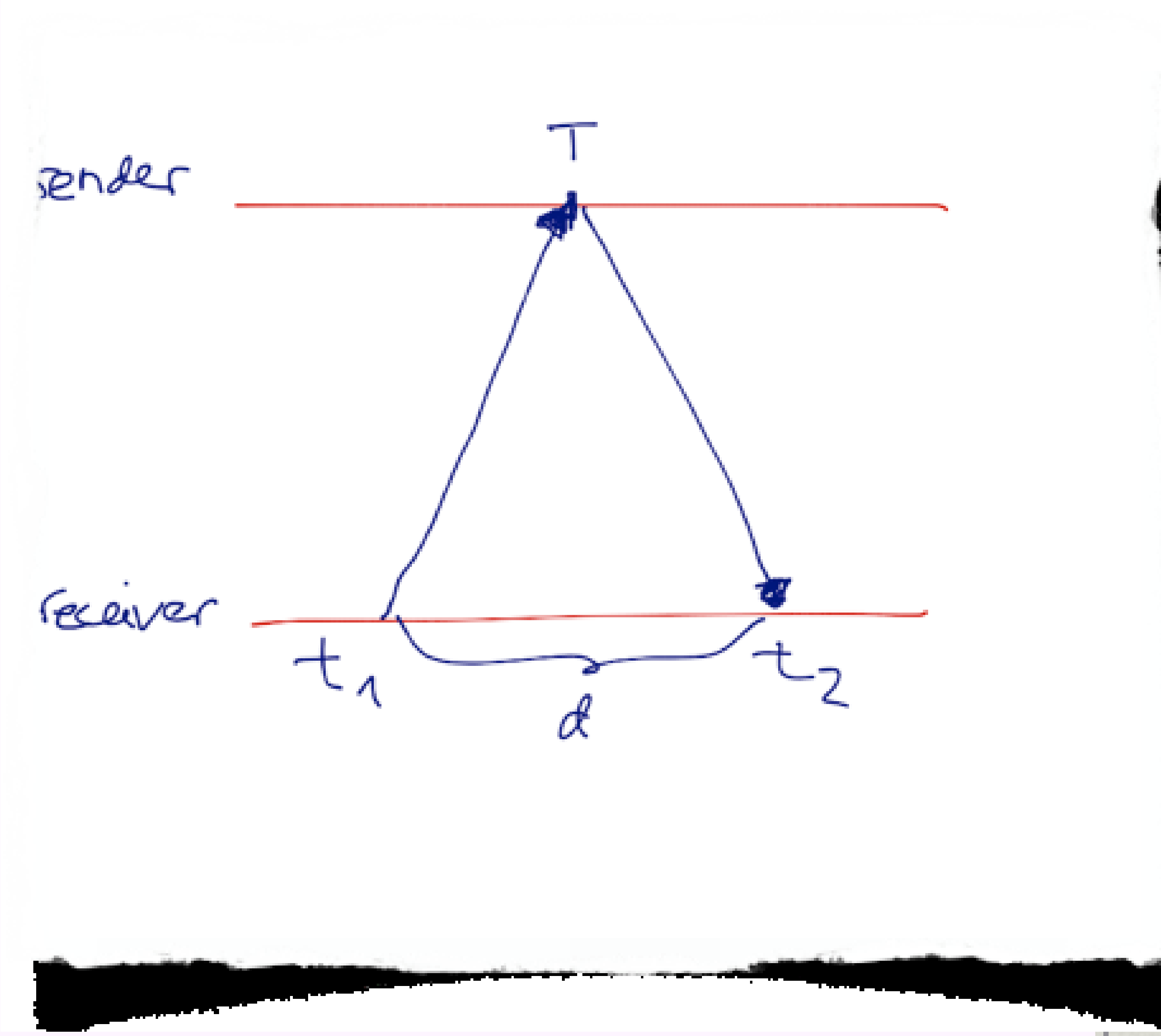
- Messages always arrive:
  - propagation delay ***exactly*** d
- Sender sends time T in a message
- Receiver sets clock to T+d
  - exact synchronization

Distributed Synchronization

- ***Synchronizing real clocks***
  - Cristian’s algorithm
  - The Berkeley Algorithm
  - Network Time Protocol (NTP)
- Logical time
  - Lamport logical clocks
  - Vector clocks

Cristian’s algorithm

- Request time, get reply
  - Measure actual round-trip time d
- Sender’s time was T between t1 and t2
- Receiver sets time to T+d/2
- Synchronization error is at most d/2
  - Can retry until we get a relatively small d



The Berkley Algorithm

- Master uses Cristian’s algorithm to get time from many clients
  - Computes average time
  - Can discard outliers
- Sends time adjustments back to all clients

The Network Time Protocol

- Uses a hierarchy of time servers
  - Class 1 servers have ***highly-accurate clocks*** connected directly to atomic clocks, etc.
- Class 2 servers get time from only Class 1 and Class 2 servers
- Class 3 servers get time from any server
- Synchronization similar to Cristian's algorithm
  - Modified to use multiple one-way messages instead of immediate round-trip
- **NOTE Accuracy: Local~1ms, Global~10ms**

Real Synchronization not needed

- Usually distributed systems do not need exact real time, but an agreement on some time and some order
- E.g.: suppose file servers S1 and S2 receive two update requests, W1 and W2, for file F
- They **need to apply W1 and W2 in the same order**, but they don't really care precisely which order...

Logical Time

- Capture just the ***order between events*** without caring about the actual time when the events happen
- Time at each process is well-defined
- Definition ($\rightarrow i$): We say $e \rightarrow i\ e'$
  - if e happens before e' at process i

Global Logical Time

- Definition (→): We define $e \rightarrow e'$ using the following rules:
  - Local ordering: $e \rightarrow e'$ if $e \rightarrow_i e'$ for any process *i*
- We say e "happens before" e' if $e \rightarrow e'$

Global Logical Time

- Definition (→): We define $e \rightarrow e'$ using the following rules:
  - Local ordering: $e \rightarrow e'$ if $e \rightarrow_i e'$ for any process *i*
  - Messages: send(m) → receive(m) for any message m
- We say e "happens before" e' if $e \rightarrow e'$

Global Logical Time

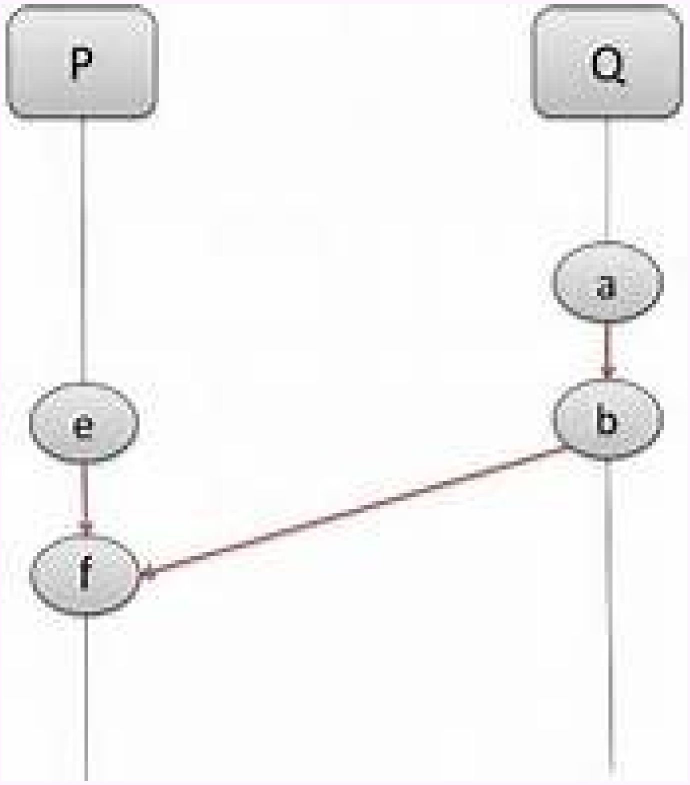
- Definition (→): We define $e \rightarrow e'$ using the following rules:
  - Local ordering: $e \rightarrow e'$ if $e \rightarrow_i e'$ for any process *i*
  - Messages: send(m) → receive(m) for any message m
  - Transitivity: $e \rightarrow e''$ if $e \rightarrow e'$ and $e' \rightarrow e''$
- We say e “happens before” e’ if $e \rightarrow e'$

Concurrency

- Definition (concurrency): We say e is concurrent with e' (written e || e') if neither $e \rightarrow e'$ nor $e' \rightarrow e$

Lamport Logical Clocks

- What does each node know?
  - Its own sequence of events
  - Communication tasks



Lamport Logical Clocks

- Assigns logical timestamps to events consistent with "happens before" ordering; we want a clock such that:

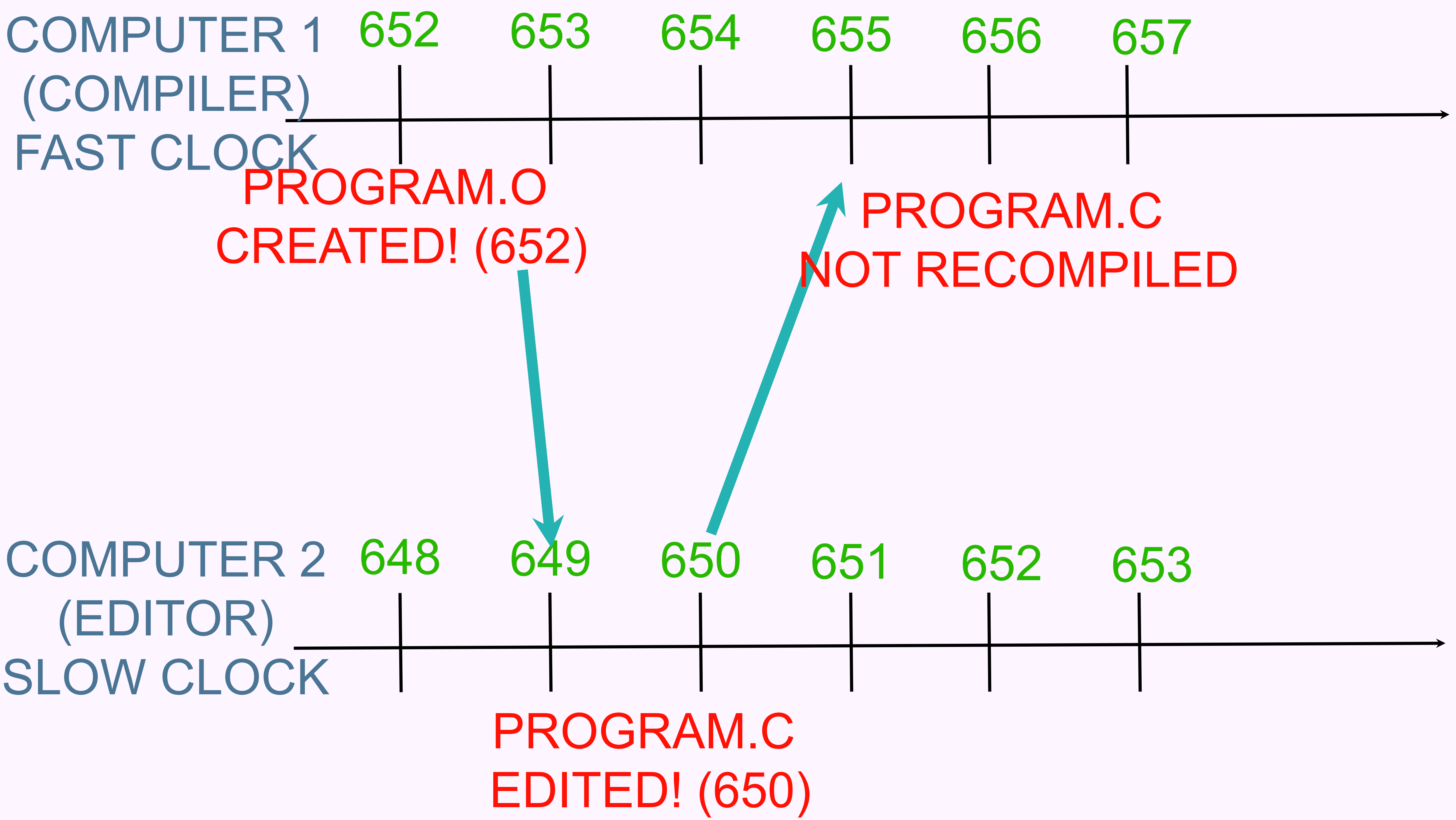
$$\text{If } e \rightarrow e', \text{ then } L(e) \leq L(e')$$

- Message receipt time is ***greater than*** sender time
- **Note**: L(e) < L(e') does not imply e → e'
- Similar rules for concurrency – L(e) = L(e') implies e‖e' (for distinct e,e') – e‖e' does not imply L(e) = L(e')
  - => Lamport clocks arbitrarily order some concurrent events

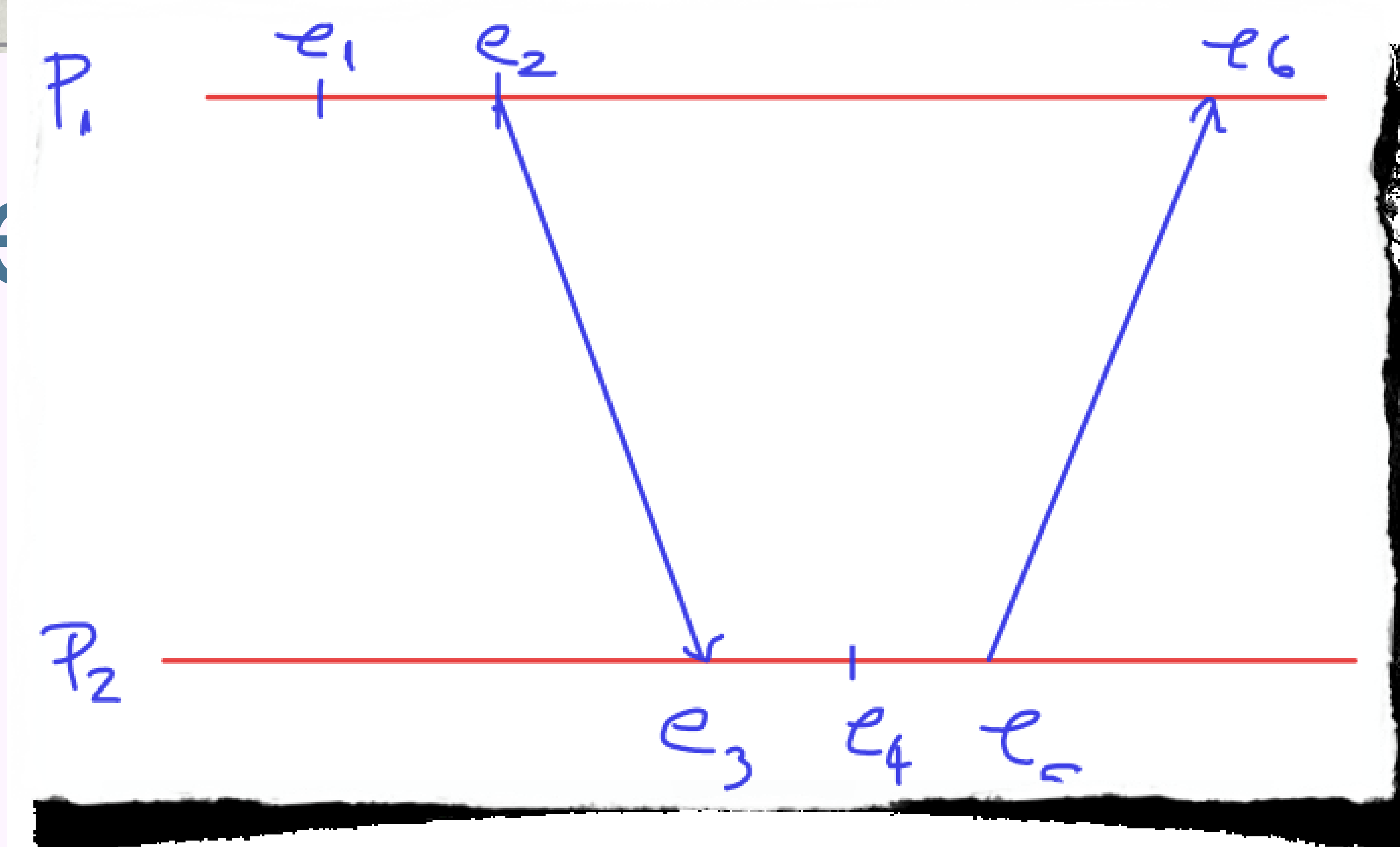
Lamport's Algorithm

- Each process i keeps a local clock, Li
- Three rules:
  1. At process i, increment Li before each event
  2. To send a message m at process i, apply rule 1 and then include the current local time in the message: i.e., send(m,Li)
  3. When receiving a message (m,t) at process j, set Lj = max(Lj,t) and then apply rule 1 before time-stamping the receive event
- The global time L(e) of an event e is just its local time
- For an event e at process i, L(e) = Li(e)

Example


COMPUTER 1
(COMPILER)
FAST CLOCK
652
653
654
655
656
657
PROGRAM.O
CREATED! (652)
PROGRAM.C
NOT RECOMPILED
COMPUTER 2
(EDITOR)
SLOW CLOCK
648
649
650
651
652
653
PROGRAM.C
EDITED! (650)

Example



e_1 – program.o created on P_1

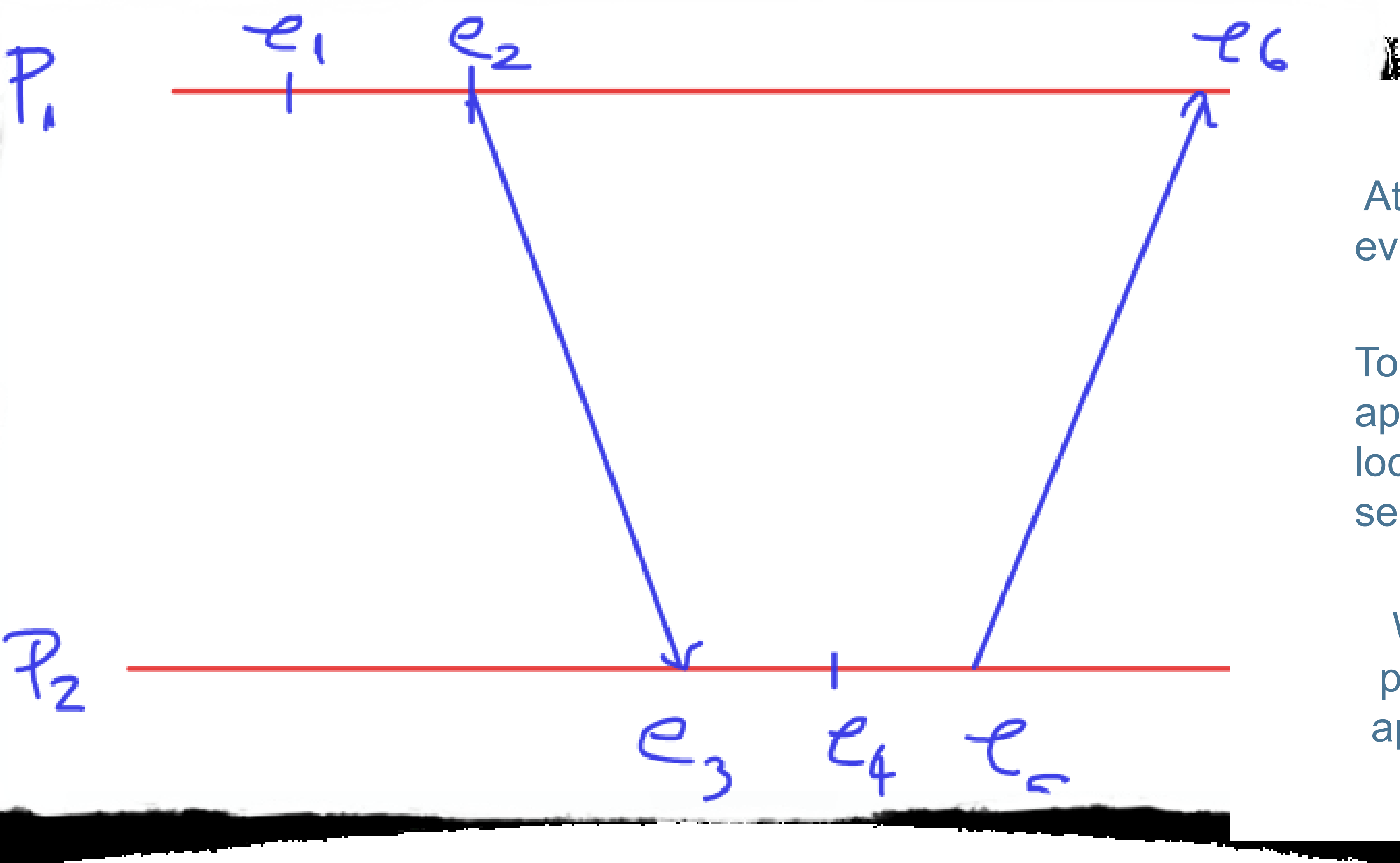
e_2 – message sent to P_2

e_3 – message arrives at P_2

e_4 – program.c edited on P_2

e_5 – message sent to P_1

e_6 – message arrives at P_1



At process i, increment Li before each event

To send a message m at process i, apply rule 1 and then include the current local time in the message: i.e., send(m,Li)

When receiving a message (m,t) at process j, set Lj = max(Lj,t) and then apply rule 1 before time-stamping the receive event

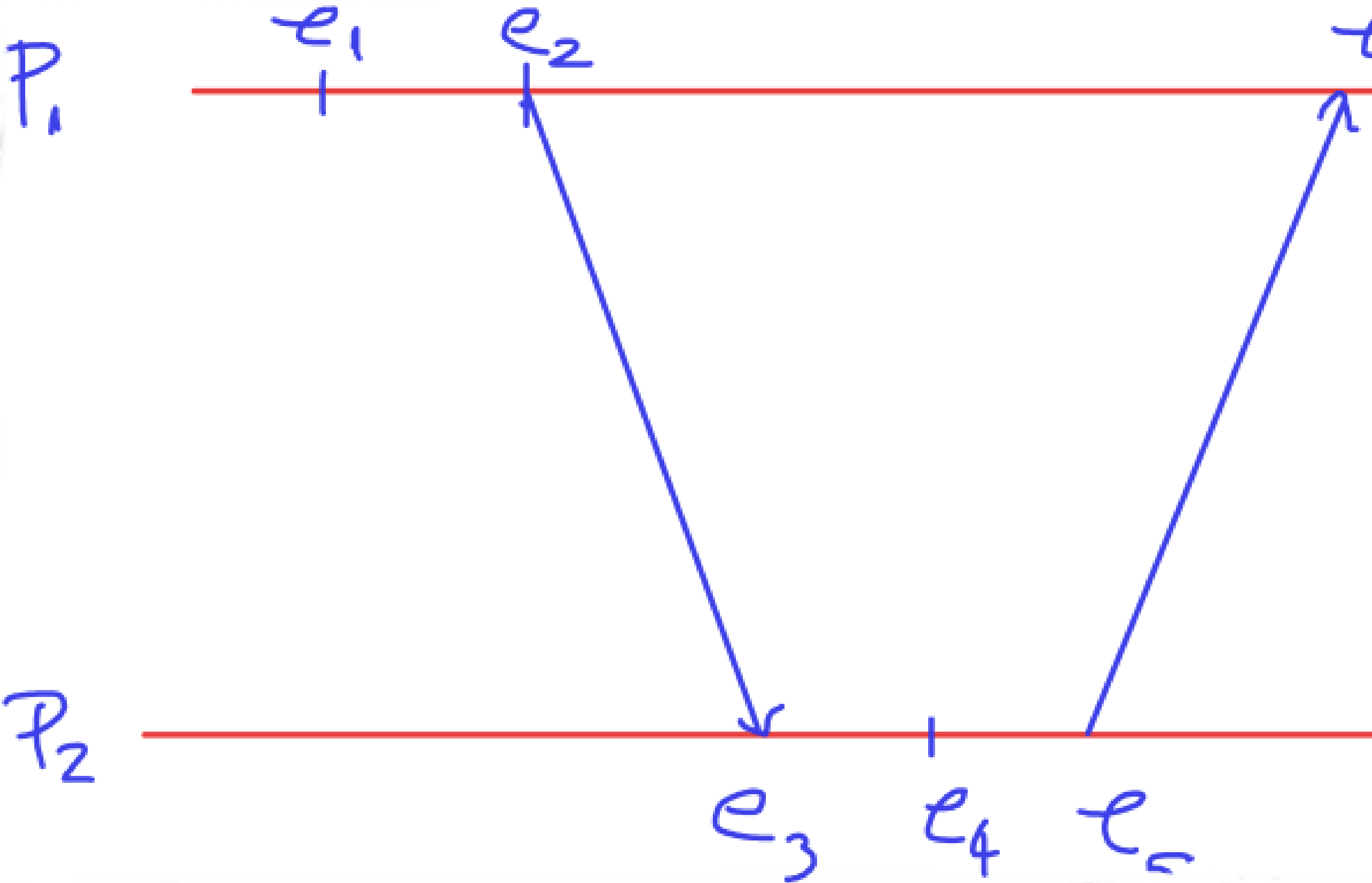
At process 1: $L(P_1) = 1$ **for** $e_1; L(P_1) = 2$ **for** $e_2; send(m, 2);$

At process 2: $L(P_2) = 1$ **for** $e_3; L(P_2) = max(1, 2) + 1 = 2 + 1$ **for** $e_3;$

At process 2: $L(P_2) = 4$ **for** $e_4; L(P_2) = 5$ **for** $e_5; send(m, 5);$

At process 1: $L(P_1) = 3$ **for** $e_6; L(P_1) = max(3, 5) + 1 = 6$ **for** e_6

$\Longrightarrow L(e_4) > L(e_1)$



At process i, increment Li before each event

To send a message m at process i, apply rule 1 and then include the current local time in the message: i.e., send(m,Li)

When receiving a message (m,t) at process j, set Lj = max(Lj,t) and then apply rule 1 before time-stamping the receive event

Or, even simpler:

$$e_1 \rightarrow e_2; e_2 \rightarrow e_3 \implies e_1 \rightarrow e_3;$$

$$e_3 \rightarrow e_4 \implies e_1 \rightarrow e_4 \implies L(e_4) \geq L(e_1)$$

Total order Lamport Clocks

- Many systems require a total ordering of events
- Use Lamport's algorithm, but break ties using process ID
  - If Li(e) = Lj(e') then if ***i < j*** then Li(e) < Lj (e)

Where are these used?!

- Anywhere where you would need to ensure (some) order of events
- **Distributed mutual exclusion** (next slide..)

Distributed Mutual Exclusion

- Maintain mutual exclusion among distributed processes
- Each process executes a loop

```
perform local ops
request critical section
perform critical section ops
leave critical section
perform local ops
```

- During critical section, processes interact with other remote processes or directly with the shared resource
  - *send message to a shared file server asking it to write something to a file*

Distributed Mutual Exclusion: Goals

- Similar to regular mutual exclusion
- Safety
  - at most one process holds the lock at any time
- Liveness: progress
  - if nobody holds the lock, a processor requesting it will acquire it
- Fairness: bounded wait and in-order (in ***logical time***!)
  - processes will not wait indefinitely;
  - will acquire locks in order of request

Distributed Mutual Exclusion: Performance Goals

- Minimize message traffic
  - distributed mutual exclusion is solved by sending messages
- Minimize synchronization delay
  - at most one process holds the lock at any time
- Assumptions
  - network is reliable but asynchronous
  - processes may fail at any time!!

Plan

- Before entering critical section, process must obtain permission from others (***Safety***)
- When exiting critical section, process must let others know that it has finished (***Liveness***)
- Process should allow others that have asked for permission earlier to enter the critical section (***Fairness***)

Centralized Lock Server

- To enter critical section
  - send **REQUEST** to central server
  - wait for **permission**
- To leave critical section
  - send **RELEASE** to central server
- Server
  - logs all requests in a queue
  - sends **OK** to process at head of queue

ADVANTAGES?

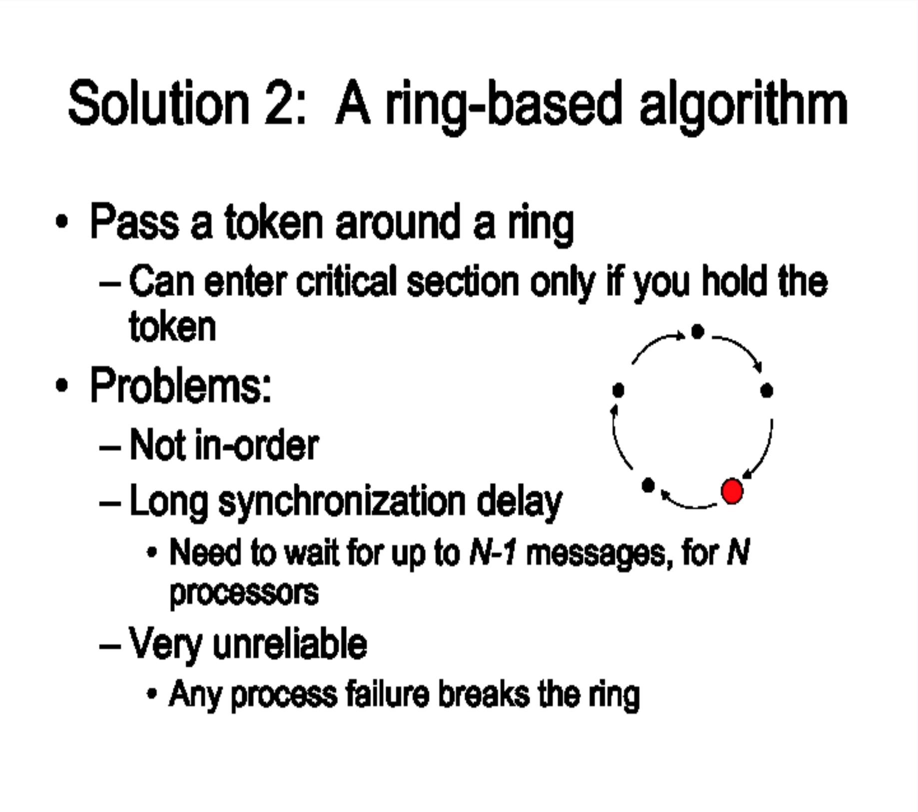
DISADVANTAGES?

Centralized Lock Server

- **Advantages**
  - Simple! YAY!
  - Only 3 messages required
- **Disadvantages**
  - Single point of failure; single performance bottleneck
  - Does not achieve fairness
  - Must elect central server

A ring-based algorithm

- Pass token around ring
  - can enter CS only if you hold token
- Problems
  - not in-order
  - long synchronization delay: need to wait N-1 messages for N processes
  - Unreliable: any process failure breaks the ring
- Can be improved by piggy-backing on the token with the time of the earliest known outstanding request



Lamport's algorithm

- Requesting process
  - Enters its **REQUEST** in its own queue (ordered by time stamps)
  - Sends a request to every node.
  - Wait for replies from all other nodes.
  - If own request is at the head of the queue (***made earlier than the replies***) and all replies have been received, enter critical section.
  - Upon exiting the critical section, send a **RELEASE** message to every process.

Lamport's algorithm

- Other process
  - If receiving **REQUEST** from process j:
    - enter it in own request queue ordered by time stamps;
    - if waiting for **REPLY** from j for an earlier request, wait until j replies
    - else **REPLY** to the **REQUEST** with timestamp
  - If receiving **RELEASE**, remove corresponding request from the queue
  - If own request is at the head of the queue and all replies have been received, enter critical section.

- Initial state

QUEUE P1:

t	action
42	(start)

QUEUE P2:

t	action
11	(start)

QUEUE P3:

t	action
14	(start)

- P3 initiates request

QUEUE P1:

t	action
42	(start)

QUEUE P2:

t	action
11	(start)

QUEUE P3:
<15.3>

t	action
14	(start)
15	request<15,3>

- P1 P2 receive and reply

t	action
42	(start)
43	recv<15,3>
44	reply 1 to <15,3>

QUEUE P1: <15, 3>

t	action
11	(start)
16	recv<15,3>
17	reply 2 to <15,3>

QUEUE P2: <15,3>

QUEUE P3: <15,3>

t	action
14	(start)
15	request<15,3>

- P3 receives replies
- It’s in front of it’s queue
- Can enter CS

t	action
42	(start)
43	recv<15,3>
44	reply 1 to <15,3>

QUEUE P1: <15, 3>

t	action
11	(start)
16	recv<15,3>
17	reply 2 to <15,3>

QUEUE P2: <15,3>

QUEUE P3: <15,3>

t	action
14	(start)
15	request<15,3>
18	recv reply 2
45	recv reply 1
46	run CS

LAMPORT CLOCKS!!!

- P1 and P2 initiate request
- Concurrently!!

t	action
42	(start)
43	recv<15,3>
44	reply 1 to <15,3>
45	request <45,1>

QUEUE P1: <45,1>

t	action
11	(start)
16	recv<15,3>
17	reply 2 to <15,3>
18	request<18,2>

QUEUE P2: <18,2>

QUEUE P3:

t	action
14	(start)
15	request<15,3>
18	recv reply 2
45	recv reply 1
46	run CS

LAMPORT CLOCKS!!!

- P3 gets requests and replies

t	action
42	(start)
43	recv<15,3>
44	reply 1 to <15,3>
45	request <45,1>
49	recv reply 3

QUEUE P1: <45,1>

t	action
14	(start)
15	request<15,3>
18	recv reply 2
45	recv reply 1
46	run CS
47	recv <45,1>
48	reply 3 to <45,1>
49	recv <18,2>
50	reply 3 to <18,2>

t	action
11	(start)
16	recv<15,3>
17	reply 2 to <15,3>
18	request<18,2>
51	recv reply 3

QUEUE P2: <18,2>,

QUEUE P3: <18,2> <45,1>

LAMPORT CLOCKS!!!

- P2 gets request <45,1>
- Delays reply because
- <18,2> is an earlier request to which P1 has not replied

t	action
42	(start)
43	recv<15,3>
44	reply 1 to <15,3>
45	request <45,1>
49	recv reply 3

QUEUE P1: <45,1>

t	action
11	(start)
16	recv<15,3>
17	reply 2 to <15,3>
18	request<18,2>
51	recv reply 3
52	recv <45,1>

QUEUE P2: <18,2>, <45,1>

QUEUE P3: <18,2> <45,1>

t	action
14	(start)
15	request<15,3>
18	recv reply 2
45	recv reply 1
46	run CS
47	recv <45,1>
48	reply 3 to <45,1>
49	recv <18,2>
50	reply 3 to <18,2>

LAMPORT CLOCKS!!!

- P1 gets <18,2>
- Replies

t	action
42	(start)
43	recv<15,3>
44	reply 1 to <15,3>
45	request <45,1>
49	recv reply 3
50	recv<18,2>
51	reply 1 to <18,2>

QUEUE

P1: <18,2>,<45,1>

t	action
11	(start)
16	recv<15,3>
17	reply 2 to <15,3>
18	request<18,2>
51	recv reply 3
52	recv <45,1>
53	recv reply 1
54	reply 2 to <45,1>
55	run CS

QUEUE P2:
<18,2>, <45,1>

QUEUE P3:
<18,2>
<45,1>

t	action
14	(start)
15	request<15,3>
18	recv reply 2
45	recv reply 1
46	run CS
47	recv <45,1>
48	reply 3 to <45,1>
49	recv <18,2>
50	reply 3 to <18,2>

LAMPORT CLOCKS!!!

Lamport's Algorithm

- **Advantages**
  - Fair
  - short sychronization delay
- **Disadvantages**
  - any process failure halts progress
  - 3*(N-1) messages per entry/exit

Algorithm	Messages per entry/exit	Synchronization delay	Liveness
Centralized	3	1 RTT	Coordinator crash =>doom
Token ring	N	<= sum(RTTs)/2	any process crash => doom
Lamport	3*(N-1)	max(RTT) across processes	any process crash => doom

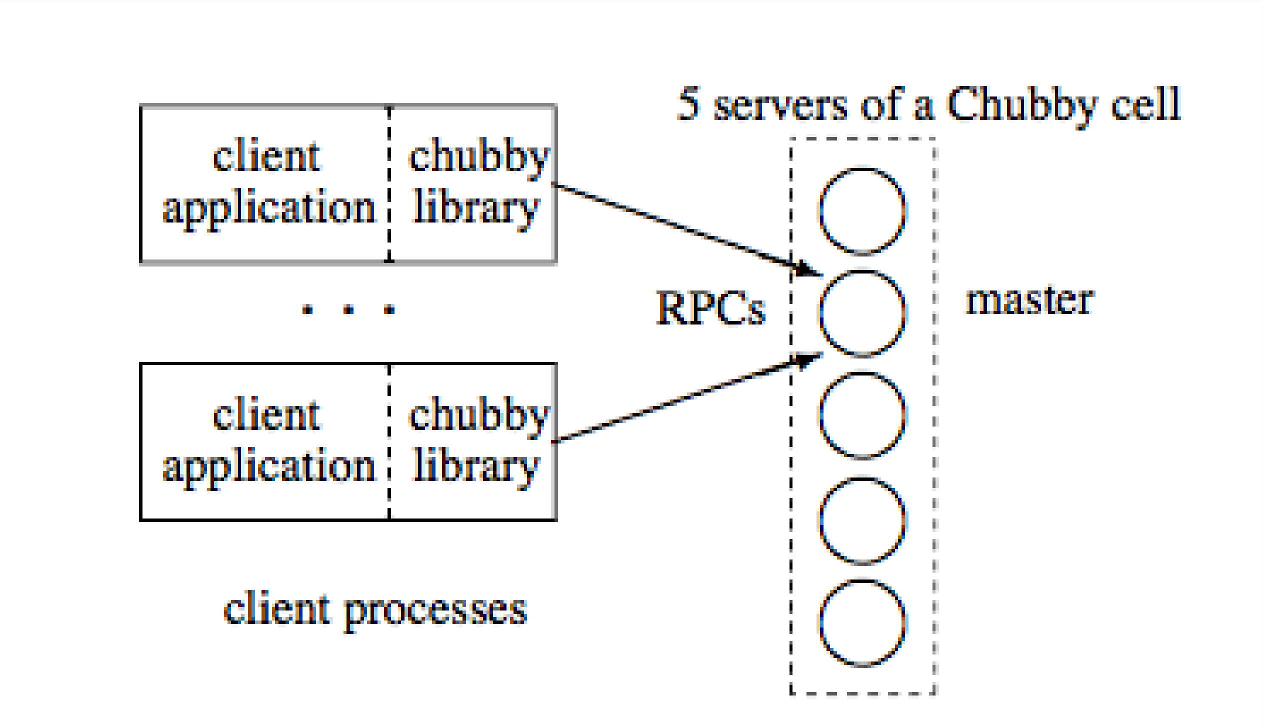
Which one is the best?

- There are better algorithms (Ricart & Agrawal, Voting etc.)
- Industry?
  - **centralized algorithm**
    - Google: Chubby
    - Yahoo: Zookeper

Which one is the best?

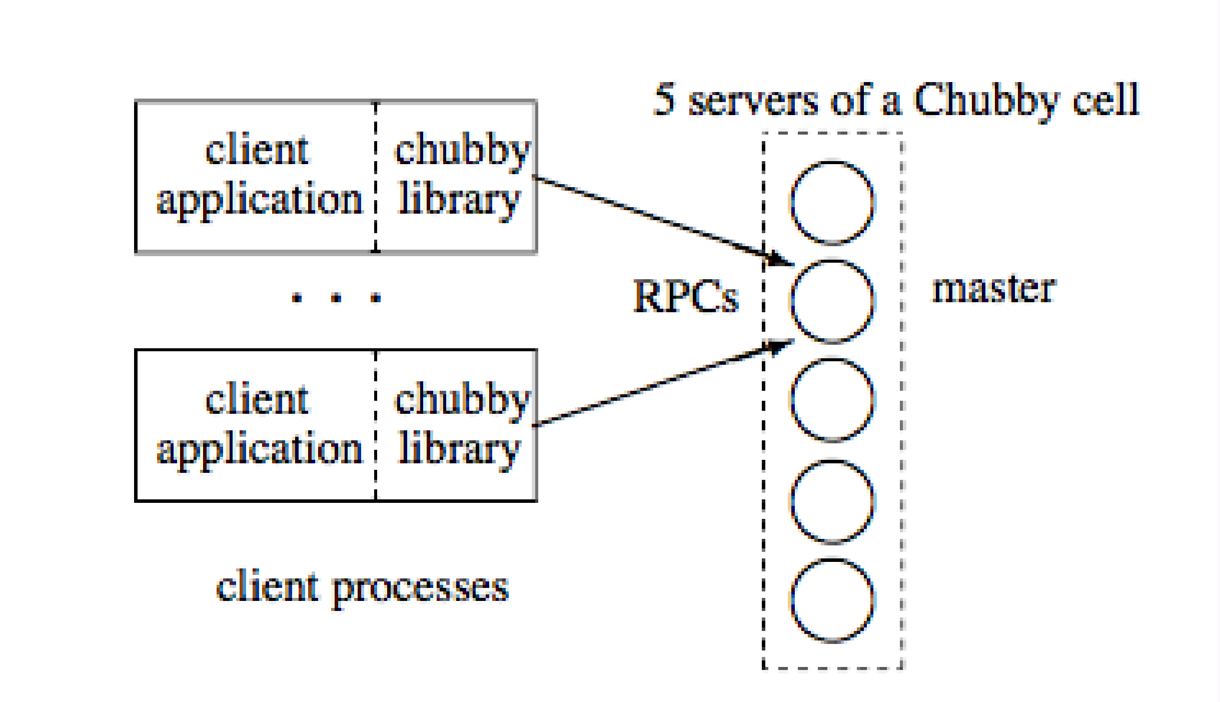
- There are better algorithms (Ricart & Agrawal, Voting etc.)
- Industry?
  - **centralized algorithm (Chubby, Zookeper)**
  - Replication for fault tolerance
  - Replicas coordinate using voting
  - App writers must avoid using the centralized lock service as much as possible

Chubby



- Intended for coarse-grained locks (client application holds critical section for a long time)
  - server failure is an issue
  - ability to add servers easily is important
- Chubby library on the client communicates with server via RPC
- Chubby cell contains usually five servers
  - one master, 4 replicas
  - distributed in different racks - why?

Chubby



- Replicas use a distributed consensus protocol to elect master
  - master has majority of votes; takes between 4s to 30s
- Replicas contain copies of a simple database
- Only master initiates reads/writes
- Once a client locates master, it redirects all requests to it
  - until master ceases to respond or notifies that it is no longer master
  - write requests are propagated to all replicas
  - reads requests are answered by the master
  - Lamport clocks used for ordering events