CS x55: Distributed Systems [Logical Clocks]

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Topics covered in this lecture

- Logical clocks
- Vector clocks
- Matrix clocks

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LOGICAL CLOCKS

Physical time in a distributed system is problematic

- This is not because of the effects of special relativity, which are negligible or non-existent for normal computers
  - Unless you count computers travelling in spaceships
- It is because of the *inability to accurately timestamp* events at different nodes
  - We need this to order any pairs of events

If two processes do not interact with each other?

- Their clocks need not be synchronized
- Lack of synchronization is not observable
  - Does not cause problems

Logical clocks

- Within a single process, events are ordered uniquely by times shown on local clock
- But we cannot synchronize clocks perfectly across a distributed system [Lamport 1978]
  - We cannot use physical time to find out the order of an arbitrary pair of events in a distributed system

We can use a scheme that is similar to physical causality to order events

(1) If two events occurred at the same process p_i (i=1, 2, …, N) ?
- Then they occurred in the order in which p_i observes them
  - This is the order $\rightarrow_i$

(2) When a message is sent between processes?
- The event of sending the message occurred before the event of receiving the message

The → relation

- Lamport called the **partial ordering** obtained by generalizing the previous 2 relationships
  - The *happened-before* or *happens-before* relation
- Sometimes also known as the relation of *causal ordering* or *potential causal ordering*

Lamport's logical clocks

- The **happens-before** relation ➔
- a and b are events in the process; and a occurs before b
  - Then a ➔ b is true
- a is event of message sent by one process;
  b is event of message being received in another process
  - Then a ➔ b is true

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Some more things about the happens-before relation

- If a ➔ b and b ➔ c; then a ➔ c
  - **Transitive**
- If events x and y occur in processes that do not exchange messages, then …
  - x ➔ y is not true
  - But, neither is y ➔ x
  - These events are said to be **concurrent**

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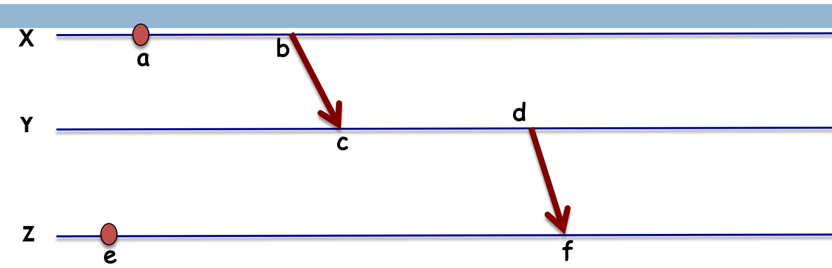
Events occurring at three processes



- $a \rightarrow b$ and $c \rightarrow d$
  - These occur within the same process
- $b \rightarrow c$ and $d \rightarrow f$
  - Events that correspond to sending and receiving messages
- We can use transitivity to say $a \rightarrow f$
- No relationship between a and e; these are **concurrent** $a \,||\, e$

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If the → relation holds between two processes

- The first event might or might-not have caused the second
  - The → relation only captures **potential causality**
    - *i.e.* two events can be related by → without a real connection between them
- EXAMPLE 1: If the server receives a request and sends a response?
  - Then reply is caused by the request
- EXAMPLE 2: A process might receive a request and subsequently issue another message
  - But this could be one that it issues every 5 minutes anyway

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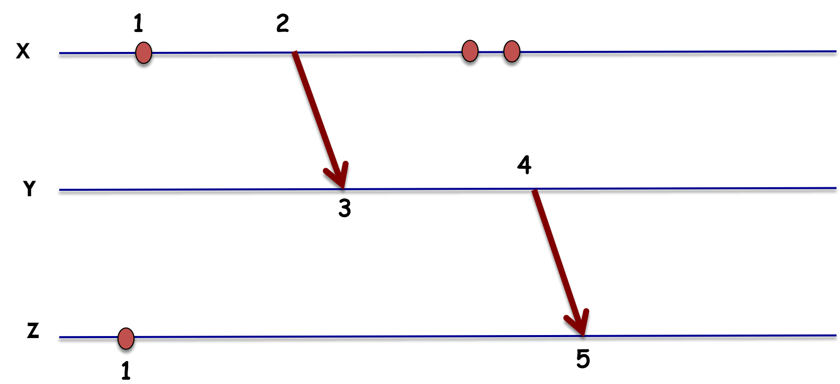
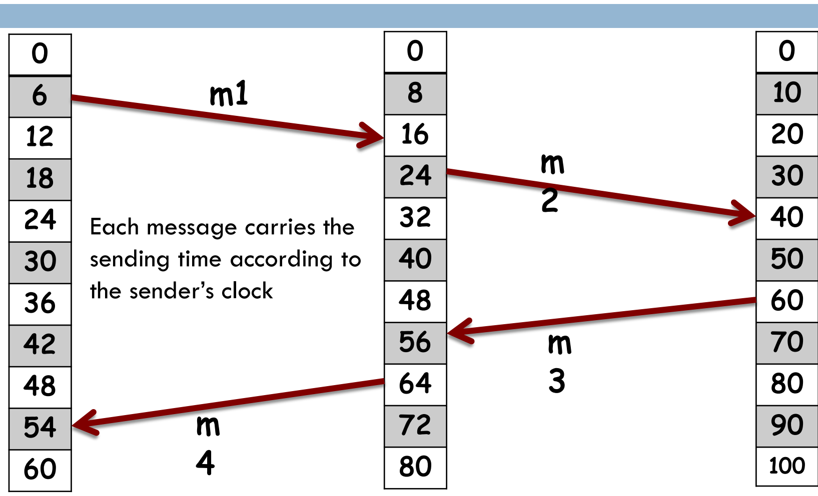
A simple example of Lamport timestamps



An example of Lamport's algorithm:



Each clock runs at a constant (but different rate)

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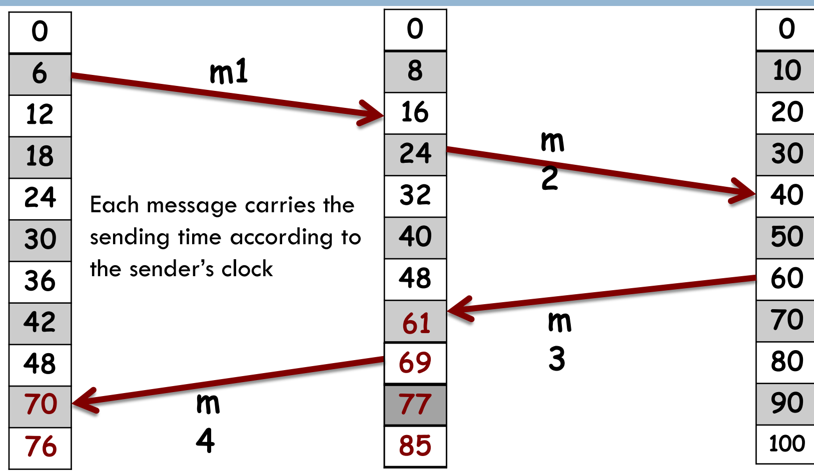


Each clock runs at a constant (but different rate)

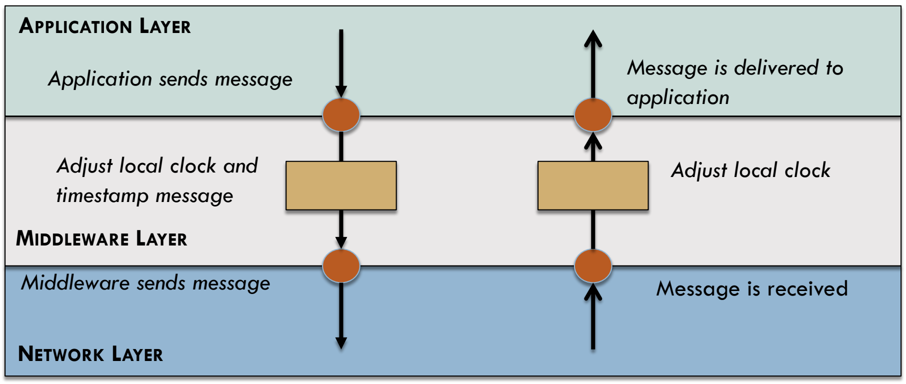
Implementing Lamport's clocks

① Before executing an event; P_i executes
$C_i = C_i + 1$

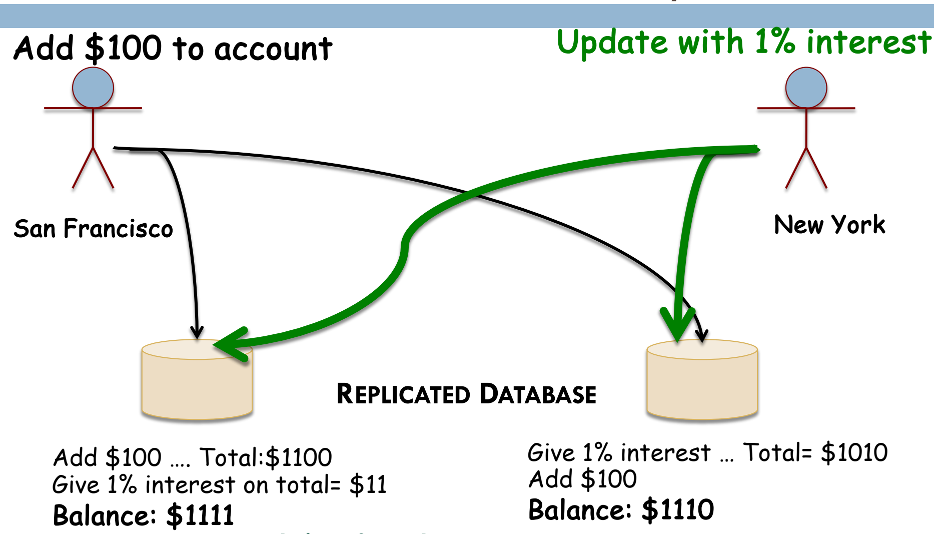
② When P_i sends a message m to P_j ; it sets m's timestamp $ts(m)$ to C_i in previous step

③ Upon receipt of message m, P_j adjusts its own local counter
$C_j = max\ \{C_j, ts(m)\}$
do step (1) and deliver message

The positioning of Lamport's clocks in distributed systems



An application of Lamport's clock: User has $1000 in bank account initially



There is a difference when the orders are reversed

- Our objective for now is consistency
- Both copies must be exactly the same

Use Lamport's clock to order messages

- Process puts received messages into local queue
  - Ordered according to the message's timestamp
- Message can be delivered only if it is **acknowledged** by all the other processes
- If a message is at the head of the queue, and acknowledged by all processes
  - It is delivered and processed

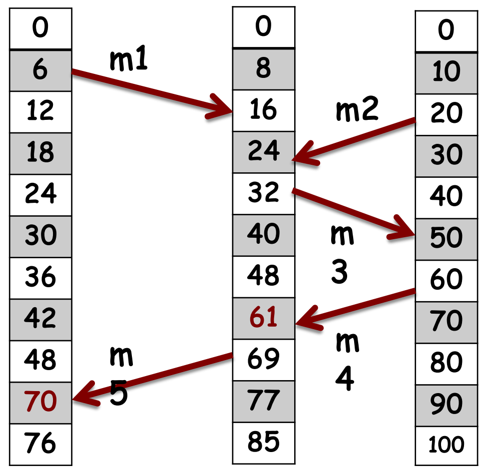
Lamport's Clocks order events based on the happened-before relationship

- If a happened before b, then $C(a) < C(b)$
- But nothing can be said about two events a and b by merely comparing their values
- $C(a) < C(b)$?
  - Does not mean a happened before b

Let's look a little closer

- $T_{snd}(m_i)$: Time m_i was sent
- $T_{rcv}(m_i)$: Time m_i was received
- $T_{snd}(m_i) < T_{rcv}(m_i)$
- BUT
  - $T_{snd}(m_i) < T_{rcv}(m_j)$?
    - NO

Concurrent message transmissions



Sending m3 MAY HAVE depended on m1

$T_{rcv}(m1) < T_{snd}(m2)$

But sending of m2 has nothing to do with receipt of m1

Lamport clocks do not capture causality

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VECTOR CLOCKS

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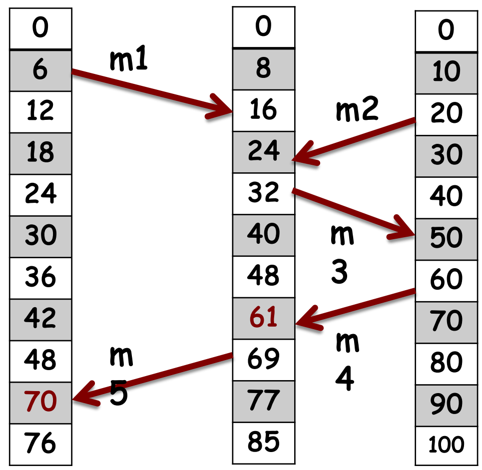


Sending m3 MAY HAVE depended on m1

But sending of m2 has nothing to do with receipt of m1

$T_{rcv}(m1) < T_{snd}(m2)$

Lamport clocks do not capture causality

Vector clocks

- Developed by Mattern [1989] and Fidge [1991] to ***overcome shortcomings*** of Lamport's clocks
  - i.e. if $C(a) < C(b)$ *then we cannot conclude* $a \rightarrow b$
- A vector clock for a system of N processes is an **array** of N integers
- Each process keeps its own vector clock VC_i
  - Process uses it vector clock to timestamp messages

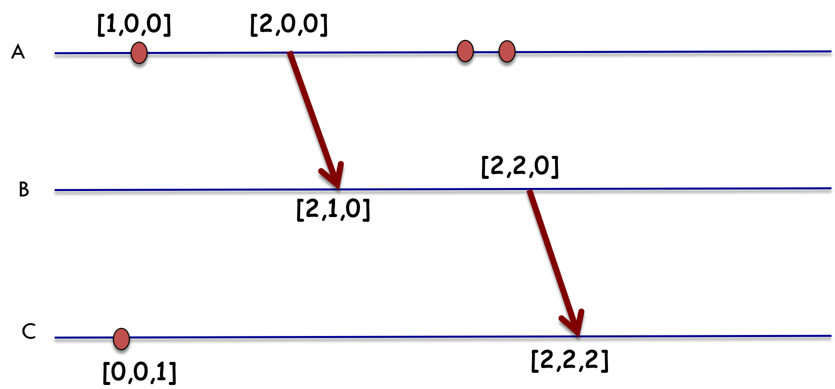
Causal precedence can be captured by Vector clocks

- Event a is known to **causally precede** event b iff $\mathrm{VC(a)} < \mathrm{VC(b)}$
  - $\mathrm{VC(a)}<\mathrm{VC(b)}$ iff $\mathrm{VC(a)[k]} \leq \mathrm{VC(b)[k]}$ for all k and *at least one* of those relationships is **strictly smaller**
- Each process $\mathrm{P_i}$ maintains a vector $\mathrm{VC_i}$
- $\mathrm{VC_i[i]}$ is number of events so far at $\mathrm{P_i}$
- If $\mathrm{VC_i[j] = k}$
  - $\mathrm{P_i}$ knows k events occurred at $\mathrm{P_j}$
  - $\mathrm{P_i}$'s knowledge of local time at $\mathrm{P_j}$

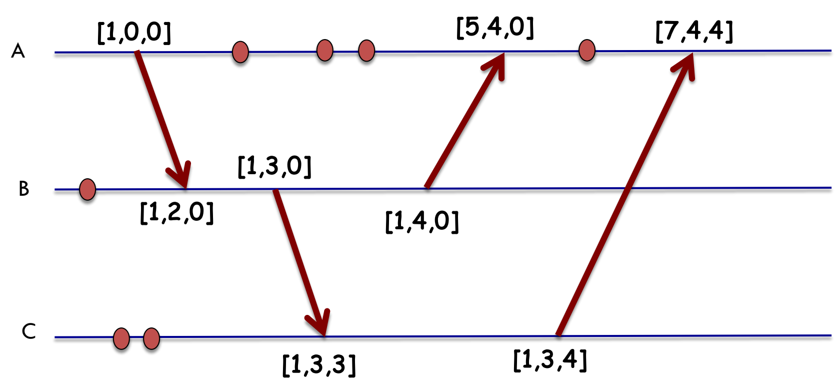
Vectors are piggybacked along with any messages that are sent

1. Before executing an event (sending, delivering, or internal) $\mathrm{P_i}$ executes
   - $\mathrm{VC_i[i] = VC_i[i] + 1}$
2. When $\mathrm{P_i}$ sends a message m to $\mathrm{P_j}$
   - Set m's timestamp $ts(m)$ to $\mathrm{VC_i}$ *after* doing (1)
3. After receiving m, process $\mathrm{P_j}$ adjusts its vector
   - $\mathrm{VC_j[k] = max\{VC_j[k],\ ts(m)[k]\}}$ for each k
   - Execute step (1) and deliver

Vector clocks example 1



Vector clocks example 2



Vector timestamps allow us to determine causality and concurrency

- Event a happened before event b iff
  - $ts(a) \leq ts\ (b)$ for each process i
    - And one of those relationships is *strictly smaller*
- If this is not true
  - Events a and b are concurrent

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Vector Clocks: Other aspects

- If event a has timestamp, $ts(a)$:
  - $ts(a)[i]–1$
    - Denotes number of events at P_i that precede a
- When P_j receives message m from P_i with timestamp $ts(m)=VC_i$
  - P_j knows about the number of events at P_i that causally preceded m
  - Also, P_j knows about how many events at *other* processes have preceded the sending of m, and on which m may causally depend

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Vector clocks: Disadvantages

- Storage and message payload is proportional to N, the number of processes
- It's been shown ([Charron-Bost 1991]) that if we are to tell if two events are concurrent by inspecting timestamps?
  - The dimension of N is unavoidable

USING VECTOR CLOCKS FOR CAUSALLY ORDERED MULTICASTING

Contrasting totally-ordered and causally-ordered **multicasting**

- Causally-ordered multicasting is **weaker than** totally-ordered multicasting
- If two messages are *not in any way related* to each other?
  - We do not care about the order in which they are delivered to applications
  - Could be delivered in *different order* at *different applications*

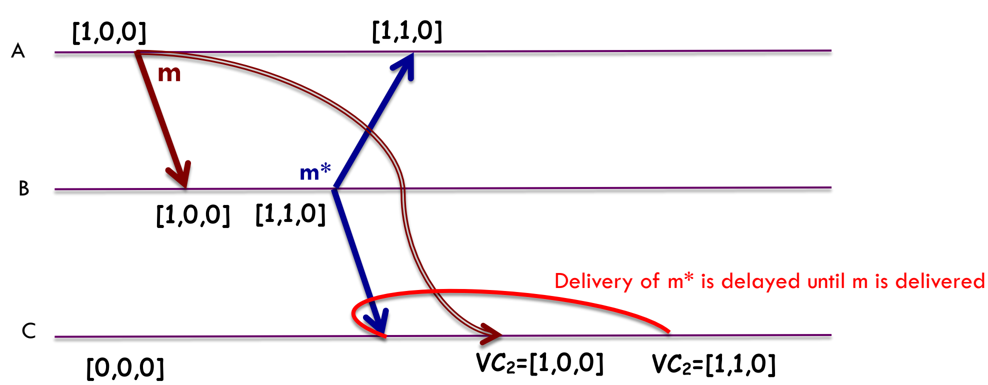
Using Vector Clocks for causally-ordered **multicasting**

- Clocks are ONLY **adjusted when sending and receiving** messages
- Upon sending a message, process P_i will only increment $VC_i[i]$ by 1
- When P_i delivers a message m with timestamp $ts(m)$ it adjusts $VC_i[k]$
  - To $max(VC_i[k], ts(m)[k])$ for each k

When process P_j receives a message m from P_i

- Delivery of the message m to the application layer is delayed until 2 conditions are met:
  1. $ts(m)[i] = VC_j[i] + 1$
     - This means m is the next message that P_j was expecting from P_i
  2. $ts(m)[k] \leq VC_j[k]$ for all $k \neq i$
     - This means that P_j has seen all messages that have been seen by P_i when it receives m

An example showing enforcement of causal communications



[Errata fixed on this slide.]

Matrix clocks

- Generalizes the notion of vector clocks
- Processes keep estimates of other processes' vector time [Raynal & Singhal, 1996]
- Essentially, a vector of vector clocks for each of the communicating processes

The contents of this slide-set are based on the following references

- *Distributed Systems: Principles and Paradigms. Andrew S. Tanenbaum and Maarten Van der Steen. 2nd Edition. Prentice Hall. ISBN: 0132392275/978-0132392273.* [Chapter 6]
- *Distributed Systems: Concepts and Design. George Coulouris, Jean Dollimore, Tim Kindberg, Gordon Blair. 5th Edition. Addison Wesley. ISBN: 978-0132143011.* [Chapter 14]
- http://en.wikipedia.org/wiki/Matrix_clocks