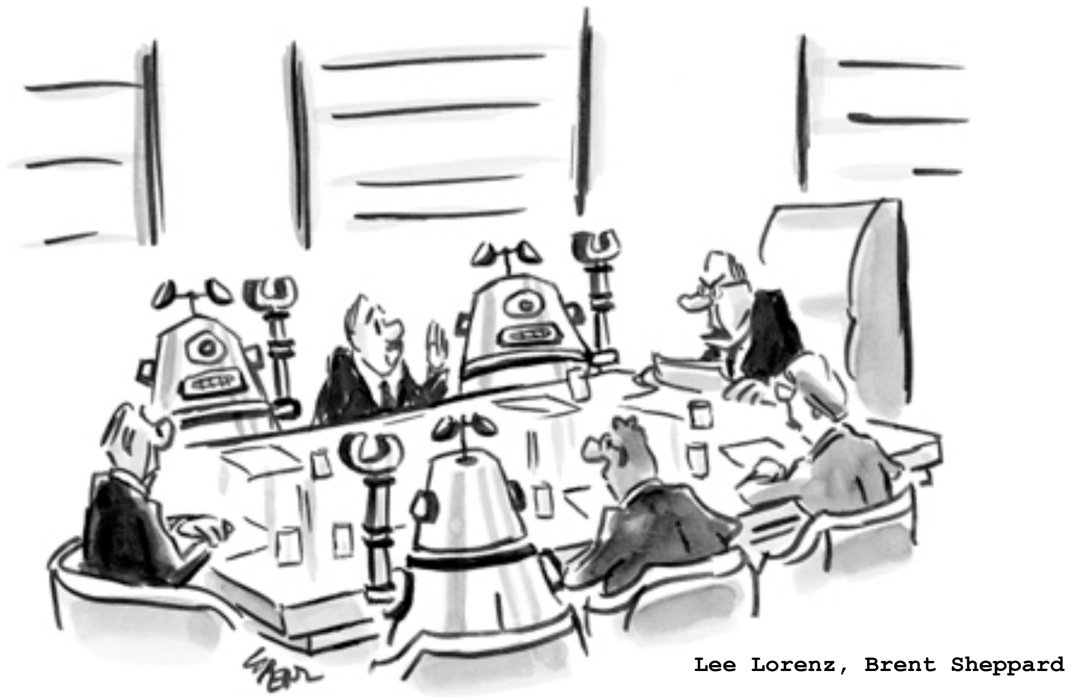


Jenkins, if I want another yes-man, I'll build one!

Versioning and Eventual Consistency

COS 461: Computer Networks
Spring 2011

Mike Freedman
http://www.cs.princeton.edu/courses/archive/spring11/cos461/

Ordering

- TCP sequence numbers uniquely order packets
  – One writer (sender) sets the sequence number
  – Reader (receiver) orders by seq number
- But recall distributed storage: may be more than one writer
  – One solution: If single server sees all the writes, can locally assign order in the order received, not sent
  – Recall partitioned storage: What about ordering writes handled by different servers?

Time and distributed systems

- With multiple events, what happens first?

A shoots B

B dies

Time and distributed systems

- With multiple events, what happens first?

B shoots A

A dies

Time and distributed systems

- With multiple events, what happens first?

A shoots B

A dies

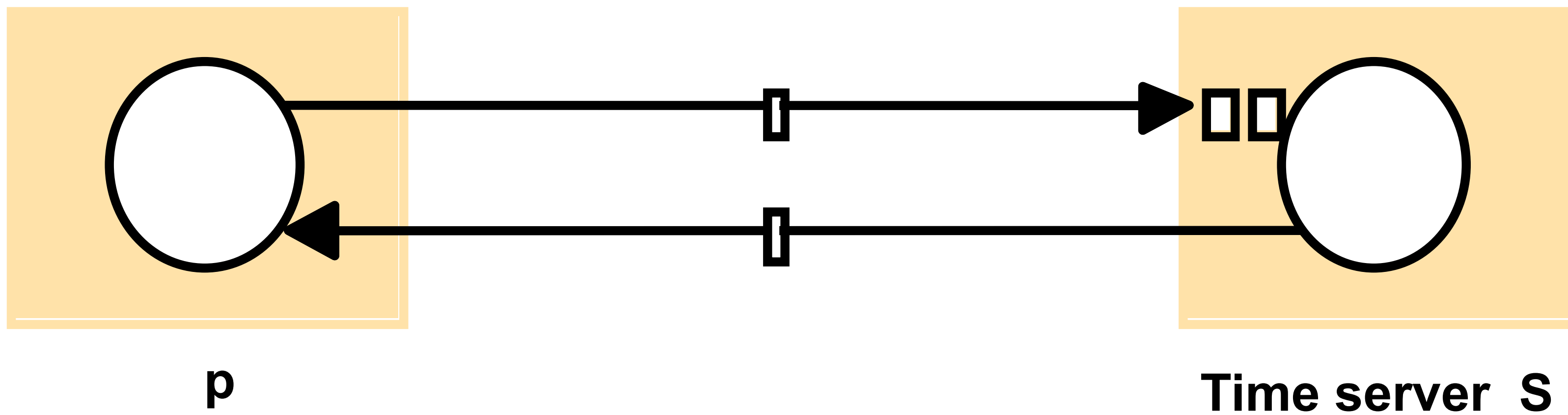
B shoots A

B dies

Just use time stamps?

- Need synchronized clocks

- Clock synch via a time server



Cristian's Algorithm

- Uses a *time server* to synchronize clocks
- Time server keeps the reference time
- Clients ask server for time and adjust their local clock, based on the response
  - But different network latency → clock skew?
- Correct for this? For links with symmetrical latency:

$$RTT = T_{resp\ received} - T_{req\ sent}$$

$$T_{new\ local} = T_{server} + (RTT / 2)$$

$$Error_{clock} = T_{new\ local} - T_{old\ local}$$

Is this sufficient?

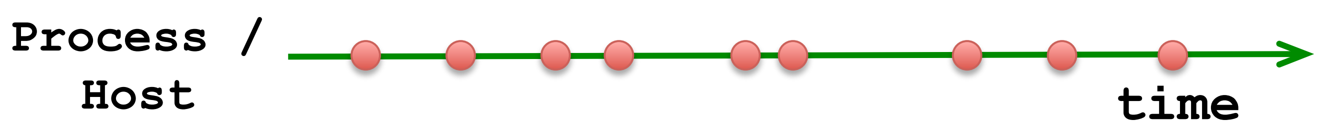
- Server latency due to load?
  - If can measure $T_{new\ local} = T_{server} + (RTT + lag / 2)$
- But what about asymmetric latency?
  - RTT / 2 not sufficient!
- What do we need to measure RTT?
  - Requires no clock drift!
- What about "almost" concurrent events?
  - Clocks have micro/milli-second precision

Events and Histories

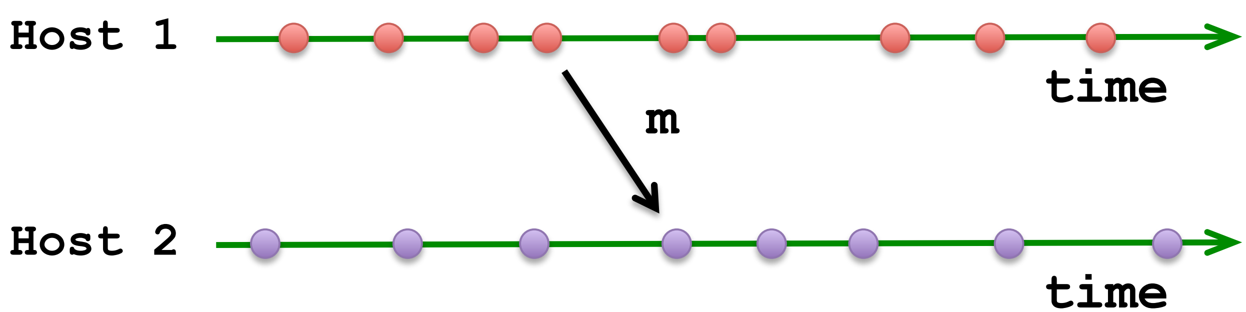
- Processes execute sequences of events
- Events can be of 3 types:
  - local, send, and receive
- The local history h_p of process p is the sequence of events executed by process

Ordering events

- Observation 1:
  - Events in a local history are totally ordered



- Observation 2:
  - For every message m, send(m) precedes receive(m)



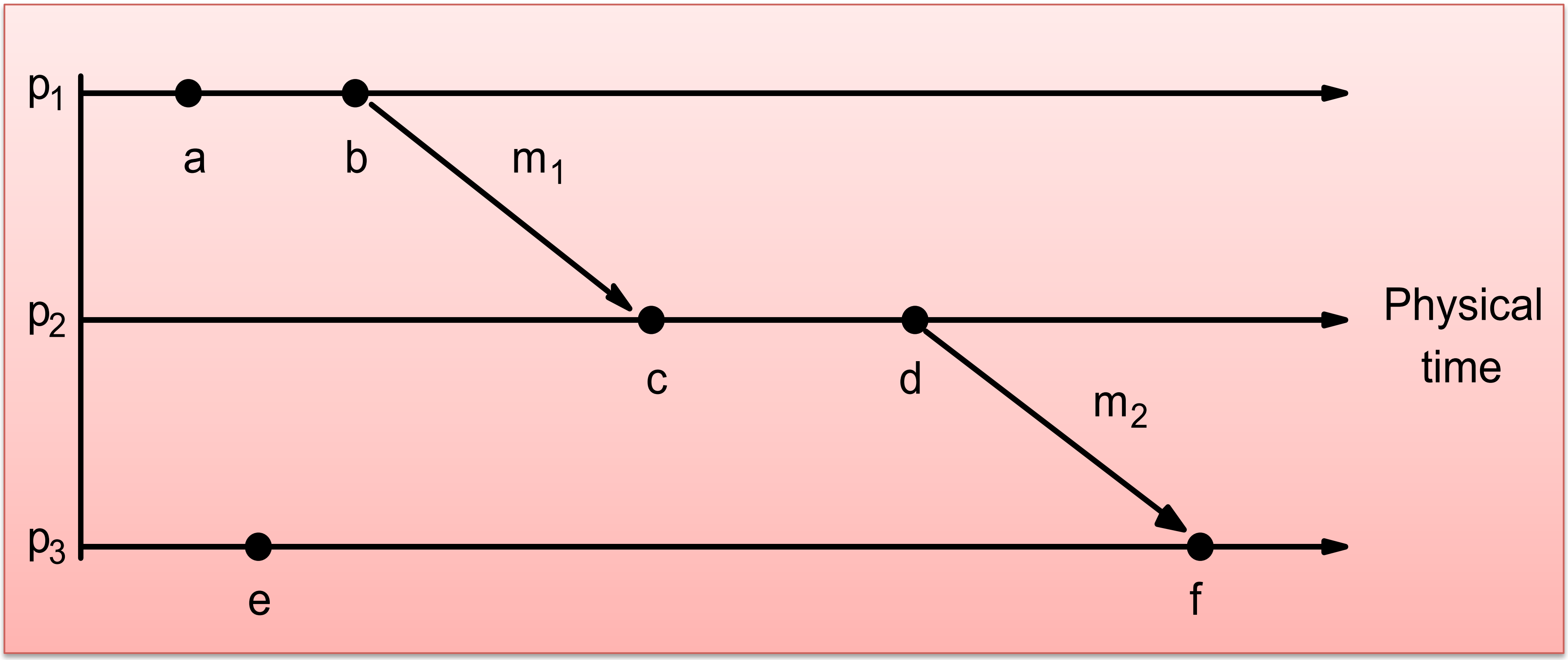
Happens-Before (Lamport [1978])

- Relative time? Define *Happens-Before* ($\rightarrow$) :
  - On the same process: $a \rightarrow b$, if $time(a) < time(b)$
  - If p1 sends *m* to p2: $send(m) \rightarrow receive(m)$
  - Transitivity: If $a \rightarrow b$ and $b \rightarrow c$ then $a \rightarrow c$

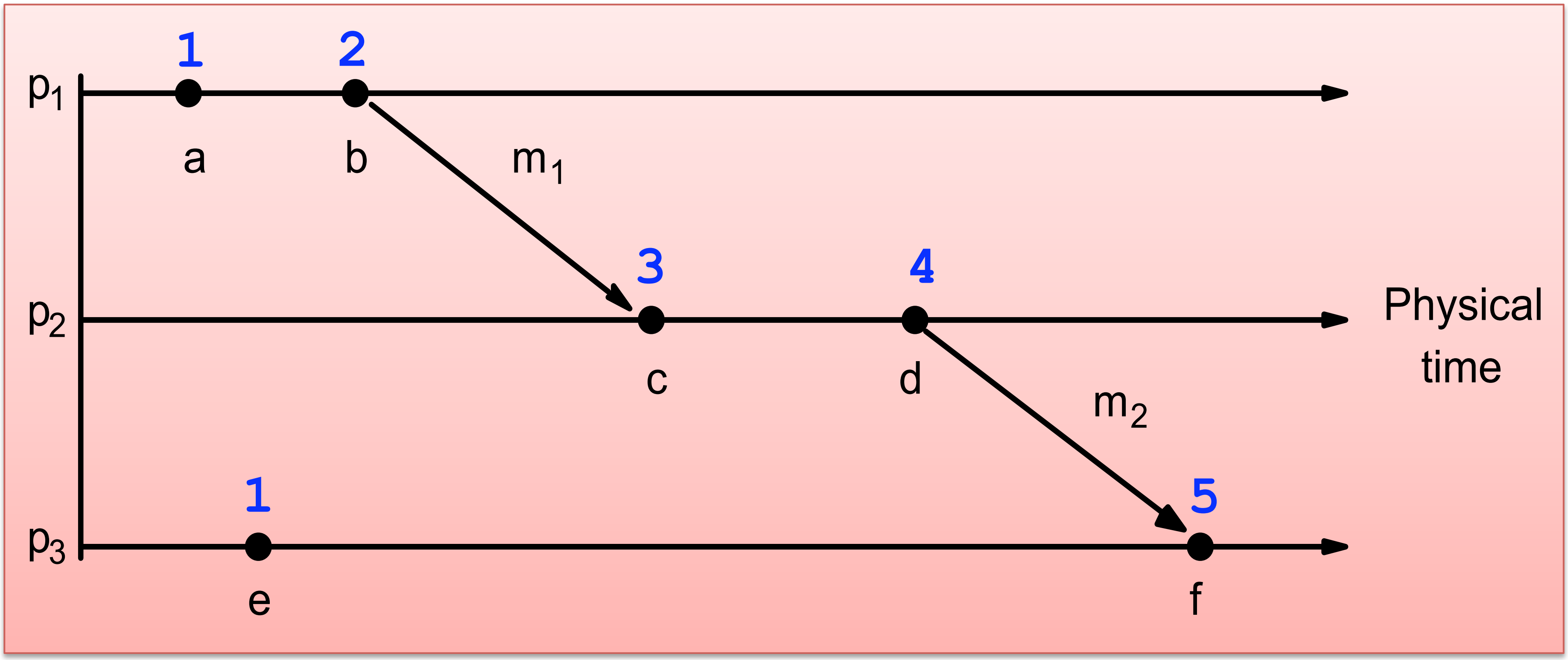
- Lamport Algorithm establishes partial ordering:
  - All processes use counter (clock) with initial value of 0
  - Counter incremented / assigned to each event as timestamp
  - A *send (msg)* event carries its timestamp
  - For *receive (msg)* event, counter is updated by

    max (receiver-counter, message-timestamp) + 1

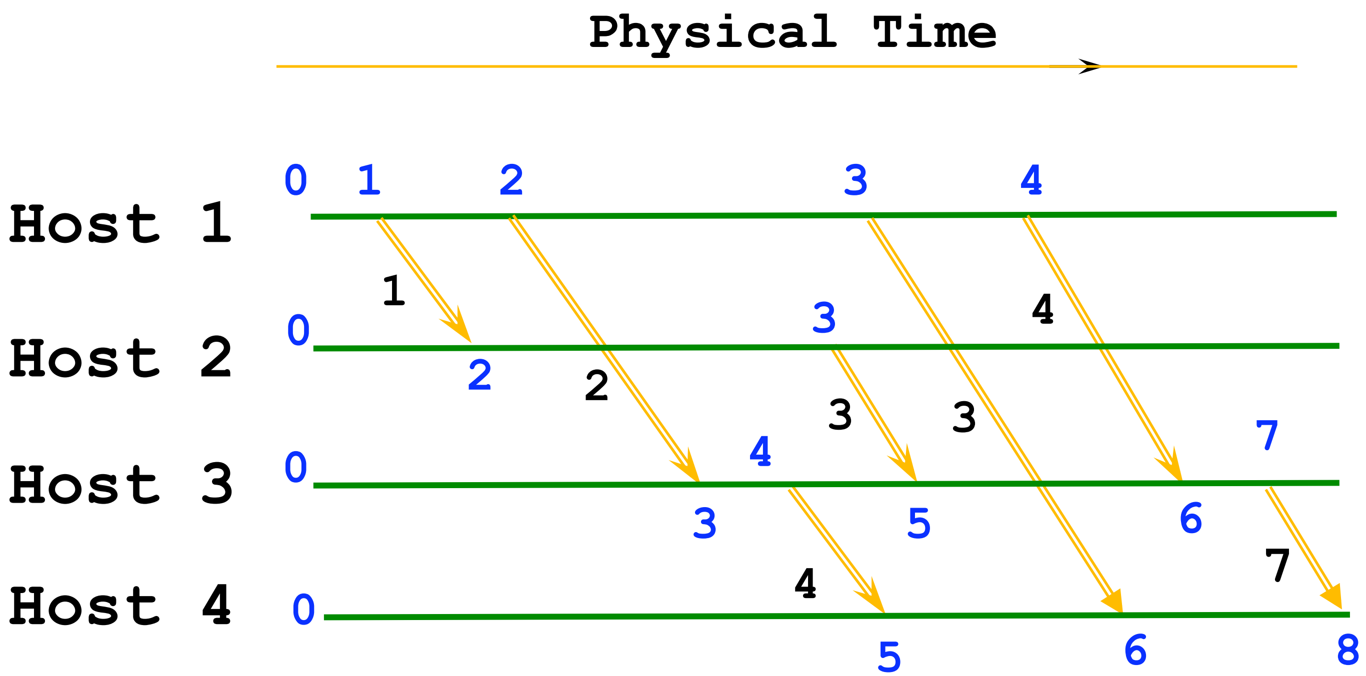
Events Occurring at Three Processes



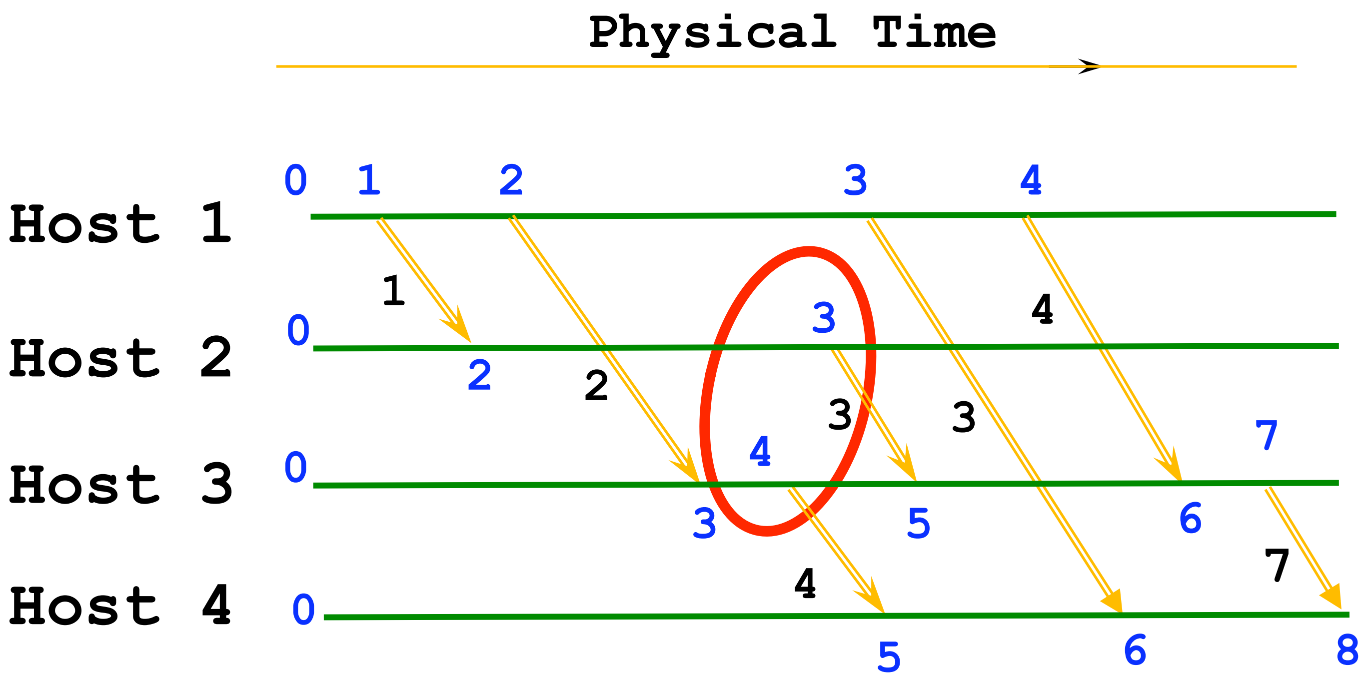
Lamport Timestamps

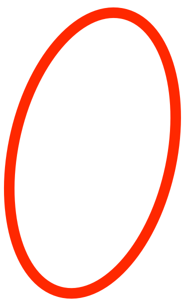


Lamport Logical Time



Lamport Logical Time





Logically concurrent events!

Vector Logical Clocks

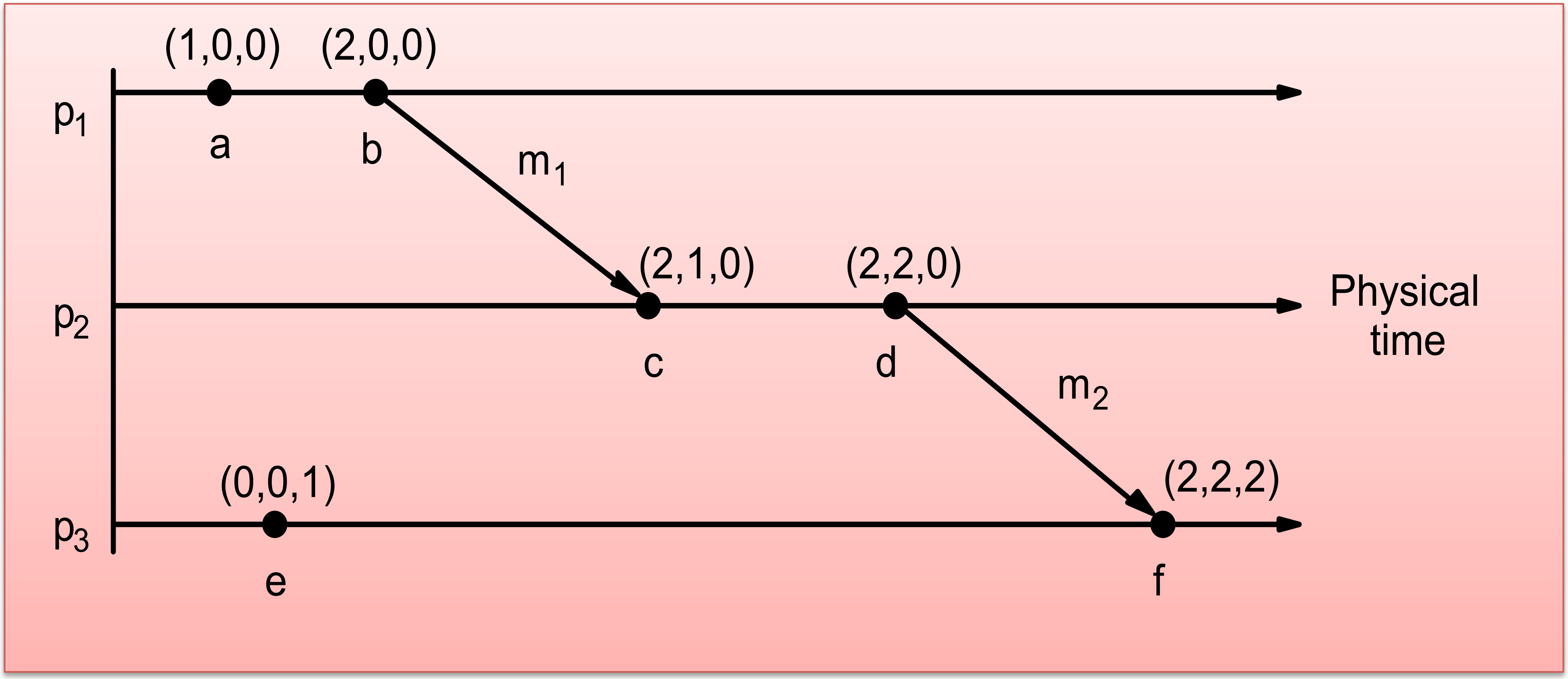
- With Lamport Logical Time
  - e precedes f $\Rightarrow$ timestamp(e) < timestamp (f), but
  - timestamp(e) < timestamp (f) $\Rightarrow$ e ~~precedes~~ f

Vector Logical Clocks

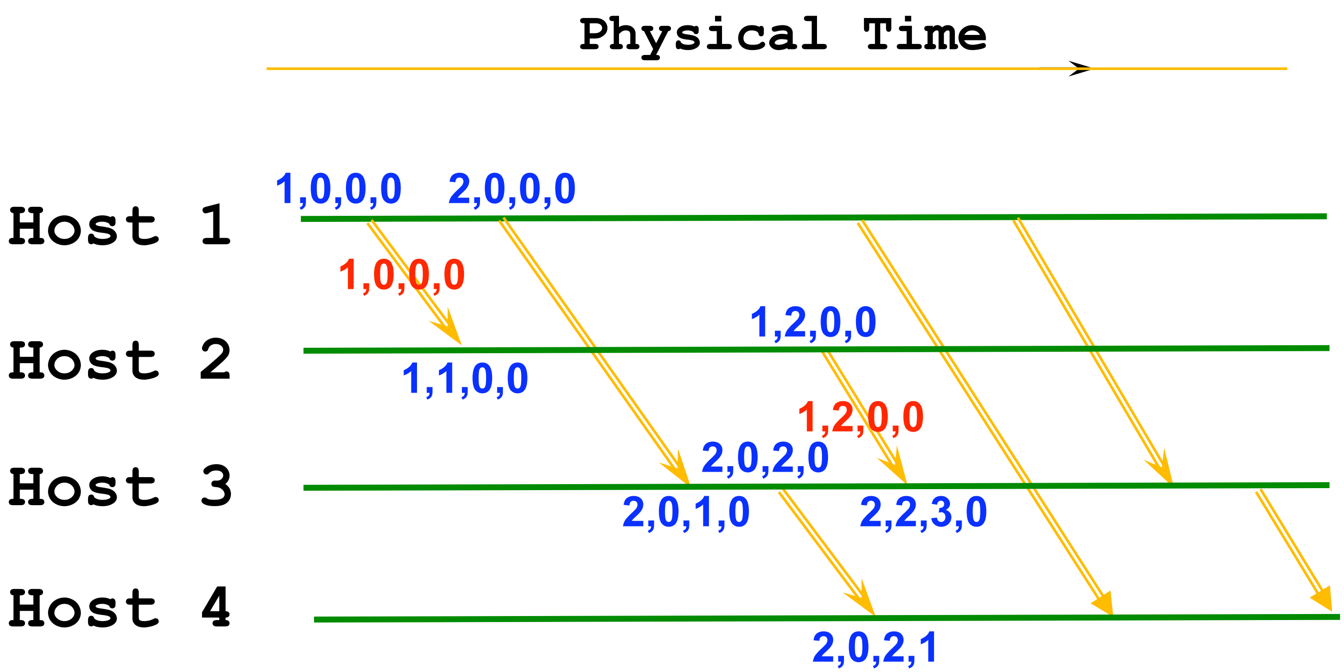
- With Lamport Logical Time
  - e precedes f $\Rightarrow$ timestamp(e) < timestamp (f), but
  - timestamp(e) < timestamp (f) $\Rightarrow$ e ~~precedes~~ f
- Vector Logical time guarantees this:
  - All hosts use a vector of counters (logical clocks), i^{th} element is the clock value for host i, initially 0
  - Each host i, increments the i^{th} element of its vector upon an event, assigns the vector to the event.
  - A send(msg) event carries vector timestamp
  - For receive(msg) event,

$$V_{receiver}[j] = \begin{cases} Max\ (V_{receiver}[j], V_{msg}[j]), & \text{if j is not self} \\ V_{receiver}[j] + 1 & \text{otherwise} \end{cases}$$

Vector Timestamps



Vector Logical Time



$$V_{receiver}[j] = \begin{cases} \text{Max } (V_{receiver}[j], V_{msg}[j]), & \text{if j is not self} \\ V_{receiver}[j] + 1 & \text{otherwise} \end{cases}$$

Comparing Vector Timestamps

- a = b   if they agree at every element
- a < b   if a[i] <= b[i] for every i, but !(a = b)
- a > b   if a[i] >= b[i] for every i, but !(a = b)
- a || b   if a[i] < b[i], a[j] > b[j], for some i,j   (*conflict!*)

- If one history is prefix of other, then one vector timestamp < other
- If one history is not a prefix of the other, then (at least by example) VTs will not be comparable.

Given a notion of time…

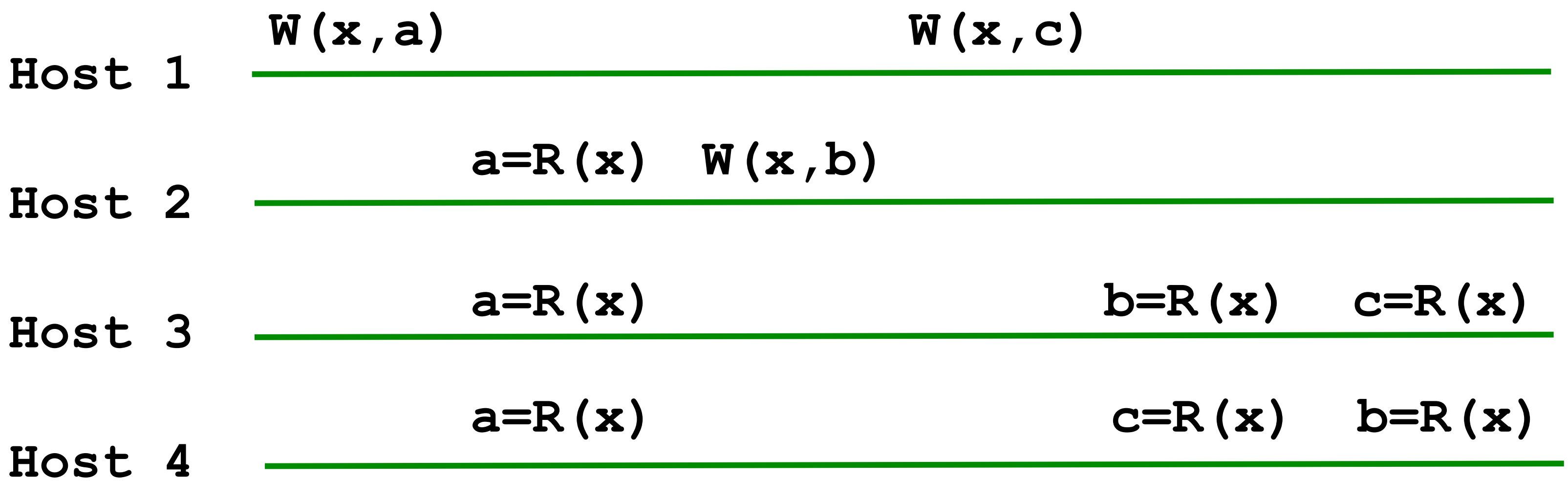
…What's a notion of consistency?

- Global total ordering? See Wednesday
- Today: Something weaker!

Causal Consistency

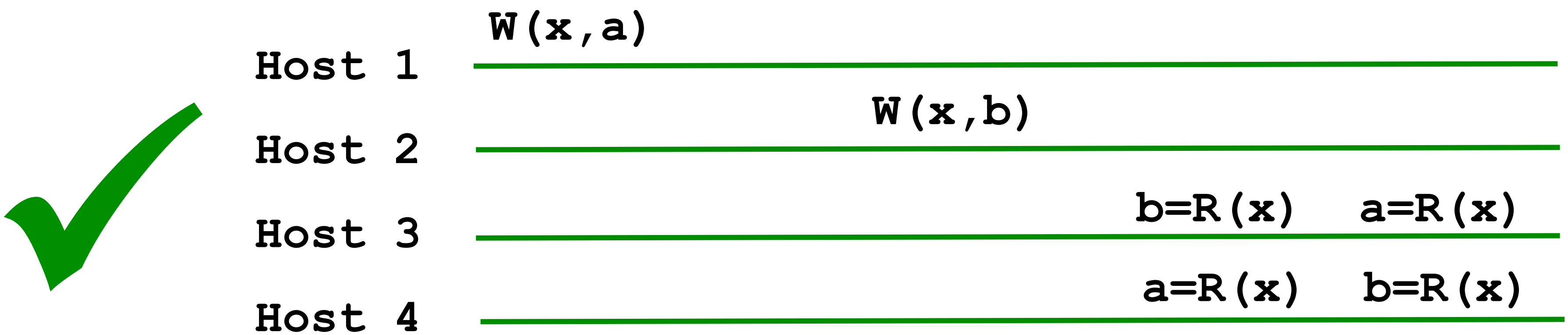
- Concurrent writes may be seen in a different order on different machines.
- Writes that are *potentially* causally related must be seen by all processes in the same order.

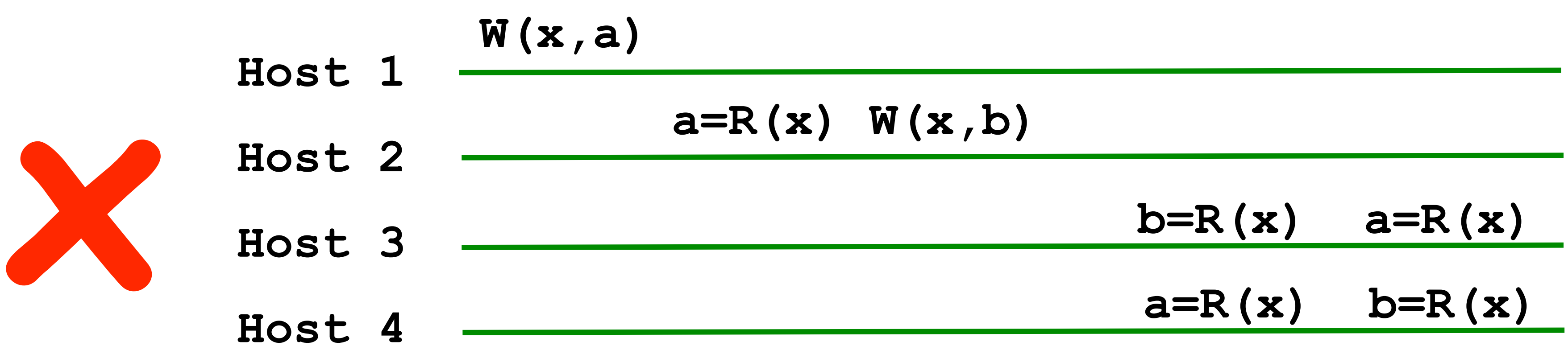
Causal Consistency



- *W(x,b)* and *W(x,c)* are concurrent
  - So all processes *may* not see them in same order
- Hosts 3 and 4 read *a* and *b* in order, as potentially causally related. No causality for *c*, however.

Examples: Causal Consistency

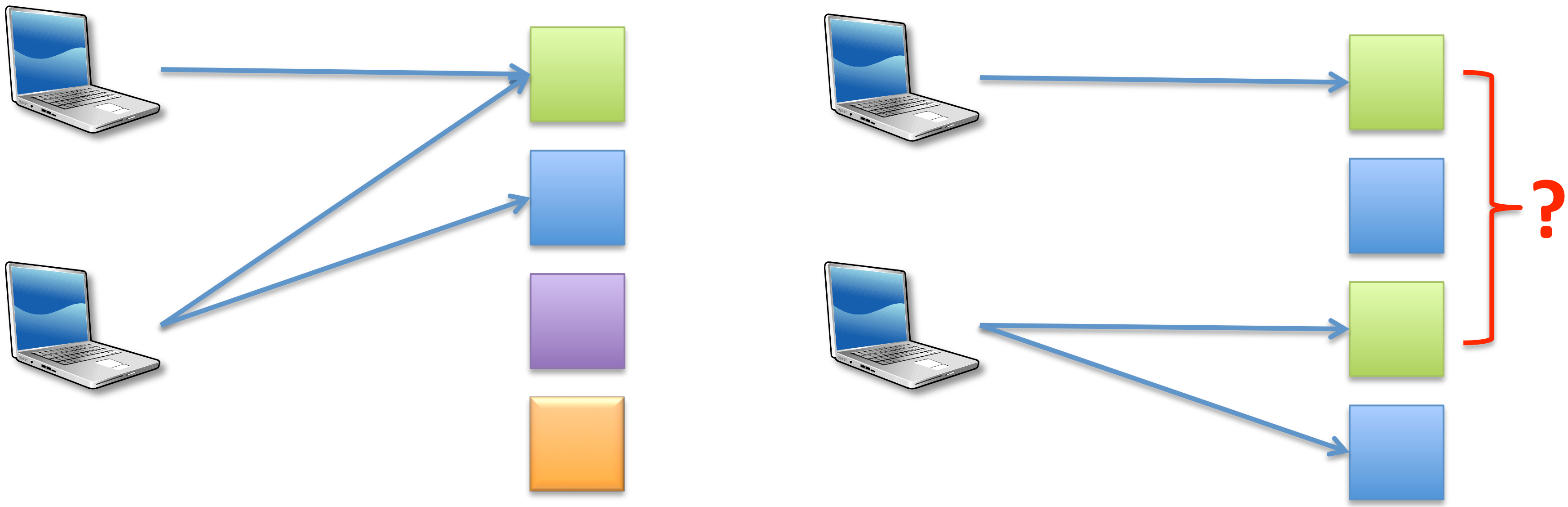




Causal Consistency

- Requires keeping track of which processes have seen which writes
  - Needs a dependency graph of which op is dependent on which other ops
  - …or use vector timestamps!

Where is consistency exposed?



- Original model b/w processes with local storage
- What if extend this to distributed storage application?
  - If single server per key, easy to locally order op's to key
  - Then, causal consistency for clients' op's to different keys
  - What if key at multiple servers for fault-tolerance/scalability?
    - Servers need consistency protocol with replication

Partial solution space for DB replication

- Master replica model
  - All writes (& ordering) happens at single master node
  - In background, master replicates data to secondary
  - Common DB replication approach (e.g., MySQL)
- Multi-master model
  - Write anywhere
  - Replicas run background task to get up to date
- Under either, reads may not reflect latest write!

Eventual consistency

- If no new updates are made to an object, after some inconsistency window closes, all accesses will return the same "last" updated value

- Prefix property:
  - If Host 1 has seen write $w_{i,2}$: i th write accepted by host 2
  - Then 1 has all writes $w_{j,2}$ (for j<i) accepted by 2 prior to $w_{i,2}$

- Assumption: write conflicts will be easy to resolve
  - Even easier if whole-"object" updates only

Systems using eventual consistency

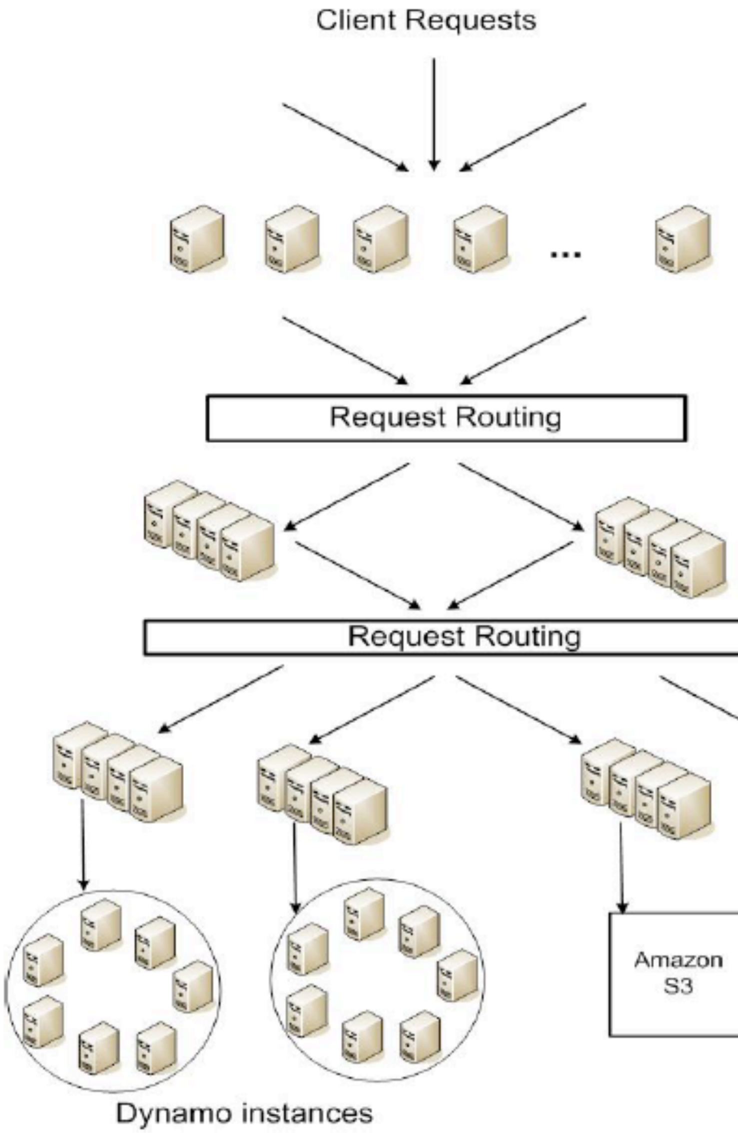
- DNS: each domain assigned to a naming authority
  - Only master authority can update the name space
  - Other NS servers act as “slave” servers, downloading DNS zone file from master authority
  - So, write-write conflicts won’t happen

```
$ ORIGIN coralcdn.org.
        @    IN    SOA    ns3.fs.net.    hostmaster.scs.cs.nyu.edu. (
                   18        ; serial
                   1200      ; refresh
                   600       ; retry
                   172800              ; expire
                   21600  )   ; minimum
```

Typical impl of eventual consistency

- Distributed, inconsistent state
  - Writes only go to some subset of storage nodes
    - By design (for higher throughput)
    - Due to transmission failures
    - Declare write as committed if received by "quorum" of nodes
- "Anti-entropy" (gossiping) fixes inconsistencies
  - Use vector clock to see which is older
  - Prefix property helps nodes know consistency status
  - If automatic, requires some way to handle write conflicts
    - Application-specific merge() function
    - Amazon's Dynamo: Users may see multiple concurrent "branches" before app-specific reconciliation kicks in

Amazon's Dynamo: Back-end storage



Problem	Technique	Advantage
Partitioning	Consistent Hashing	Incremental Scalability
High Availability for writes	Vector clocks with reconciliation during reads	Version size is decoupled from update rates.
Handling temporary failures	Sloppy Quorums	Availability and durability when some replicas not available.
Recovering permanent failures	Anti-entropy using crypto-hash trees	Synchronizes divergent replicas in background.
Membership and failure detection	Gossip-based membership and failure detection	Avoids needing centralized registry.

Summary

- Global time doesn't exist in distributed system
- Logical time can be established via version #'s
- Logical time useful in various consistency models
  - Strong > Causal > Eventual
- Wednesday
  - What are algorithms for achieving strong consistency?
  - What's possible among distributed replicated?
    - Strong consistency, availability, partition tolerance: Pick two