CS5412: REPLICATION, CONSISTENCY AND CLOCKS

Lecture X

Ken Birman

Recall that clouds have tiers

- Up to now our focus has been on client systems and the network, and the way that the cloud has reshaped both
- We looked very superficially at the tiered structure of the cloud itself
  - Tier 1: Very lightweight, responsive "web page builders" that can also route (or handle) "web services" method invocations. Limited to "soft state".
  - Tier 2: (key,value) stores and similar services that support tier 1. Basically, various forms of caches.
  - Inner tiers: Online services that handle requests not handled in the first tier. These can store persistent files, run transactional services. But we shield them from load.
  - Back end: Runs offline services that do things like indexing the web overnight for use by tomorrow morning's tier-1 services.

Replication

- A central feature of the cloud
- To handle more work, make more copies
  - In the first tier, which is highly elastic, data center management layer pre-positions inactive copies of virtual machines for the services we might run
    - Exactly like installing a program on some machine
  - If load surges, creating more instances just entails
    - Running more copies on more nodes
    - Adjusting the load-balancer to spray requests to new nodes
  - If load drops… just kill the unwanted copies!
    - Little or no warning. Discard any "state" they created locally.

Replication is about keeping copies

- The term may sound fancier but the meaning isn't

- Whenever we have many copies of something we say that we've replicated that thing
  - But usually replica does connote "identical"
  - Instead of *replication* we use the term *redundancy* for things like alternative communication paths (e.g. if we have two distinct TCP connections from some client system to the cloud)
  - Redundant things might not be identical. Replicated things usually play identical roles and have equivalent data.

Things we can replicate in a cloud

- Files or other forms of data used to handle requests
  - If all our first tier systems replicate the data needed for end-user requests, then they can handle all the work!
  - Two cases to consider: in one the data itself is “write once” like a photo. Either you have a replica, or don’t
  - In the other the data evolves over time, like the current inventory count for the latest iPad in the Apple store
- Computation
  - Here we replicate some *request* and then the work of computing the answer can be spread over multiple programs in the cloud
  - We benefit from parallelism by getting a faster answer
  - Can also provide fault-tolerance

Many things “map” to replication

- As we just saw, data (or databases), computation
- Fault-tolerant request processing
- Coordination and synchronization (e.g. “who’s in charge of the air traffic control sector over Paris?”)
- Parameters and configuration data
- Security keys and lists of possible users and the rules for who is permitted to do what
- Membership information in a DHT or some other service that has many participants

So… focus on replication!

- If we can get replication right, we'll be on the road to a highly assured cloud infrastructure
- Key is to understand what it means to correctly replicate data at cloud scale…
- … then once we know what we *want* to do, to find scalable ways to implement needed abstraction(s)

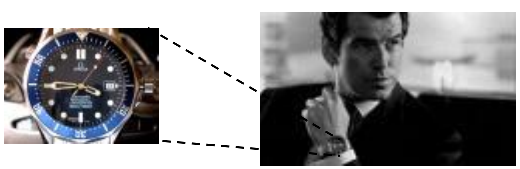
Concept of "consistency"

- We would say that a replicated entity behaves in a consistent manner if mimics the behavior of a non-replicated entity
  - E.g. if I ask it some question, and it answers, and then you ask it that question, your answer is either the same or reflects some update to the underlying state
  - Many copies but acts like just one

- An inconsistent service is one that seems "broken"

Consistency lets us ignore implementation

A <u>consistent</u> distributed system will often have many components, but users observe behavior indistinguishable from that of a single-component reference system



Reference Model

Implementation

Dangers of Inconsistency

My rent check bounced? That can't be right!

- Inconsistency causes bug
  - Clients would never be able to trust servers… a free-for-all

- Weak or "best effort" consistency?
  - Common in today's cloud replication schemes
  - But strong security guarantees demand consistency
  - Would you trust a medical electronic-health records system or a bank that used "weak consistency" for better scalability?

Leslie Lamport's insight

- To formalize notions of consistency, start by formalizing notions of time
- Once we do this we can be rigorous about notions like "before" or "after" or "simultaneously"
  - If we try to write down conditions for correct replication these kinds of terms often arise

What time is it?

- In distributed system we need practical ways to deal with time
  - E.g. we may need to agree that update A occurred before update B
  - Or offer a "lease" on a resource that expires at time 10:10.0150
  - Or *guarantee* that a time critical event will reach all interested parties within 100ms

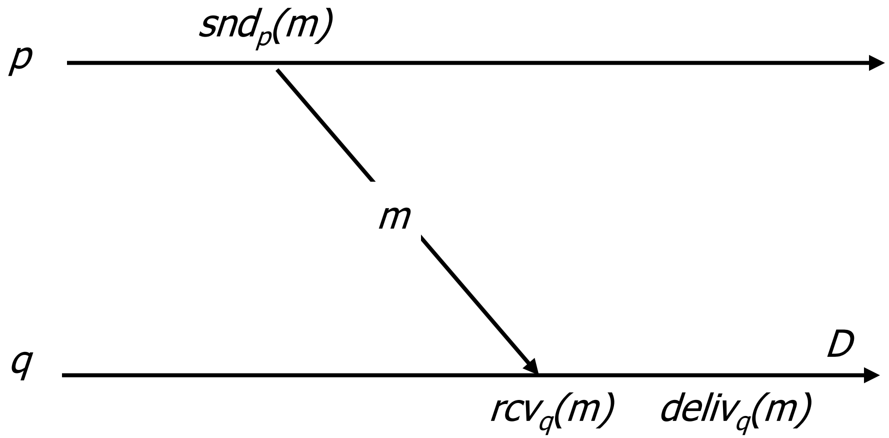
But what does time "mean"?

- Time on a global clock?
  - E.g. on Cornell clock tower?
  - ... or perhaps on a GPS receiver?
- … or on a machine's local clock
  - But was it set accurately?
  - And could it drift, e.g. run fast or slow?
  - What about faults, like stuck bits?
- … or could try to agree on time

Lamport's approach

- Leslie Lamport suggested that we should reduce time to its basics
  - Time lets a system ask "Which came first: event A or event B?"
  - In effect: time is a means of labeling events so that…
    - If A happened before B, TIME(A) < TIME(B)
    - If TIME(A) < TIME(B), A happened before B

Drawing time-line pictures:



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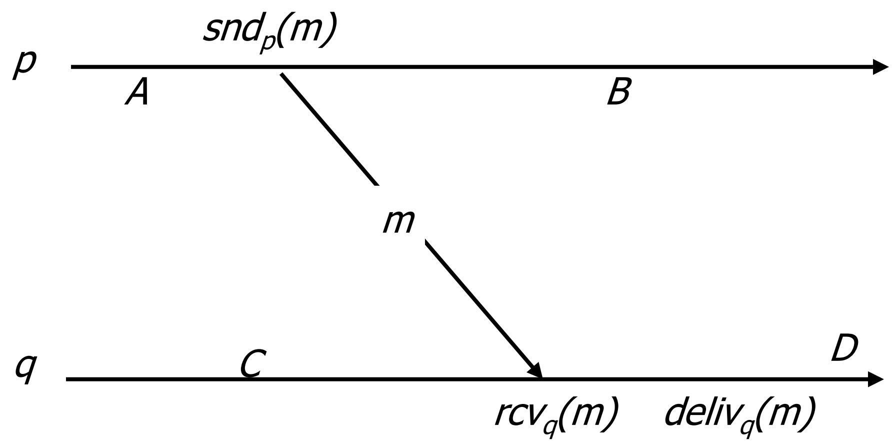
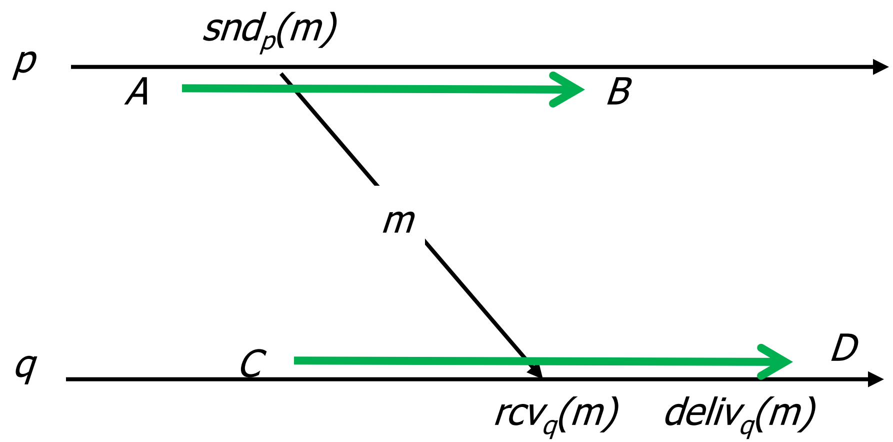


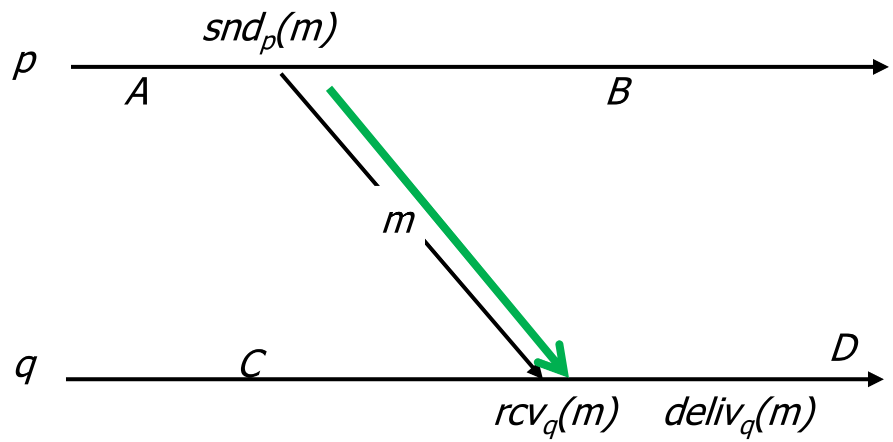
- A, B, C and D are "events".
  - Could be anything meaningful to the application
  - So are snd(m) and rcv(m) and deliv(m)
- What ordering claims are meaningful?

Drawing time-line pictures:



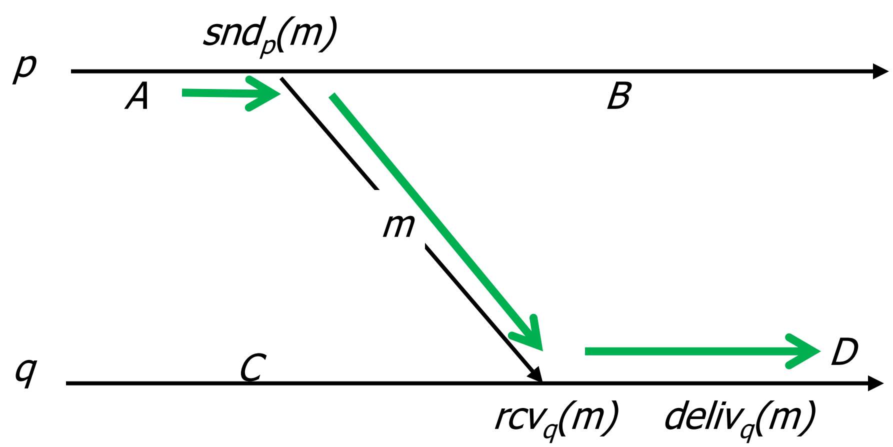
- A happens before B, and C before D
  - "Local ordering" at a single process
  - Write $A \xrightarrow{p} B$ and $C \xrightarrow{q} D$

Drawing time-line pictures:



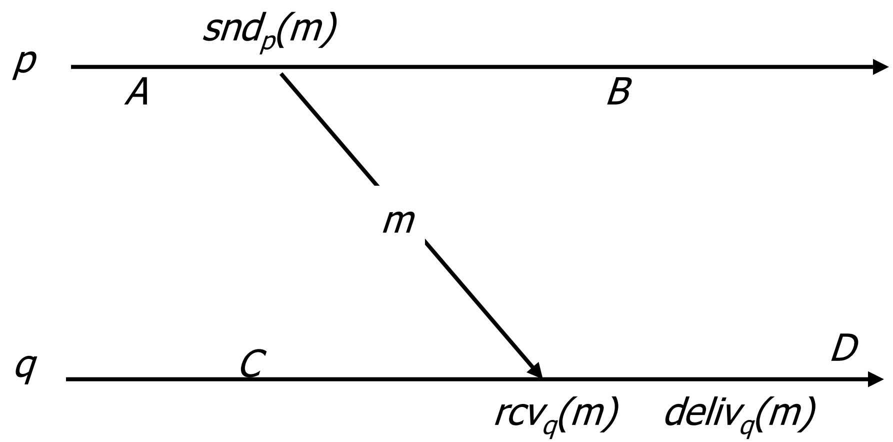
- $snd_p(m)$ also happens before $rcv_q(m)$
  - "Distributed ordering" introduced by a message
  - Write $snd_p(m) \xrightarrow{M} rcv_q(m)$

Drawing time-line pictures:



- A happens before D
  - Transitivity: A happens before $snd_p(m)$, which happens before $rcv_q(m)$, which happens before D

Drawing time-line pictures:



- B and D are concurrent
  - Looks like B happens first, but D has no way to know. No information flowed…

Happens before "relation"

- We say that "A happens before B", written $A \rightarrow B$, if
  1. $A \rightarrow^{P} B$ according to the local ordering, or
  2. A is a *snd* and B is a *rcv* and $A \rightarrow^{M} B$, *or*
  3. A and B are related under transitive closure of rules (1) and (2)

- Notice that, so far, this is just a mathematical notation, not a "systems tool"
  - Given a trace of what happened in a system we could use these tools to talk about the trace
  - But need a way to "implement" this idea

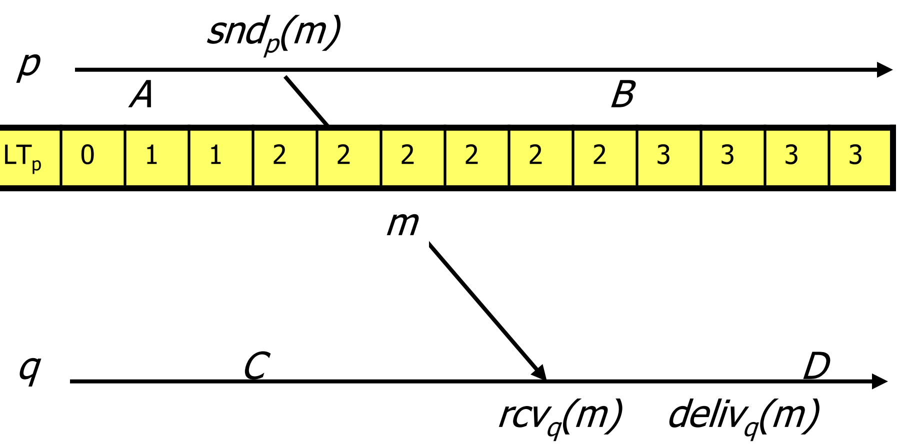
Logical clocks

- A simple tool that can capture parts of the happens before relation
- First version: uses just a single integer
  - Designed for big (64-bit or more) counters
  - Each process *p* maintains LT_p, a local counter
  - A message *m* will carry LT_m

Rules for managing logical clocks

- When an event happens at a process *p* it increments LT_p.
  - Any event that matters to *p*
  - Normally, also *snd* and *rcv* events (since we want receive to occur "after" the matching send)
- When p sends *m*, set
  - $LT_m = LT_p$
- When q receives *m*, set
  - $LT_q = \max(LT_q, LT_m)+1$

Time-line with LT annotations



LT_p	0	1	1	2	2	2	2	2	2	3	3	3	3
LT_q	0	0	0	1	1	1	1	3	3	3	4	5	5

- $LT(A) = 1$, $LT(snd_p(m)) = 2$, $LT(m) = 2$
- $LT(rcv_q(m))=max(1,2)+1=3$, etc…

Logical clocks

- If A happens before B, $A \rightarrow B$, then $LT(A) < LT(B)$
- But converse might not be true:
  - If $LT(A) < LT(B)$ can't be sure that $A \rightarrow B$
  - This is because processes that don't communicate still assign timestamps and hence events will "seem" to have an order

Can we do better?

- One option is to use *vector* clocks
- Here we treat timestamps as a list
  - One counter for each process
- Rules for managing vector times differ from what did with logical clocks

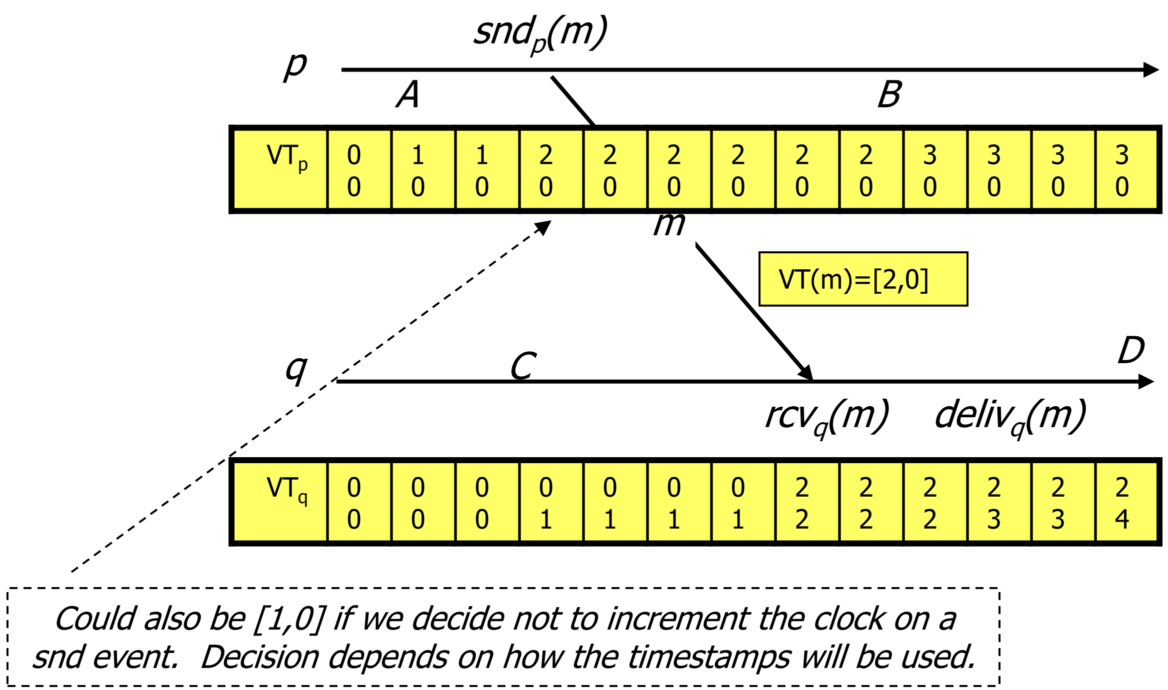
History of vector clocks?

- Originated in work at UCLA on file systems that allowed updates from multiple sources concurrently
  - Jerry Popek's FICUS system
  - Today version systems (e.g. SVN, CVS) use the idea
- Also gradually adopted in distributed systems
- Most of the "formal" work was done by Fidge and Mattern in Europe, long after idea was in wide use

Vector clocks

- Clock is a vector: e.g. VT(A)=[1, 0]
  - We'll just assign p index 0 and q index 1
  - Vector clocks require either agreement on the numbering, or that the actual process id's be included with the vector
- Rules for managing vector clock
  - When event happens at p, increment $VT_p[index_p]$
    - Normally, also increment for snd and rcv events
  - When sending a message, set $VT(m)=VT_p$
  - When receiving, set $VT_q=max(VT_q, VT(m))$

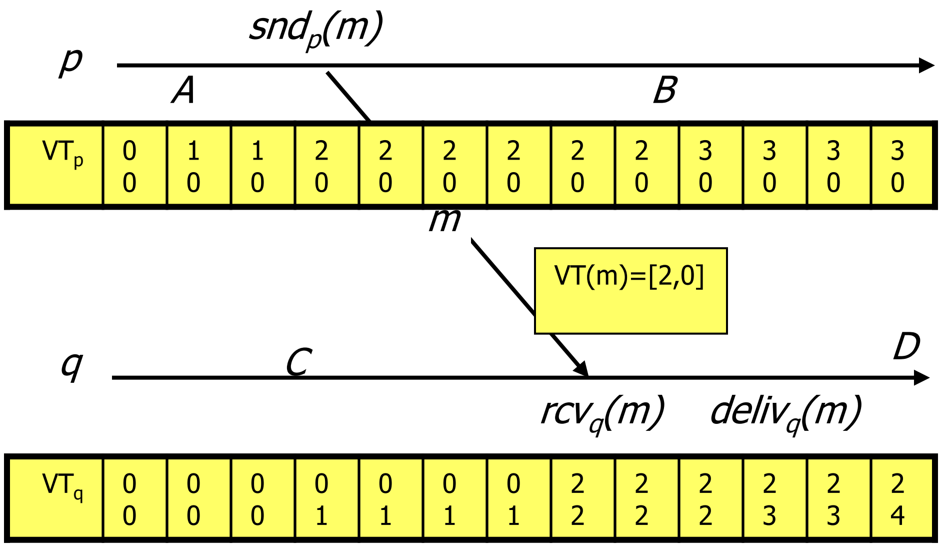
Time-line with VT annotations



Rules for comparison of VTs

- We'll say that $VT_A \leq VT_B$ if
  - $\forall_I$, $VT_A[i] \leq VT_B[i]$
- And we'll say that $VT_A < VT_B$ if
  - $VT_A \leq VT_B$ but $VT_A \neq VT_B$
  - That is, for some i, $VT_A[i] < VT_B[i]$
- Examples?
  - [2,4] ≤ [2,4]
  - [1,3] < [7,3]
  - [1,3] is "incomparable" to [3,1]

Time-line with VT annotations



- VT(A)=[1,0]. VT(D)=[2,4]. So VT(A)<VT(D)
- VT(B)=[3,0]. So VT(B) and VT(D) are incomparable

Vector time and happens before

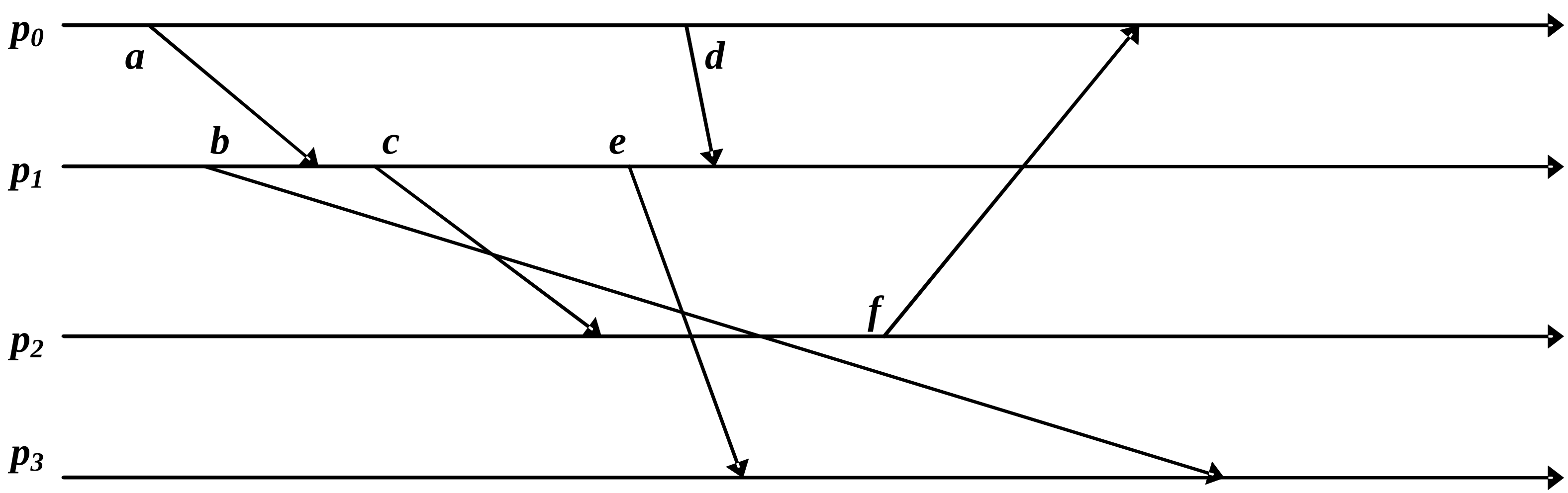
- If $A \rightarrow B$, then $VT(A) < VT(B)$
  - Write a chain of events from A to B
  - Step by step the vector clocks get larger
- If $VT(A) < VT(B)$ then $A \rightarrow B$
  - Two cases: if A and B both happen at same process p, trivial
  - If A happens at p and B at q, can trace the path back by which q "learned" $VT_A[p]$
- Otherwise A and B happened concurrently

Temporal distortions

- Things can be complicated because we can't predict
  - Message delays (they vary constantly)
  - Execution speeds (often a process shares a machine with many other tasks)
  - Timing of external events
- Lamport looked at this question too

Temporal distortions

- What does “now” mean?



Temporal distortions

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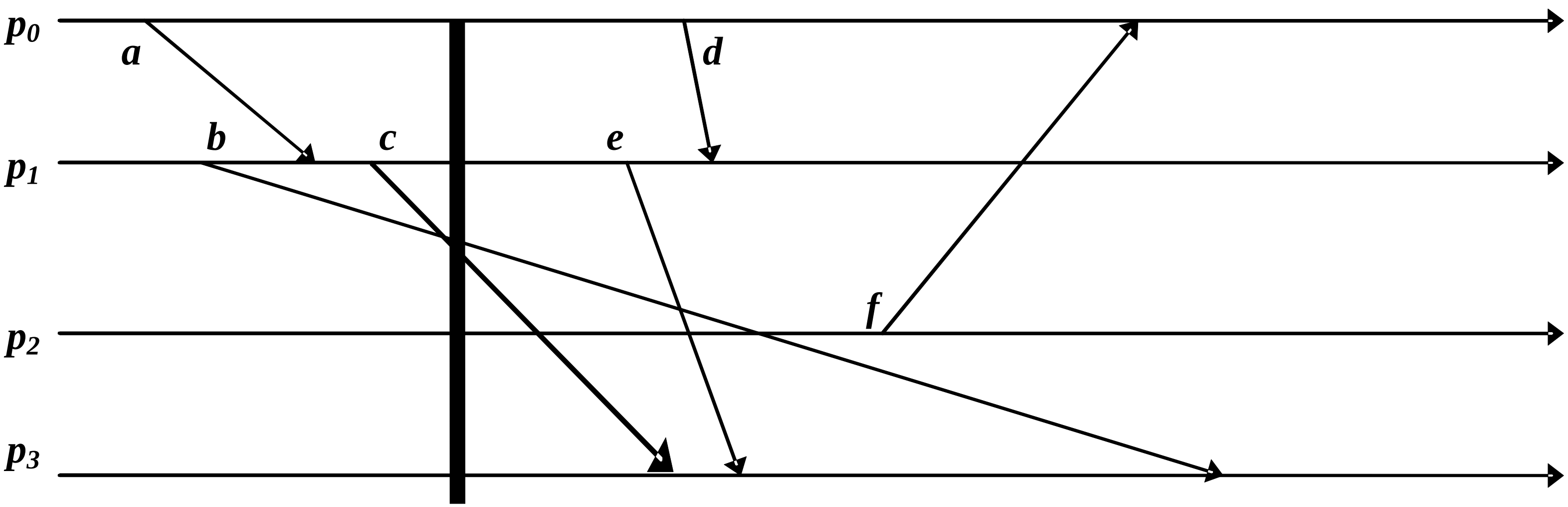
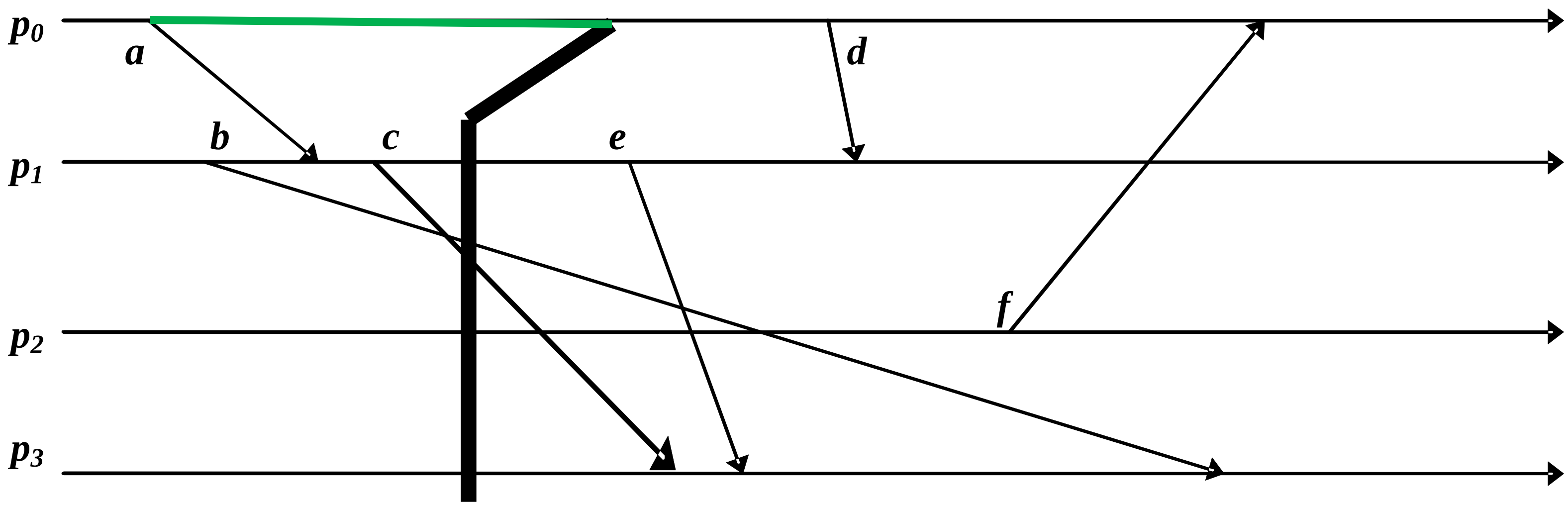


Temporal distortions

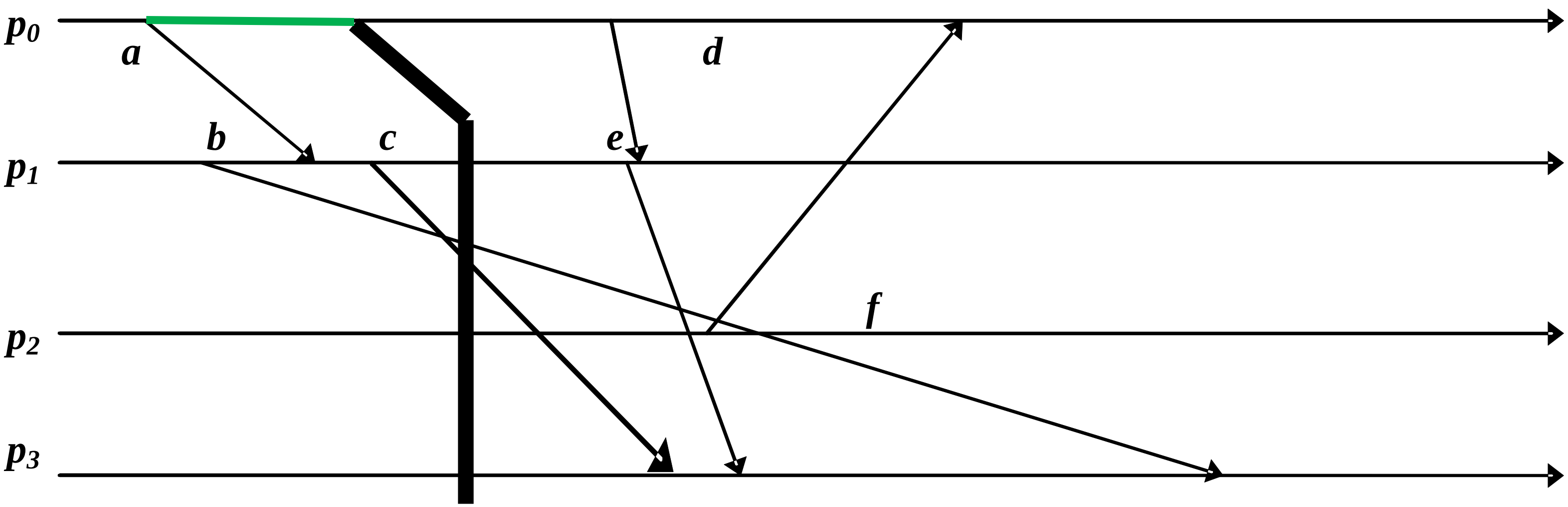
- Timelines can "stretch"…



- … caused by scheduling effects, message delays, message loss…

Temporal distortions

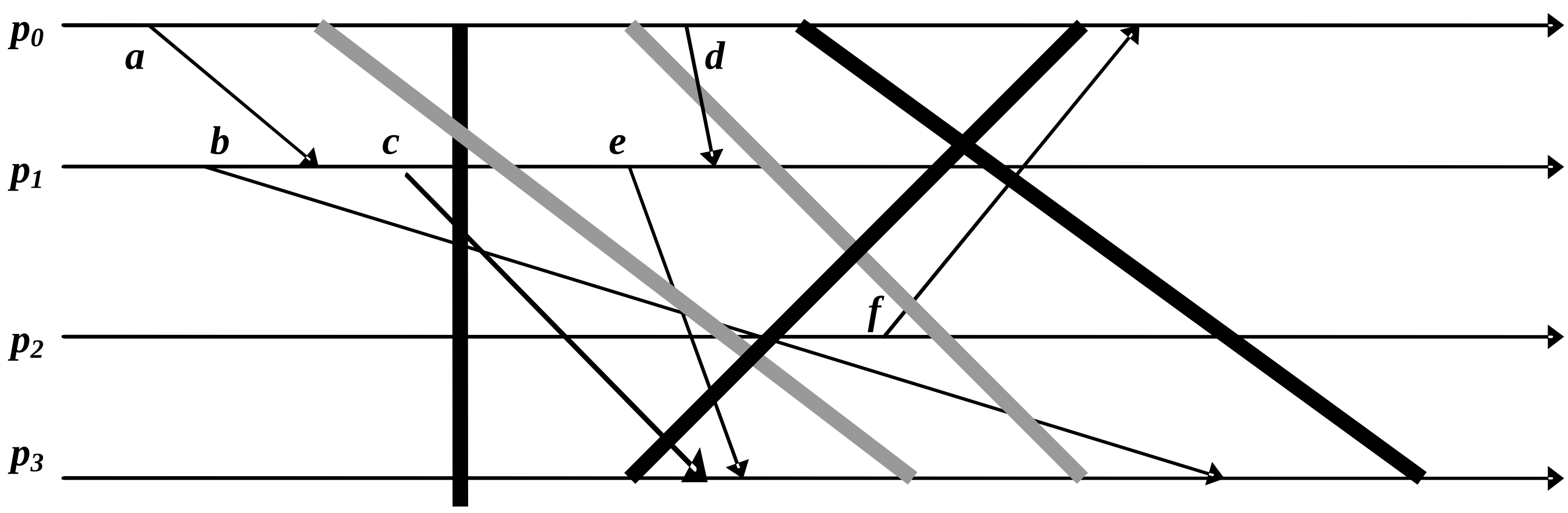
- Timelines can “shrink”



- E.g. something lets a machine speed up

Temporal distortions

- Cuts represent instants of time.



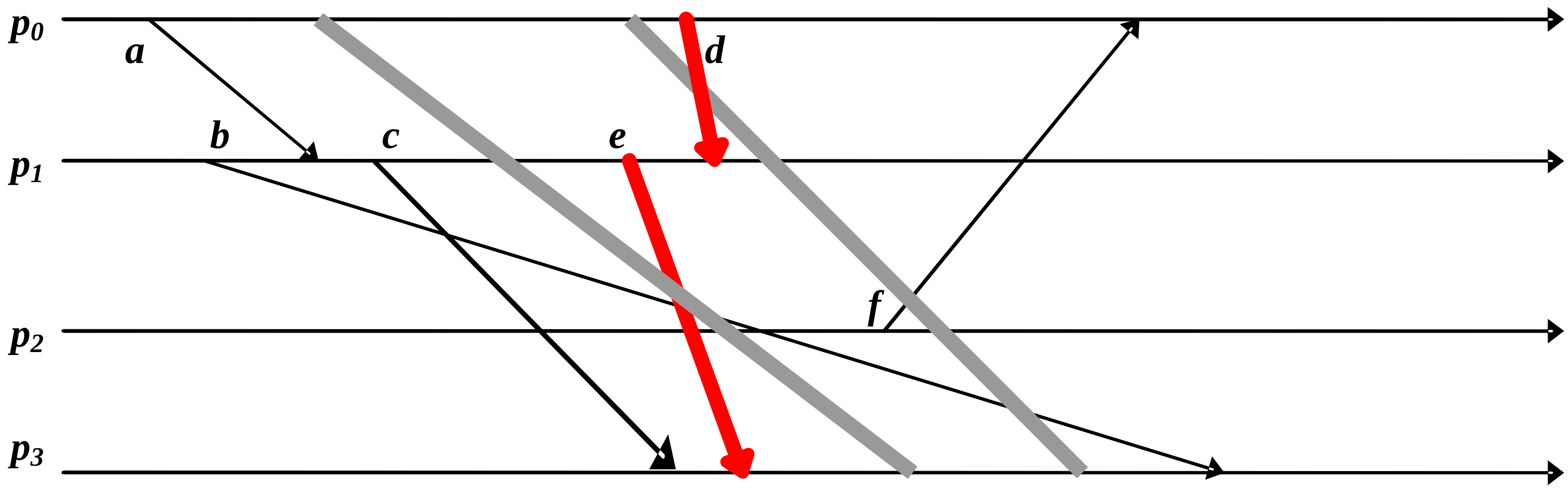
- But not every "cut" makes sense
  - Black cuts could occur but not gray ones.

Consistent cuts and snapshots

- Idea is to identify system states that "might" have occurred in real-life
  - Need to avoid capturing states in which a message is received but nobody is shown as having sent it
  - This the problem with the gray cuts

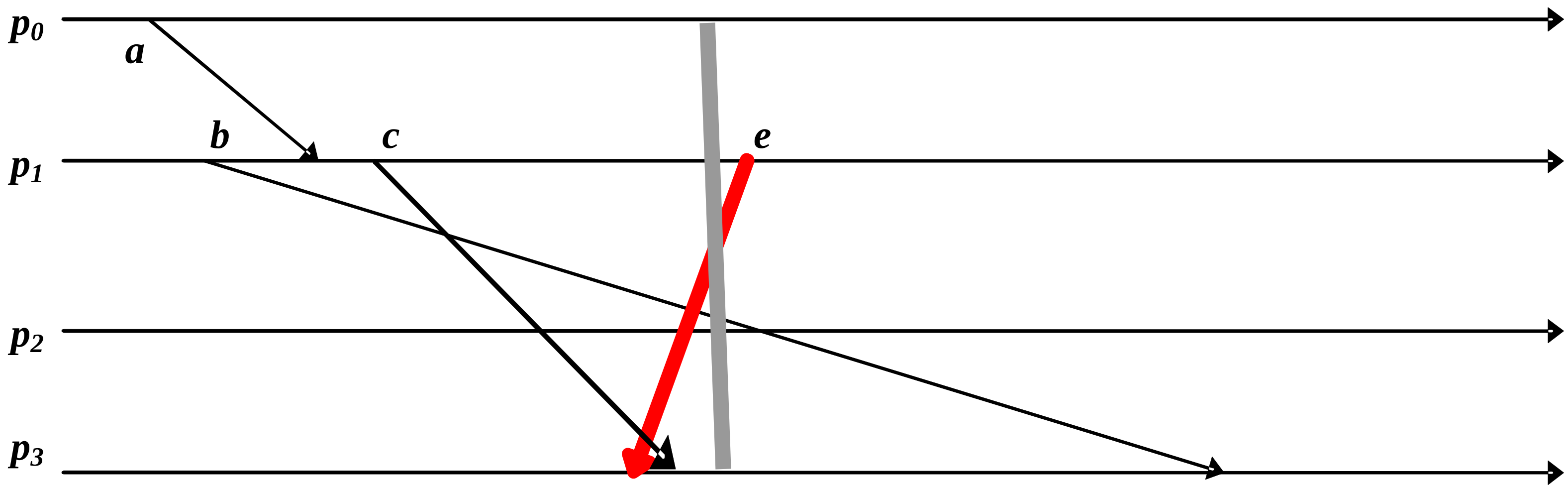
Temporal distortions

- Red messages cross gray cuts “backwards”



Temporal distortions

- Red messages cross gray cuts "backwards"



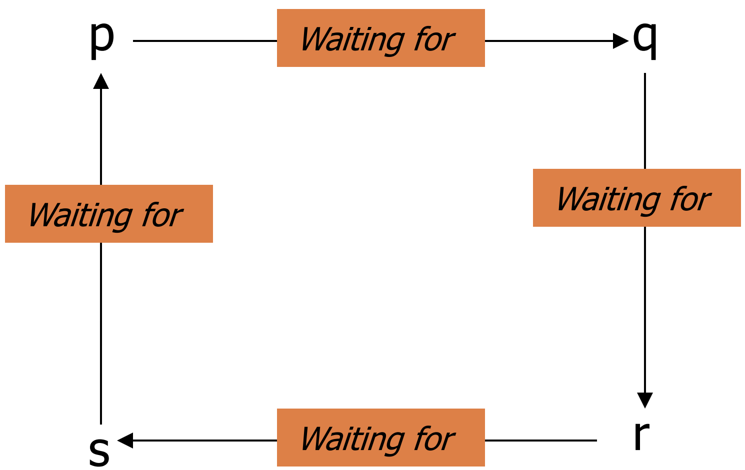
- In a nutshell: the cut includes a message that "was never sent"

Application: Deadlock detection

- p worries: perhaps we have a deadlock
- p is waiting for q, so sends "what's your state?"
- q, on receipt, is waiting for r, so sends the same question… and r for s…. And s is waiting on p.

Suppose we detect this state

- We see a cycle…

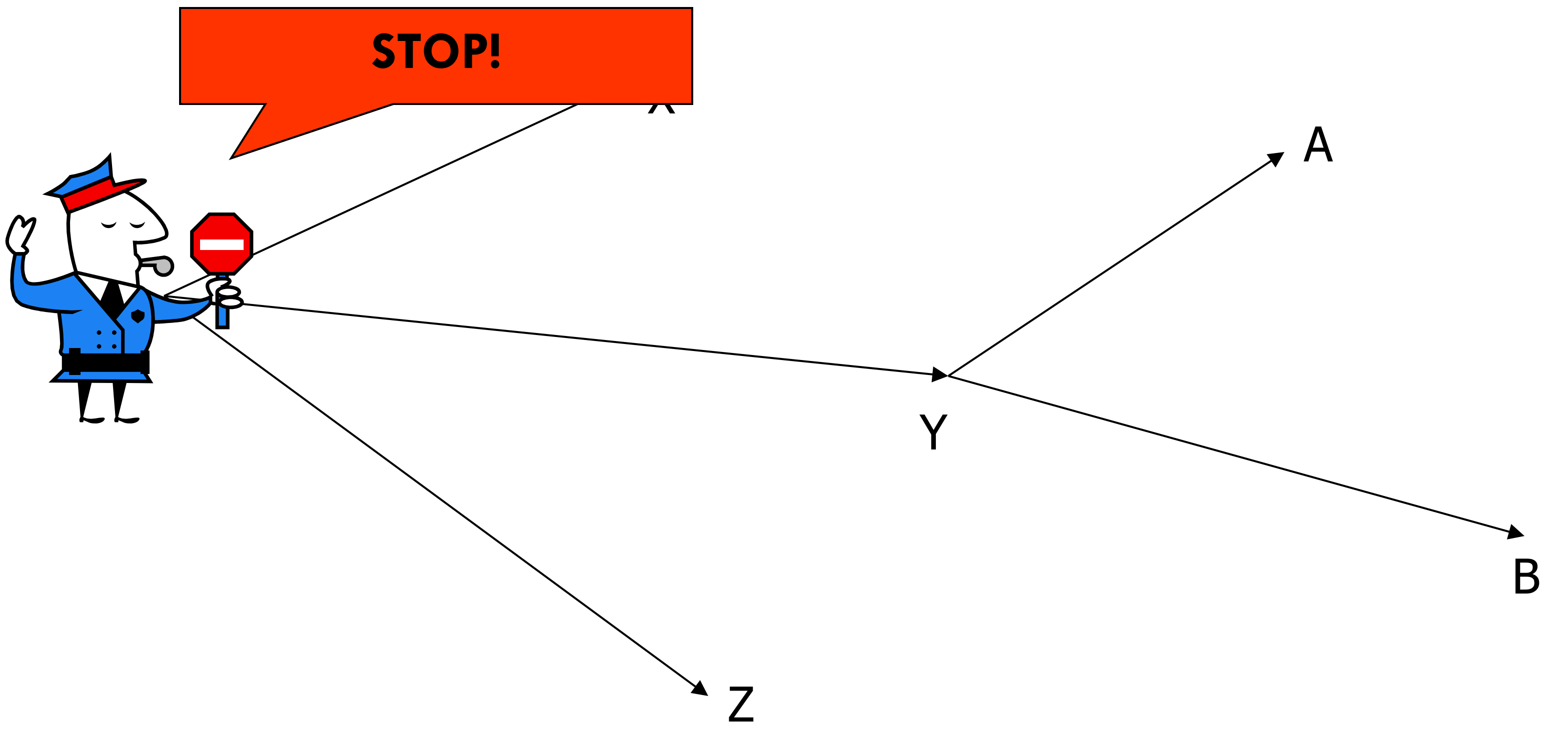


- … but is it a deadlock?

Phantom deadlocks!

- Suppose system has a *very high rate* of locking.
- Then perhaps a lock release message "passed" a query message
  - i.e. we see "q waiting for r" and "r waiting for s" but in fact, by the time we checked r, q was no longer waiting!
- In effect: we checked for deadlock on a gray cut – an inconsistent cut.

One solution is to “freeze” the system



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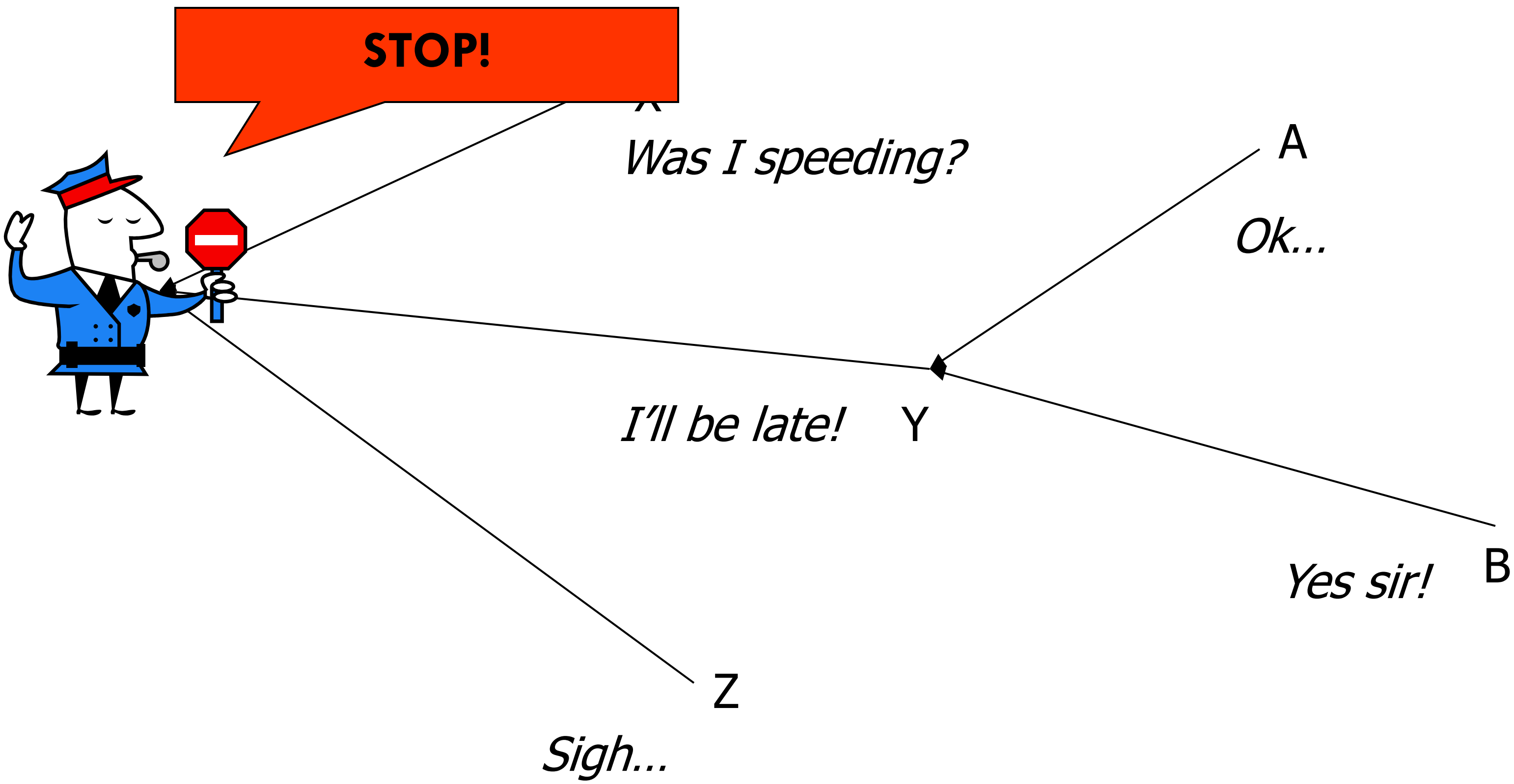

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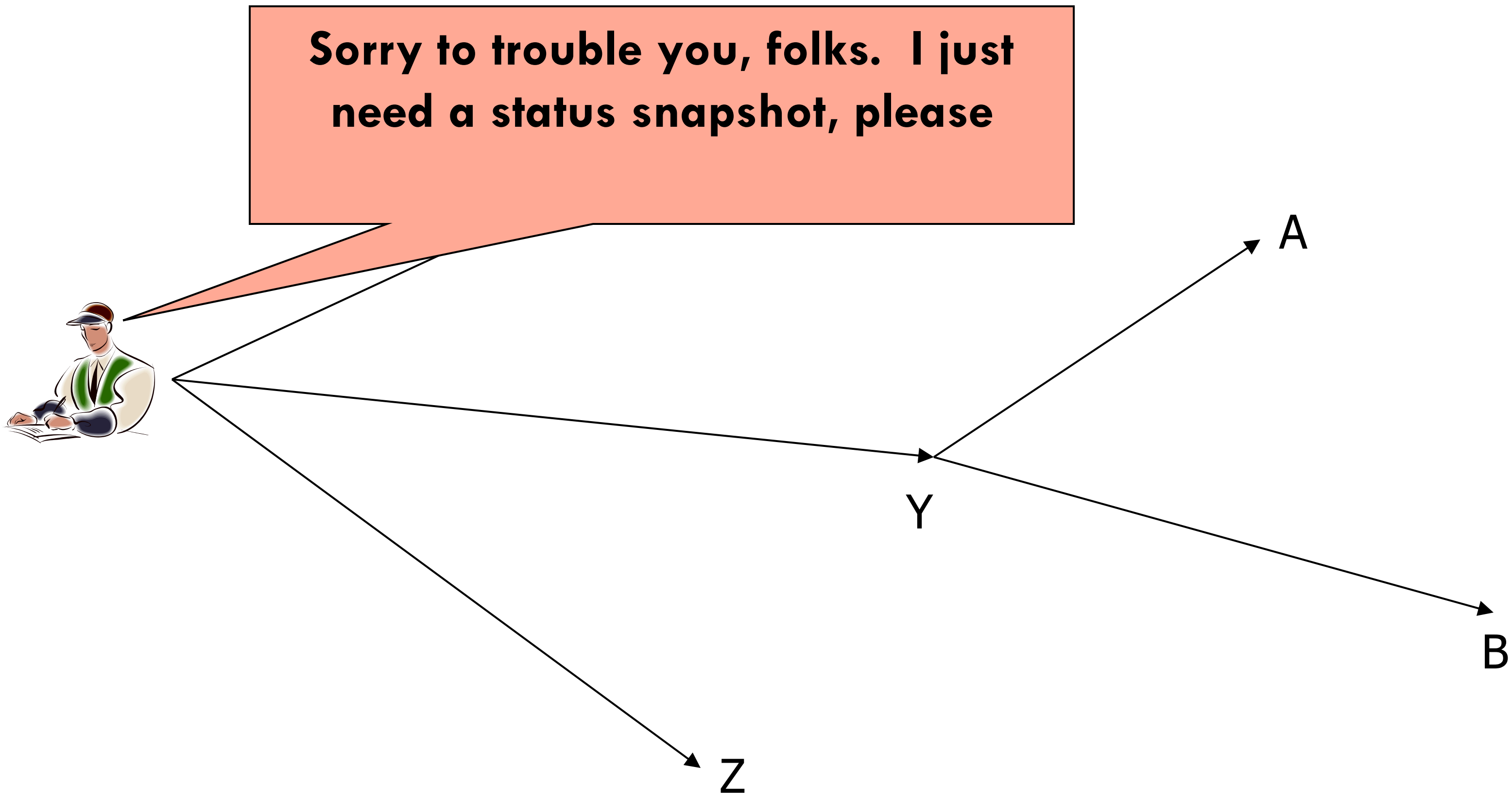

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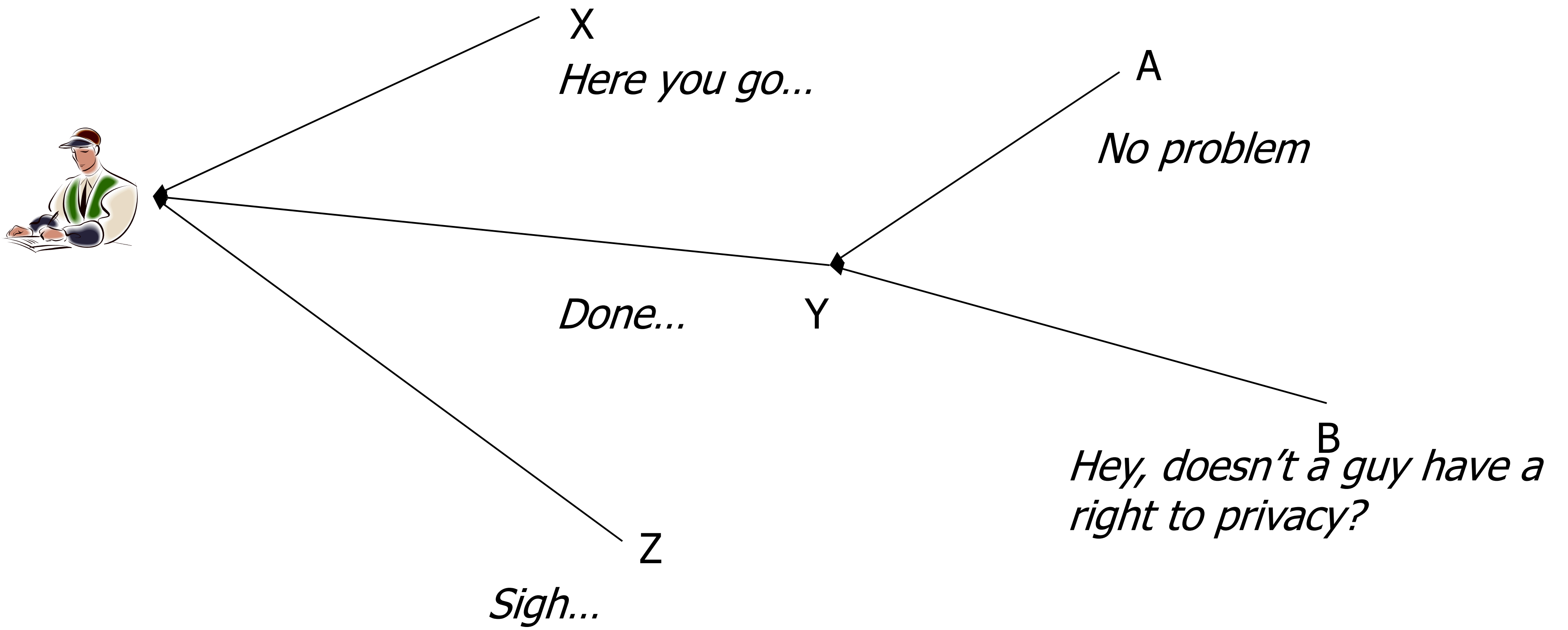

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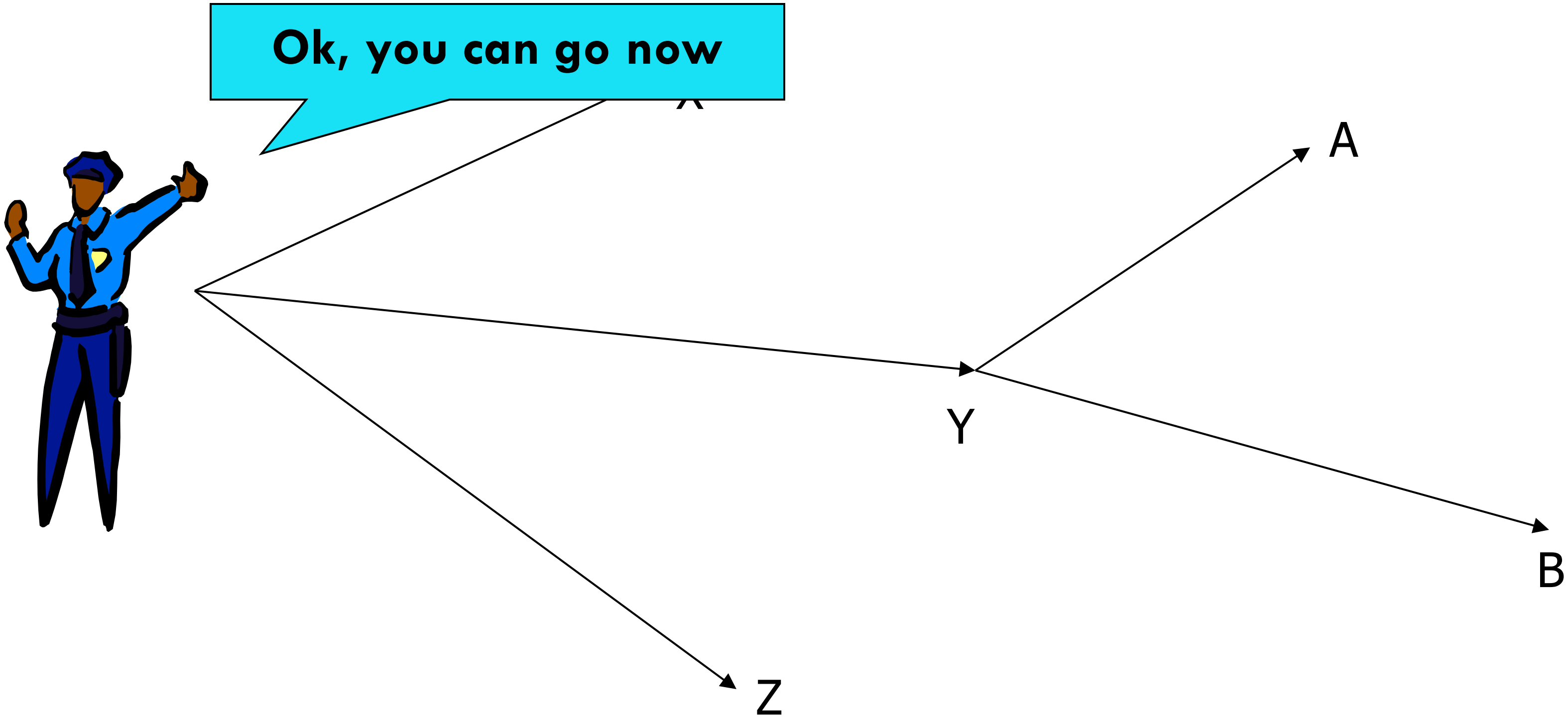


Why does it work?

- When we check bank accounts, or check for deadlock, the system is idle
- So if "P is waiting for Q" and "Q is waiting for R" we really mean "simultaneously"
- But to get this guarantee we did something very costly because no new work is being done!

Consistent cuts and snapshots

- Goal is to draw a line across the system state such that
  - Every message "received" by a process is shown as having been sent by some other process
  - Some pending messages might still be in communication channels
- And we want to do this *while running*

Turn idea into an algorithm

- To start a new snapshot, p_i …
  - Builds a message: "P_i is initiating snapshot k".
    - The tuple (p_i, k) uniquely identifies the snapshot
  - Writes down its own state
  - Starts recording incoming messages on all channels

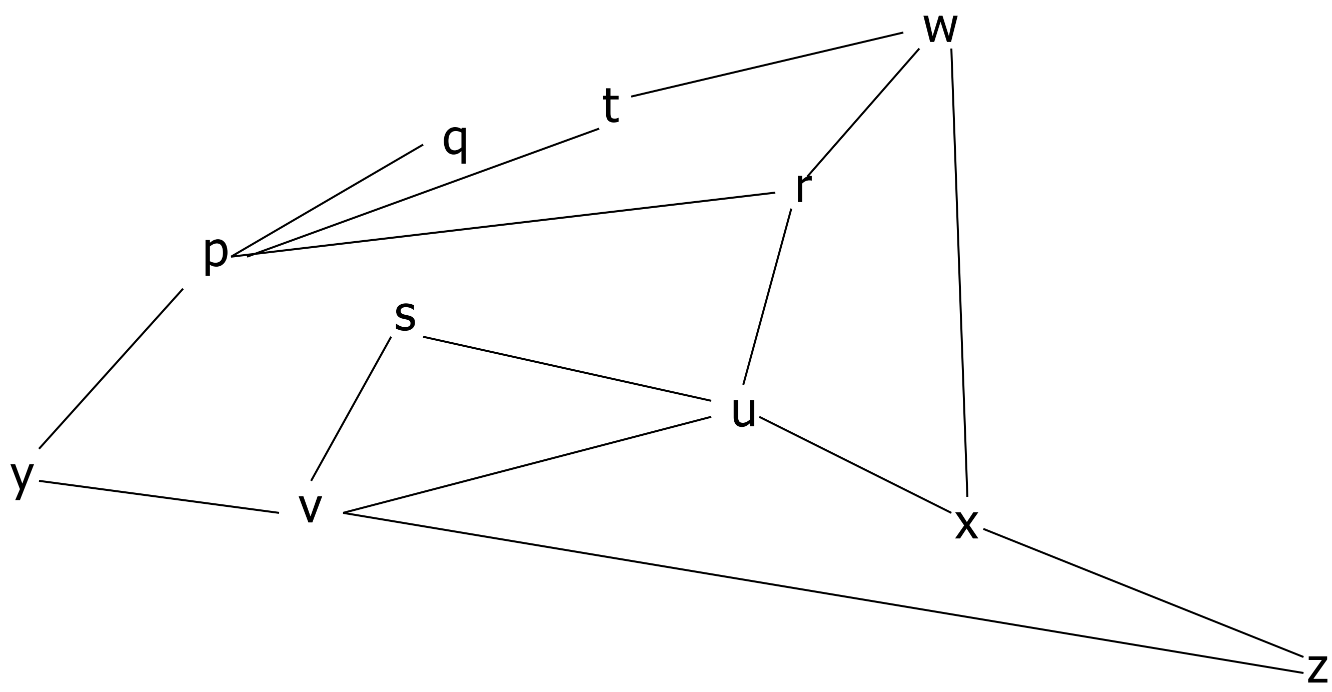
Turn idea into an algorithm

- Now p_i tells its neighbors to start a snapshot
- In general, on first learning about snapshot (p_i, k), p_x
  - Writes down its state: p_x's contribution to the snapshot
  - Starts "tape recorders" for all communication channels
  - Forwards the message on all outgoing channels
  - Stops "tape recorder" for a channel when a snapshot message for (p_i, k) is received on it
- Snapshot consists of all the local state contributions and all the tape-recordings for the channels

Chandy/Lamport

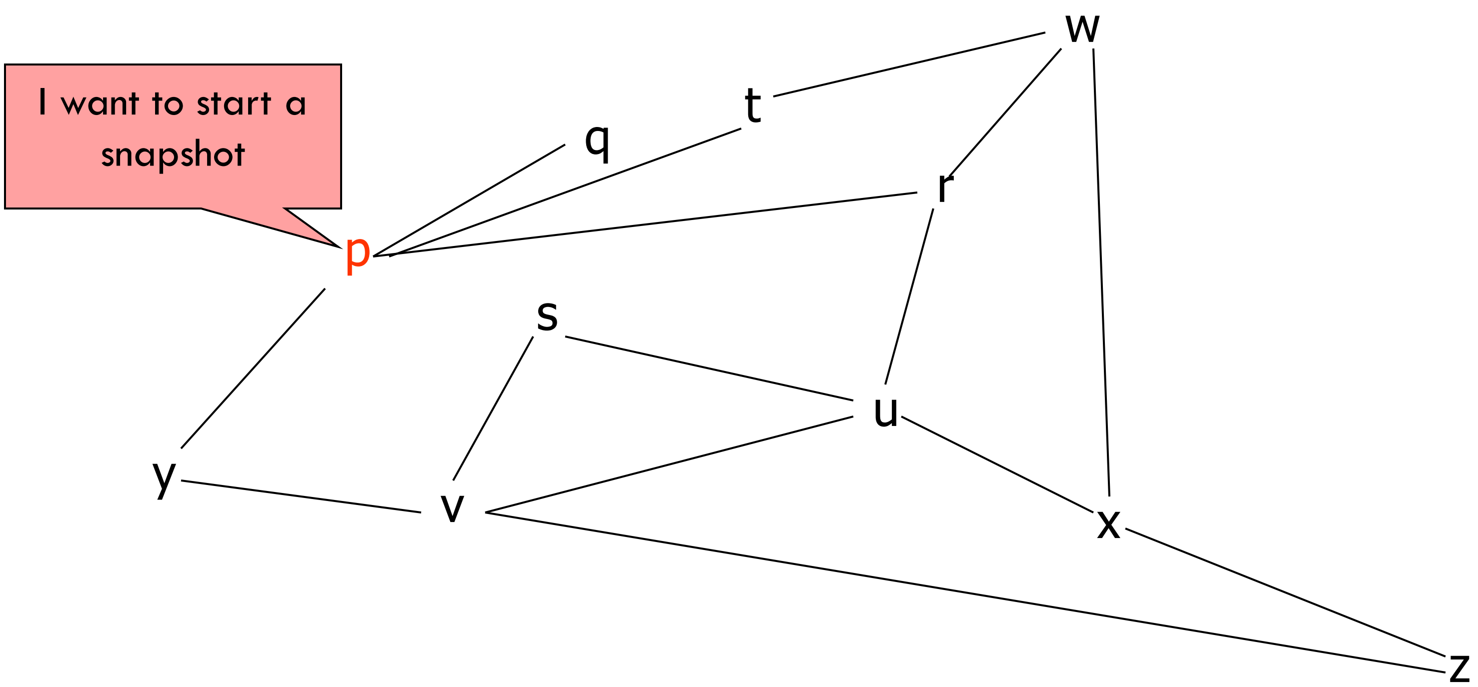
- Outgoing wave of requests… incoming wave of snapshots and channel state
- Snapshot ends up accumulating at the initiator, p_i
- Algorithm doesn't tolerate process failures or message failures.

Chandy/Lamport



A network

Chandy/Lamport



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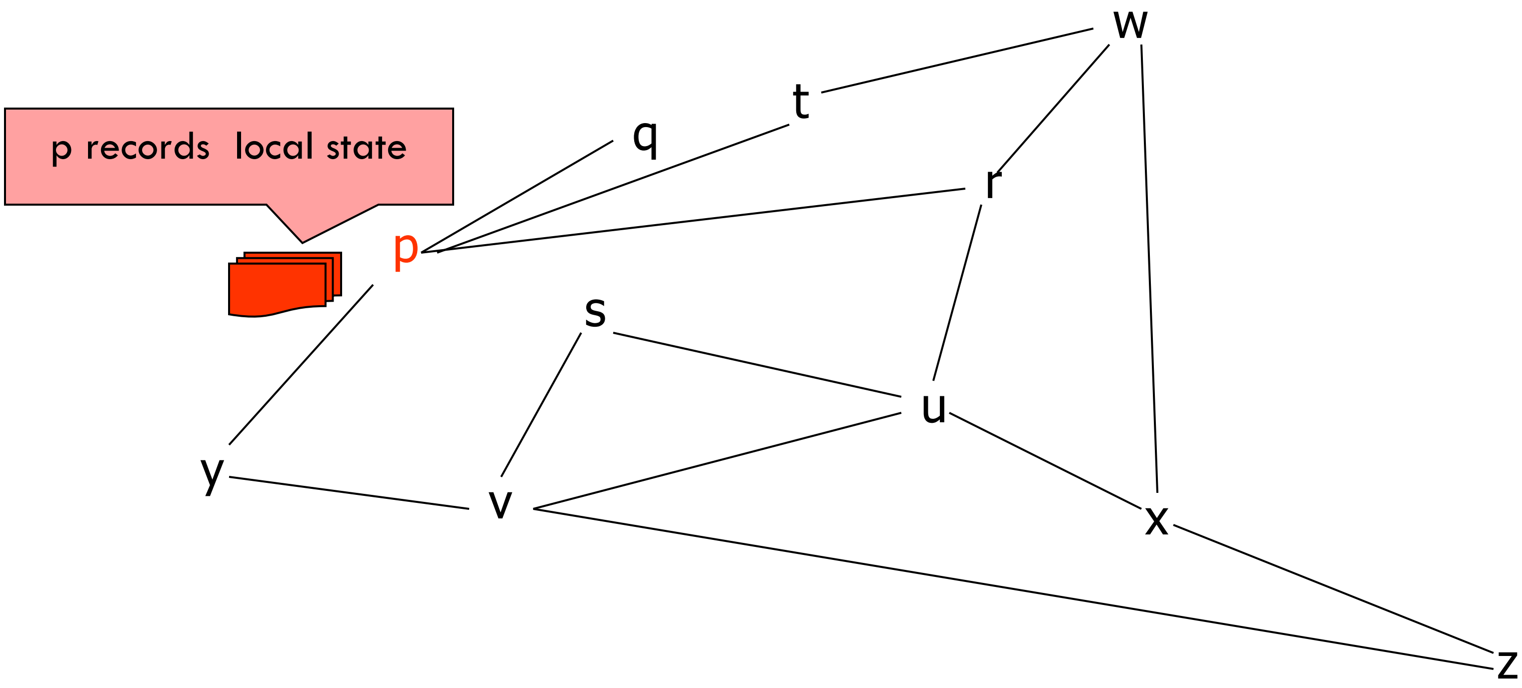

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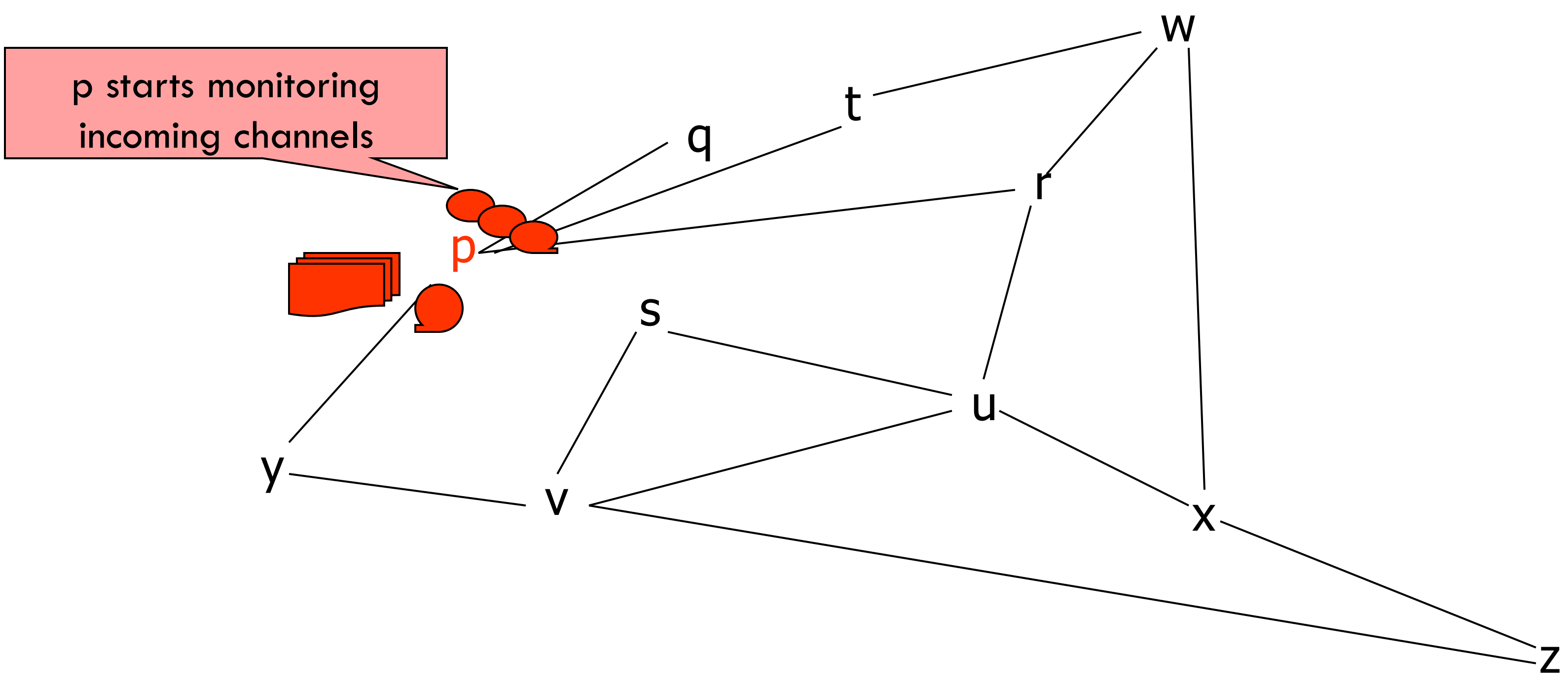

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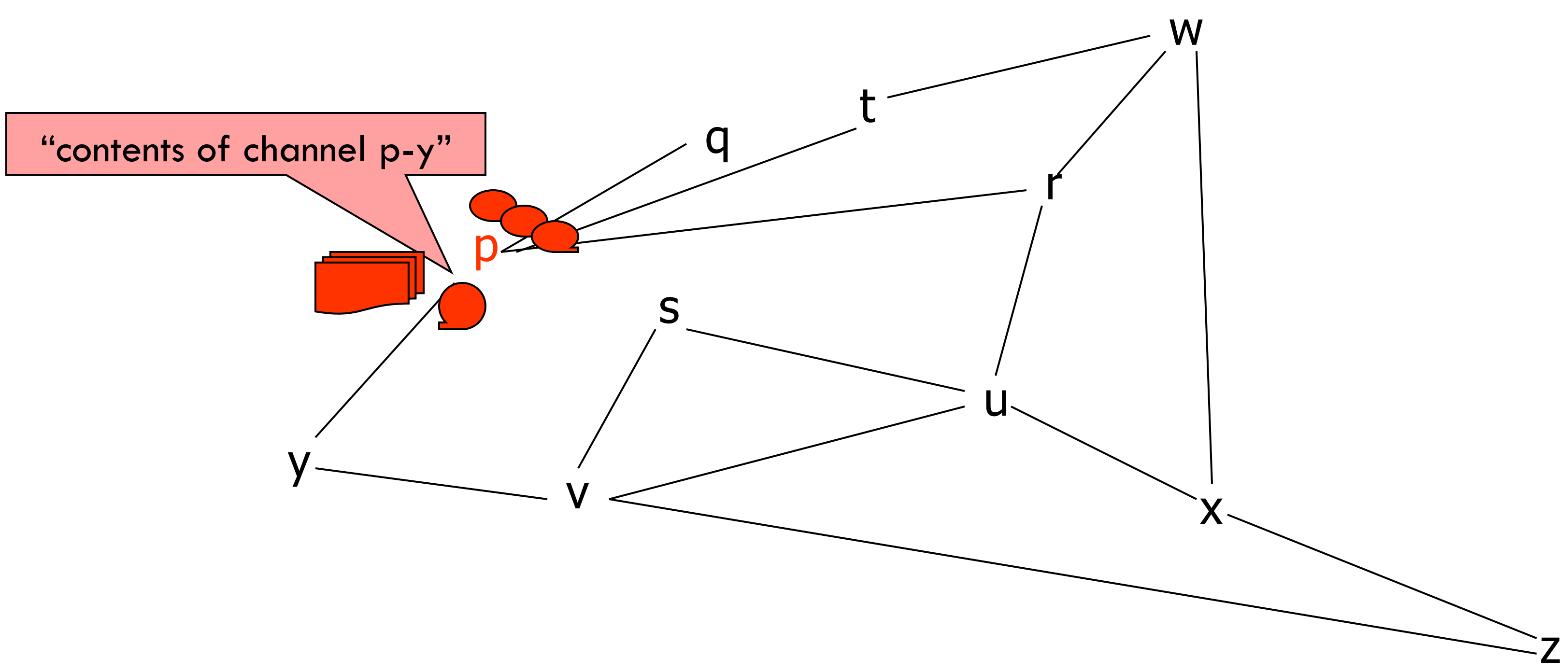

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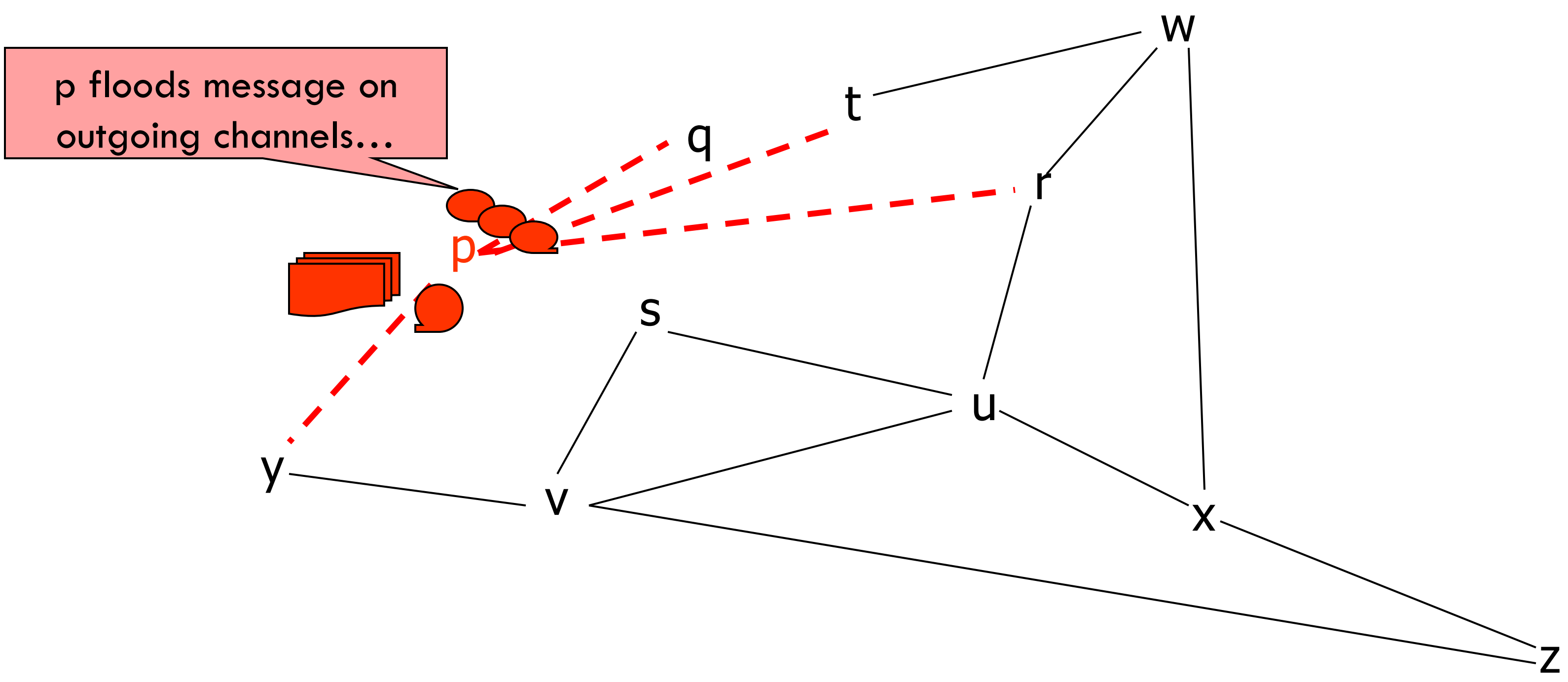

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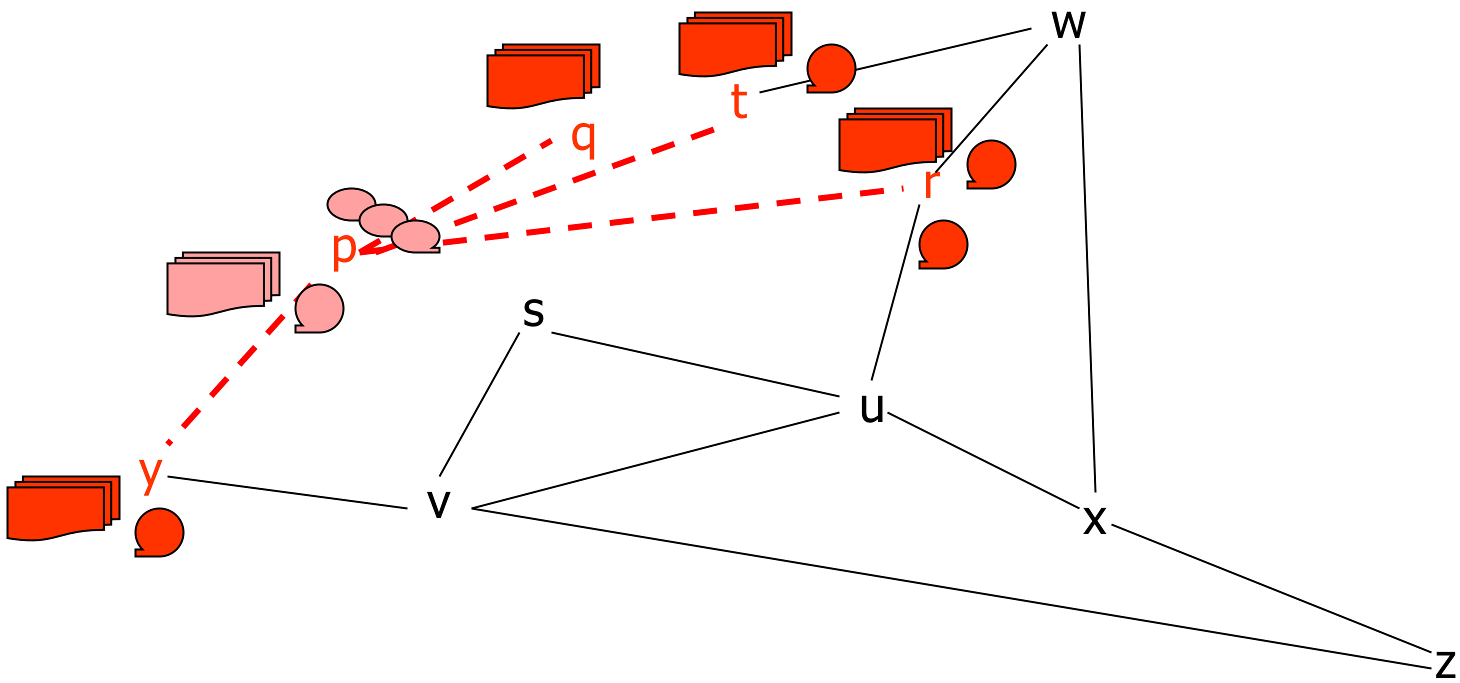

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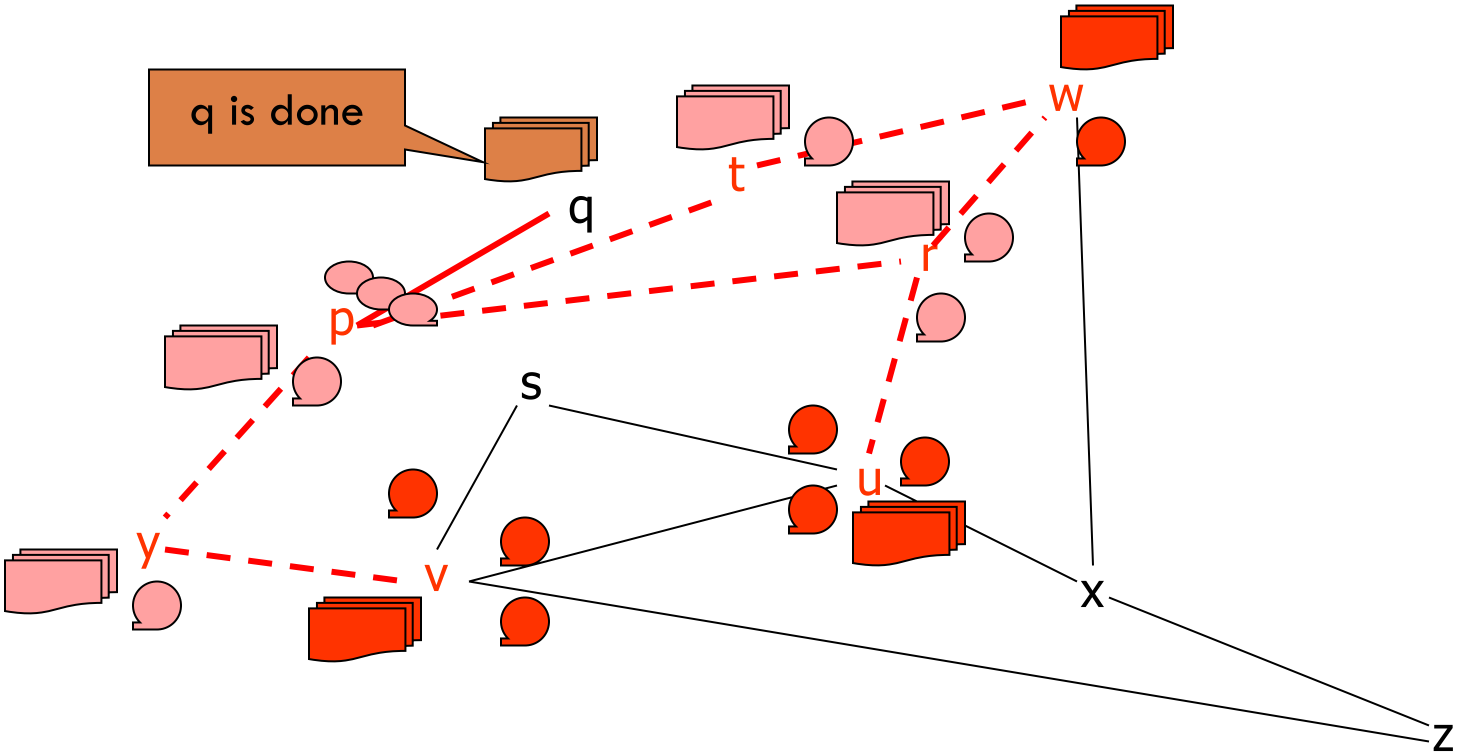

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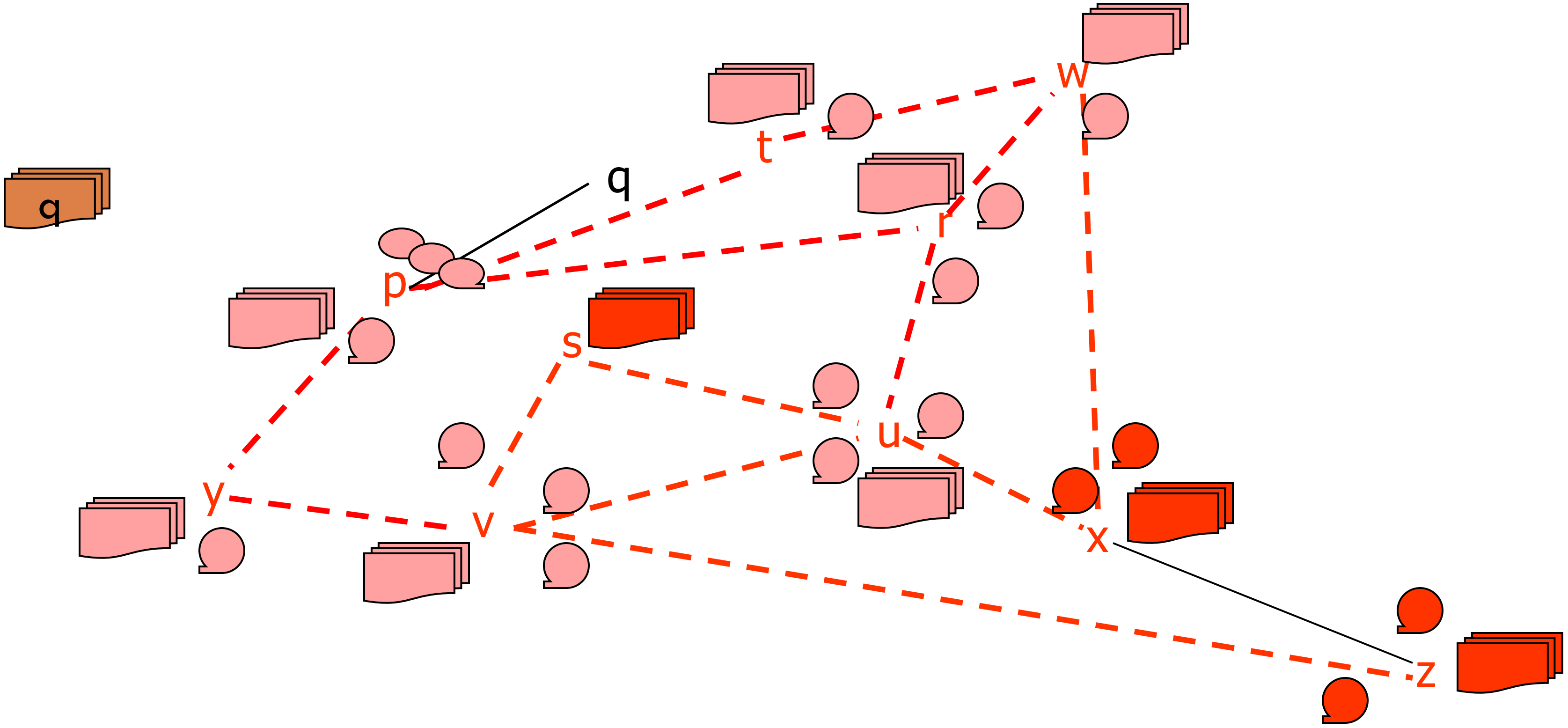

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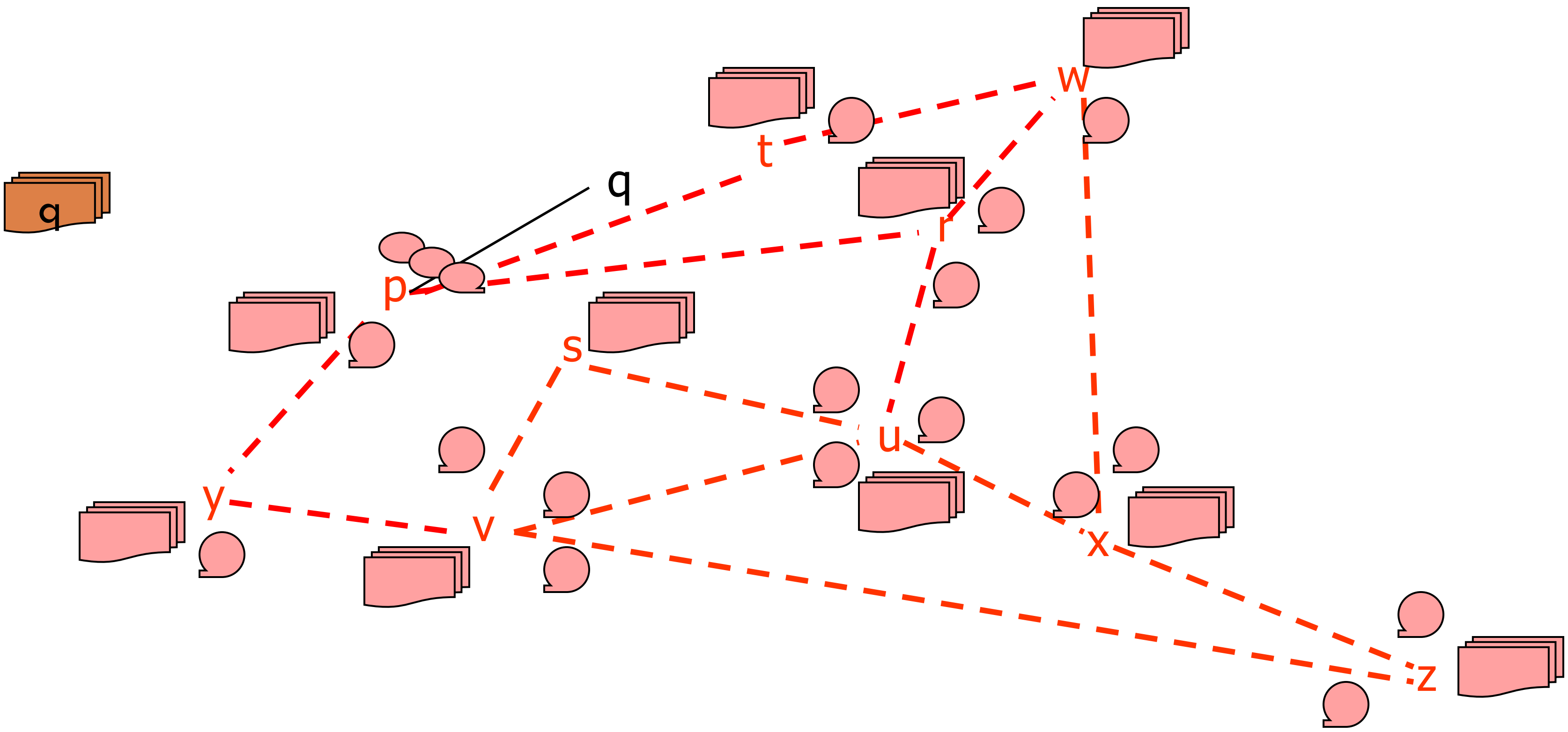

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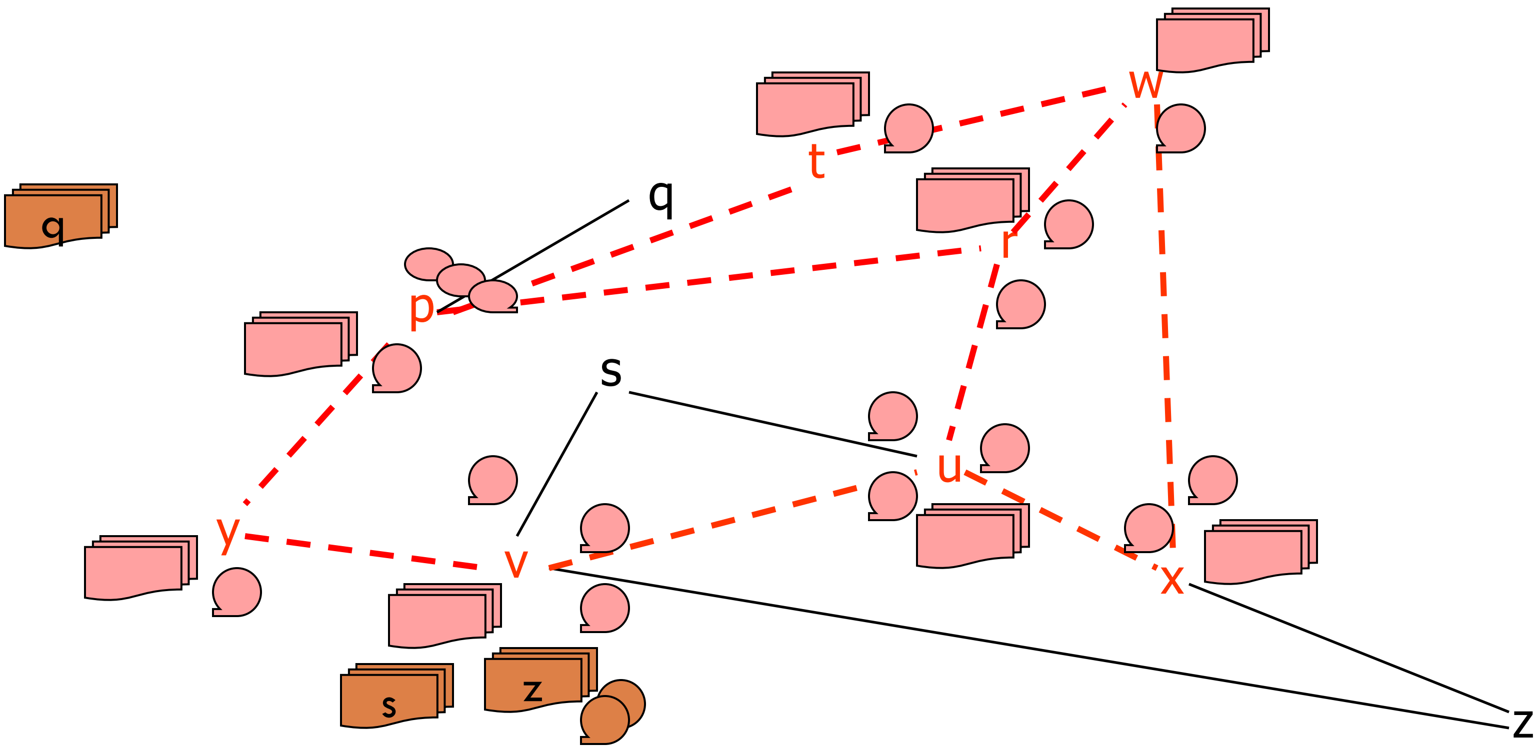

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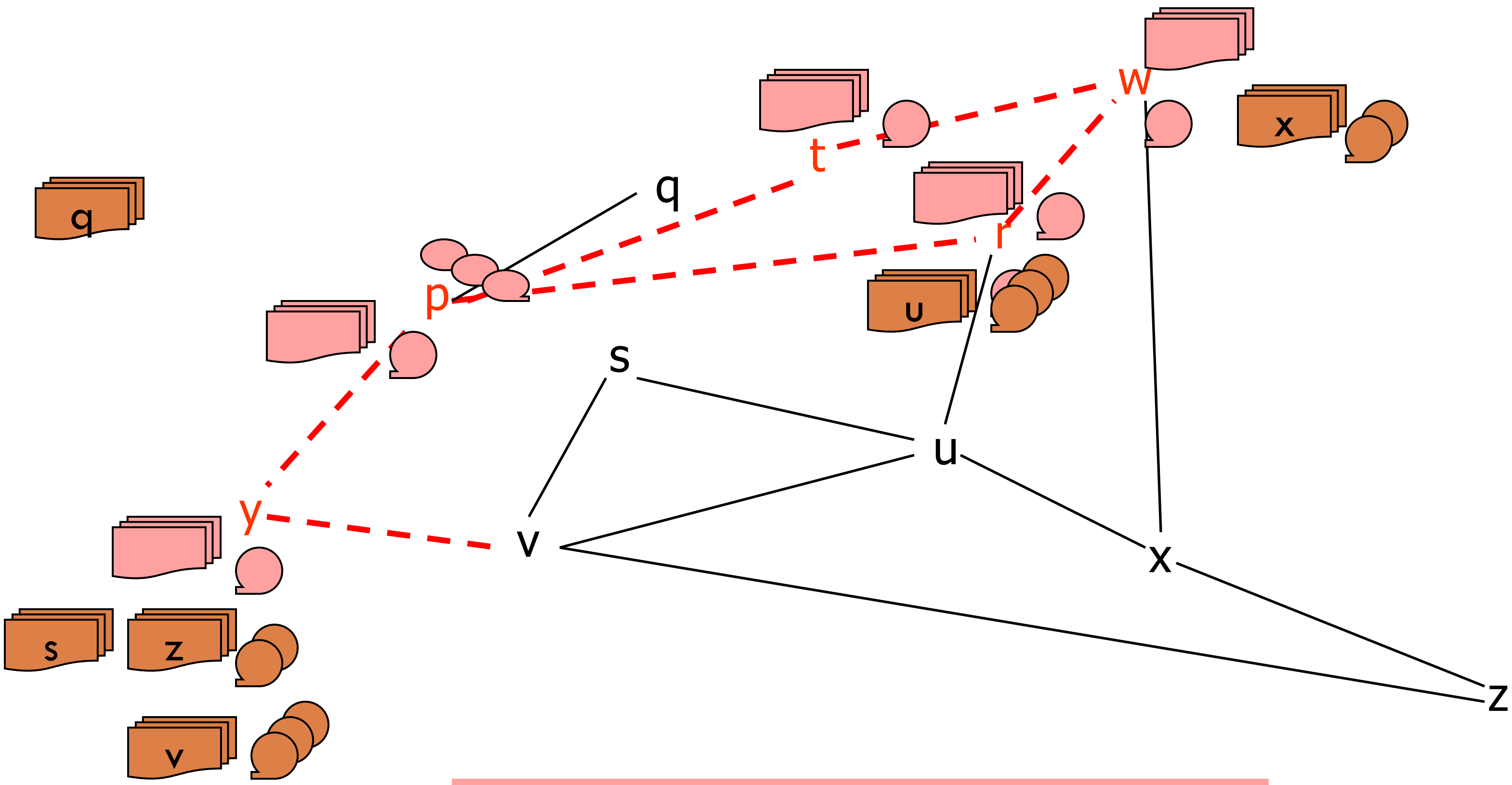

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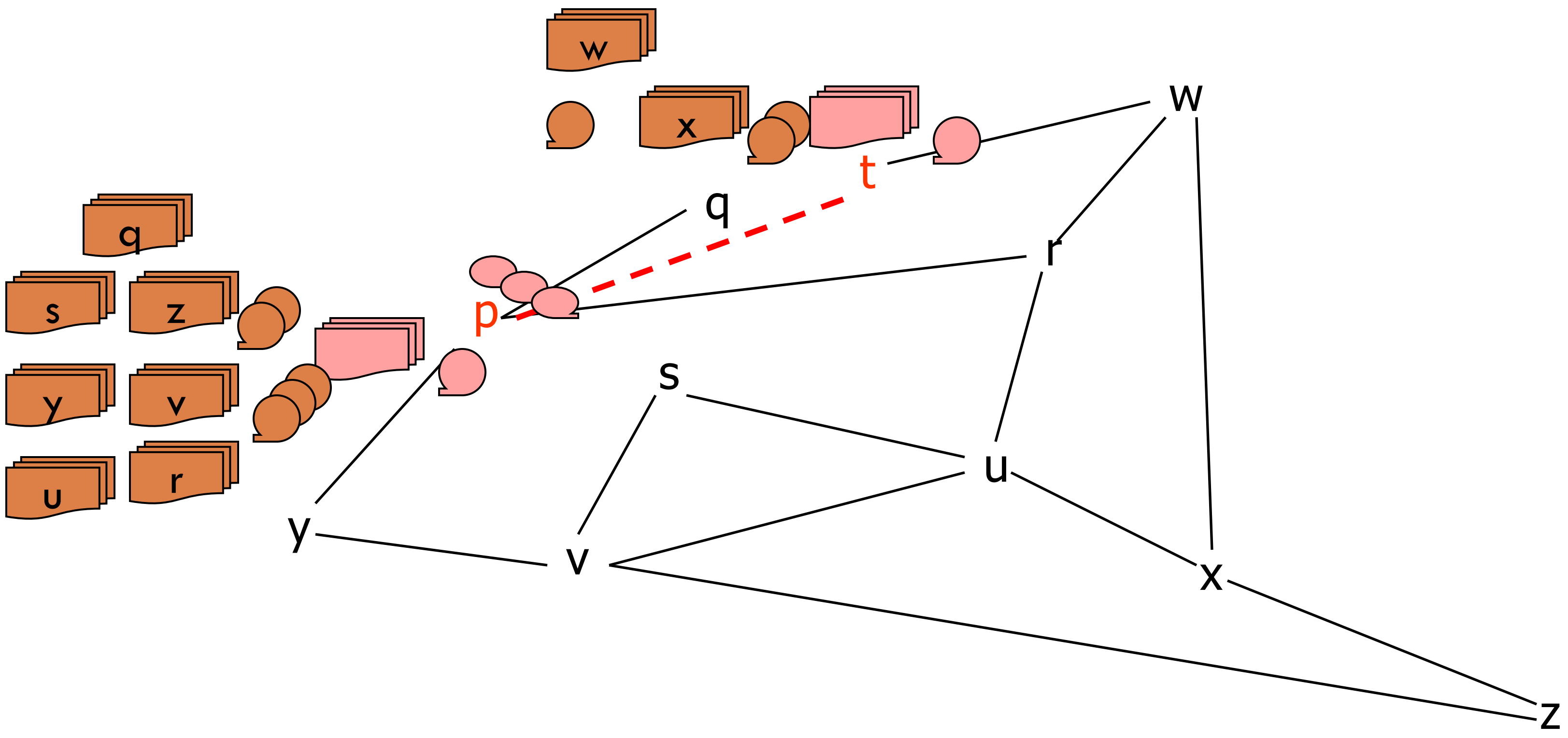

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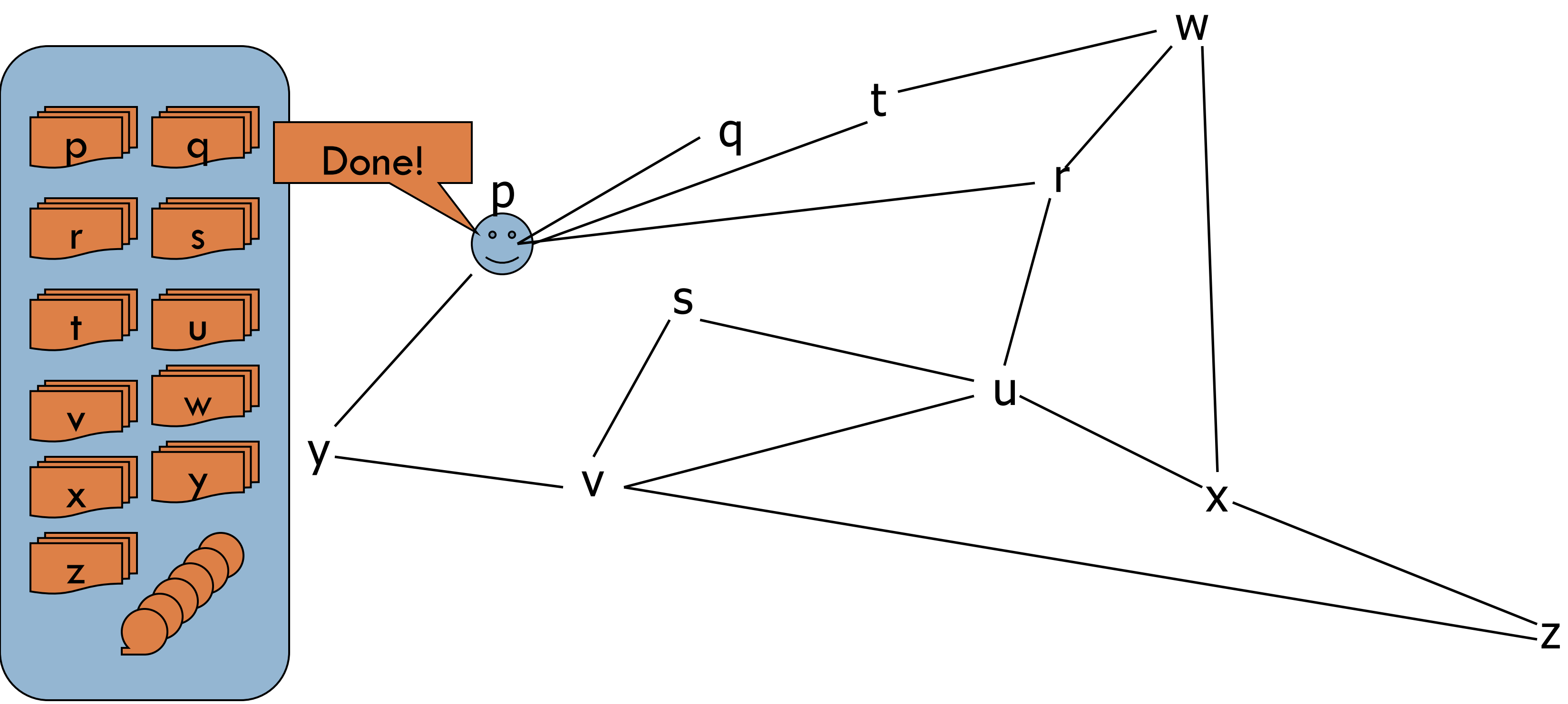

A snapshot of a network

Chandy/Lamport "snapshot"

- Once we collect the state snapshots plus the channel contents we have a consistent cut from the system
  - It "could" have occured as a concurrent instant in the system execution (although in fact, it obviously didn't)
  - Processing such a snapshot requires understanding the state in this form
  - But many algorithms use this *pattern* of messages without necessarily writing down the whole state or logging all the messages in the channels

Relation to vector time?

- In book the connection of consistent cuts to notion of logical time is explored
  - A consistent cut is a snapshot taken at a set of concurrent points in a system trace
  - In effect, all the members of the system concurrently write down their states
  - We can restate Chandy/Lamport to implement it precisely in this manner!
- But out of time today, so we'll leave that for you to read about in Chapter 10 of the text

Conclusions

- By formalizing notion of time we can build tools for thinking about fancier ideas such as consistency of replicated data
- Today we looked more closely at time than at consistency.
  - We introduced idea of consistency to motivate need to look closely at time
  - But didn't tie the logical or vector timestamp ideas back to implementation of replicated data
- Next lectures will make this connection explicit