Vector Clocks and Distributed Snapshots

COS 418: Distributed Systems
Lecture 4

Wyatt Lloyd

Today

1. Logical Time: Vector clocks

2. Distributed Global Snapshots

Lamport Clocks Review

Q: a → b => LC(a) < LC(b)

Q: LC(a) < LC(b) => b -/-> a (a → b or a || b)

Q: a || b => nothing

Lamport Clocks and causality

- Lamport clock timestamps do not capture causality
- Given two timestamps C(a) and C(z), want to know whether there's a chain of events linking them:

$$a \rightarrow b \rightarrow \ldots \rightarrow y \rightarrow z$$

Vector clock: Introduction

- One integer can't order events in more than one process
- So, a Vector Clock (VC) is a vector of integers, one entry for each process in the entire distributed system
    - Label event e with VC(e) = [c_1, c_2 …, c_n]
        - Each entry c_k is a count of events in process k that causally precede e

Vector clock: Update rules

- Initially, all vectors are [0, 0, …, 0]

- Two update rules:

1. For each local event on process i, increment local entry c_i

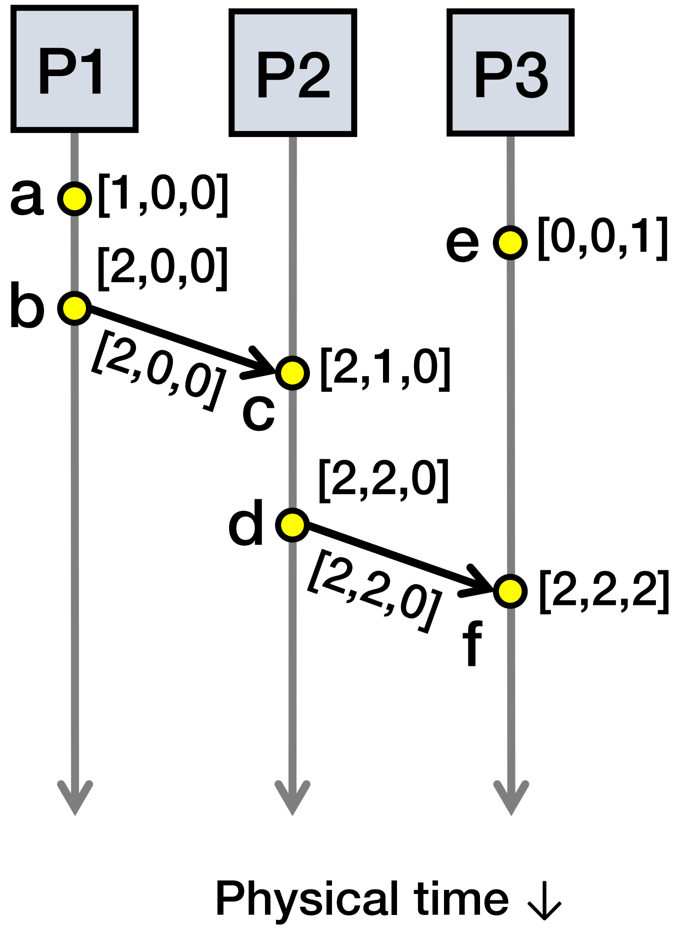
2. If process j receives message with vector $[d_1, d_2, \ldots, d_n]$:
    - Set each local entry $c_k = \max\{c_k, d_k\}$
    - Increment local entry c_j

Vector clock: Example

- All processes' VCs start at [0, 0, 0]

- Applying local update rule

- Applying message rule
  - Local vector clock piggybacks on inter-process messages



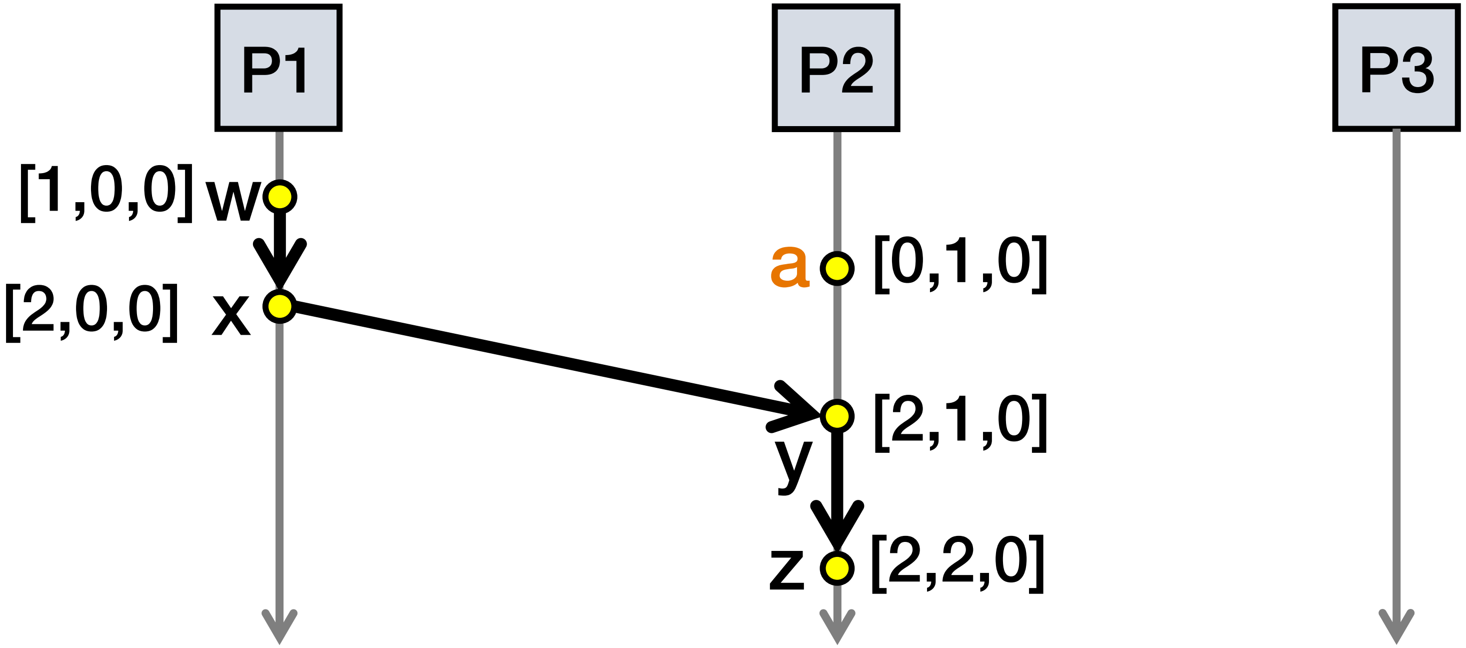
Comparing vector timestamps

- Rule for comparing vector timestamps:
  - V(a) = V(b) when $a_k = b_k$ for all k
  - V(a) < V(b) when $a_k \leq b_k$ for all k and V(a) ≠ V(b)

- Concurrency:
  - a || b if $a_i < b_i$ and $a_j > b_j$, some i, j

Vector clocks capture causality

- V(w) < V(z) then there is a chain of events linked by Happens-Before (→) between a and z
- V(a) || V(w) then there is no such chain of events between a and w



Two events a, z

Lamport clocks: C(a) < C(z)

Conclusion: z -/-> a, i.e., either a → z or a || z

Vector clocks: V(a) < V(z)

Conclusion: a → z

Vector clock timestamps precisely capture happens-before relation (potential causality)

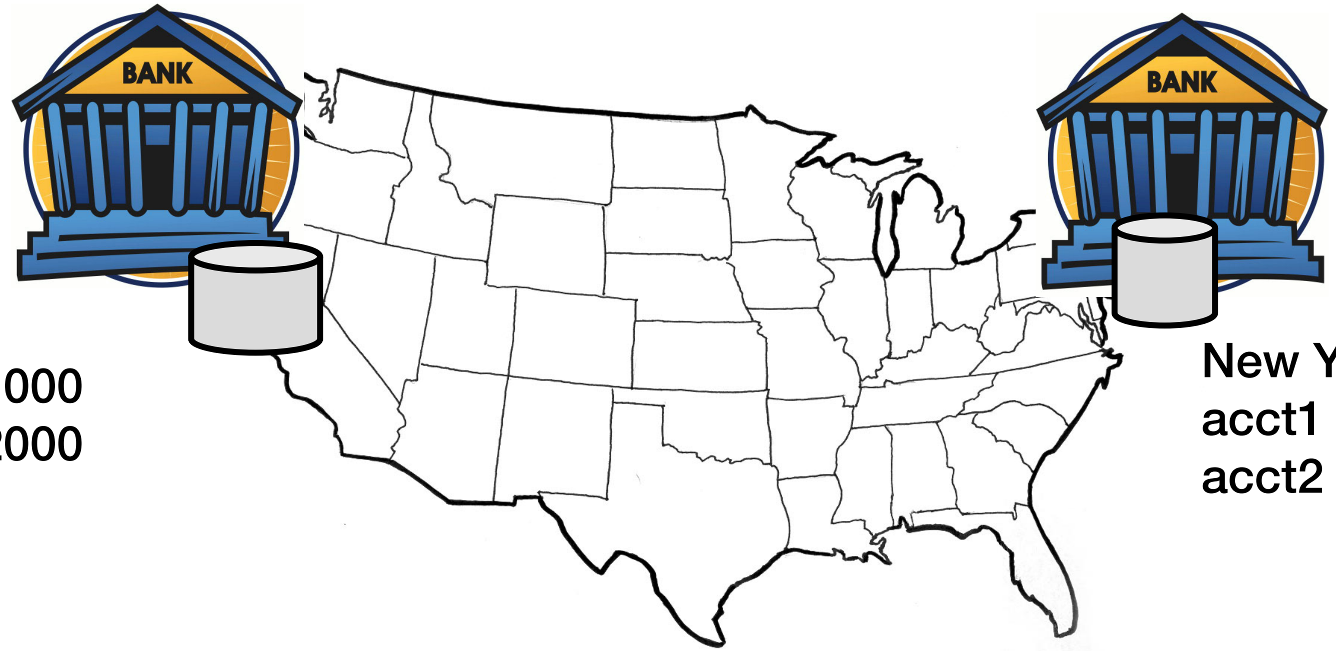
Today

1. Logical Time: Vector clocks

2. Distributed Global Snapshots
   - FIFO Channels
   - Chandy-Lamport algorithm
   - Reasoning about C-L: Consistent Cuts

Distributed Snapshots

- What is the state of a distributed system?



San Francisco
acct1 balance = $1000
acct2 balance = $2000

New York
acct1 balance = $1000
acct2 balance = $2000

System model

- N processes in the system with no process failures
  - Each process has some state it keeps track of
- There are two first-in, first-out, unidirectional channels between every process pair P and Q
  - Call them channel(P, Q) and channel(Q, P)
  - The channel has state, too: the set of messages inside
  - All messages sent on channels arrive intact, unduplicated, in order

Aside: FIFO communication channel

- “All messages sent on channels arrive intact, unduplicated, in order”

- Q: Arrive?
- Q: Intact?
- Q: Unduplicated?
- Q: In order?

- At-least-once retransmission
- Network layer checksums
- At-most-once deduplication
- Sender include sequence numbers, receiver only delivers in sequence order

- TCP provides all of these when processes don’t fail

Global snapshot is global state

- Each distributed application has a number of processes running on a number of physical servers

- These processes communicate with each other via channels

- A global snapshot captures
  1. The local states of each process (e.g., program variables), and
  2. The state of each communication channel

Why do we need snapshots?

- Checkpointing: Restart if the application fails
- Collecting garbage: Remove objects that aren't referenced
- Detecting deadlocks: The snapshot can examine the current application state
  - Process A grabs Lock 1, B grabs 2, A waits for 2, B waits for 1... ... ...
- Other debugging: A little easier to work with than printf…

Just synchronize local clocks?

- Each process records state at some agreed-upon time

- But system clocks skew, significantly with respect to CPU process' clock cycle
  - And we wouldn't record messages between processes

- Do we need synchronization?

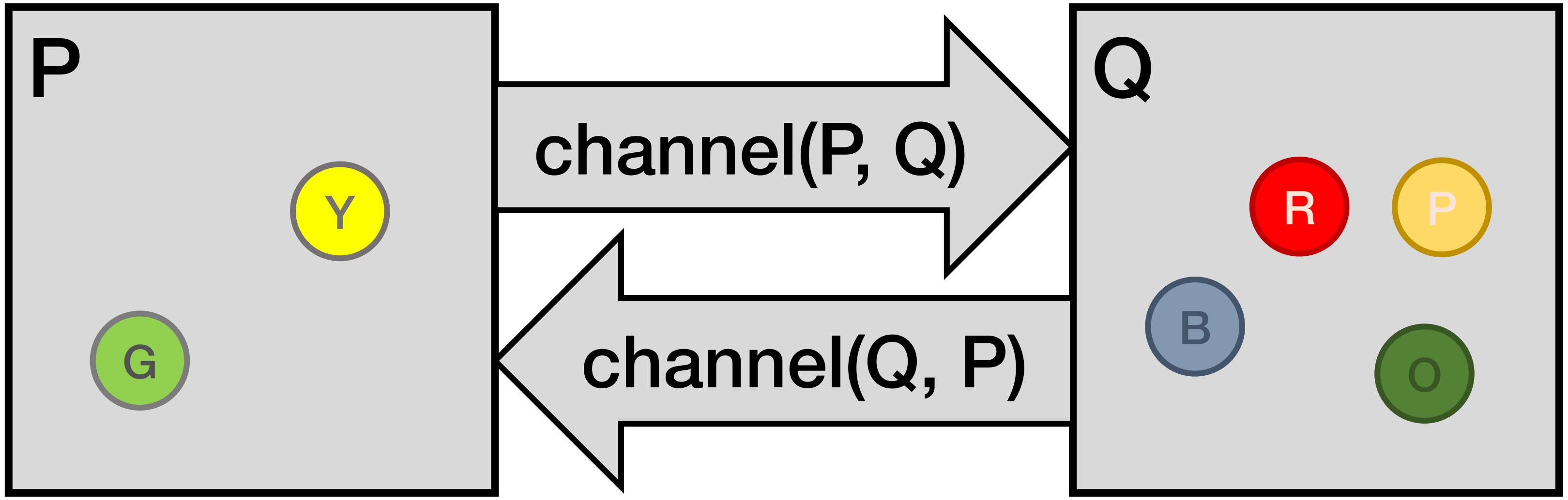
- What did Lamport realize about ordering events?

System model: Graphical example

- Let's represent process state as a set of colored tokens

- Suppose there are two processes, P and Q:

Process P: Process Q:



Correct global snapshot = Exactly one of each token

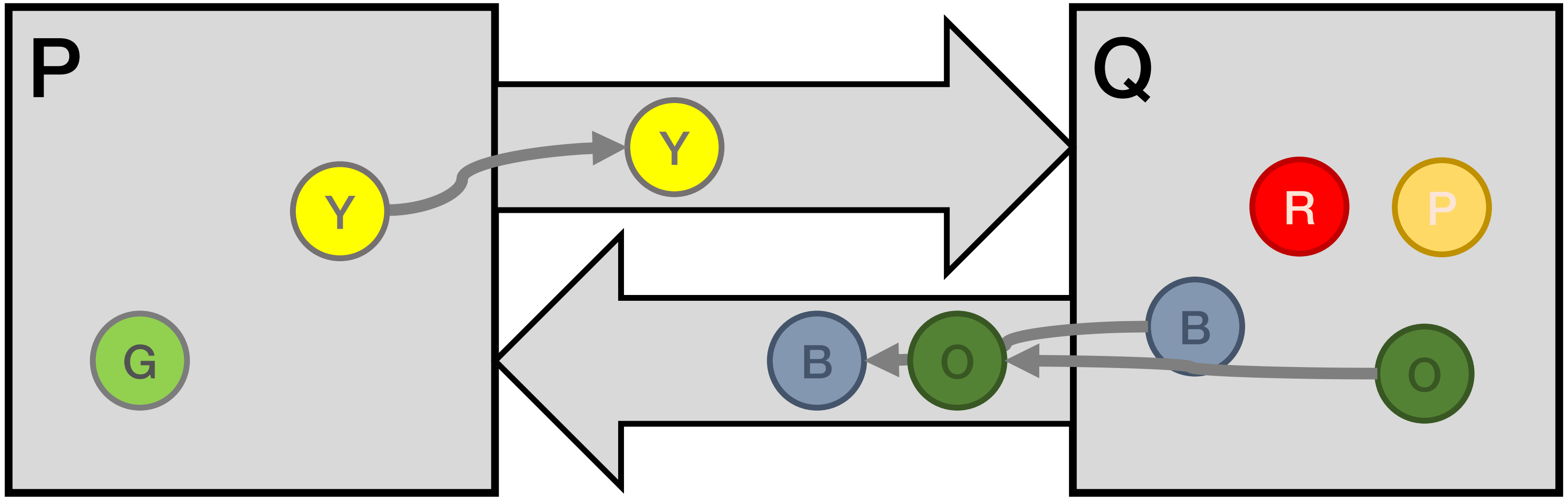
When is inconsistency possible?

- Suppose we take snapshots only from a process perspective
- Suppose snapshots happen independently at each process
- Let's look at the implications...

Problem: Disappearing tokens

- P, Q put tokens into channels, then snapshot

This snapshot misses Y, B, and O tokens



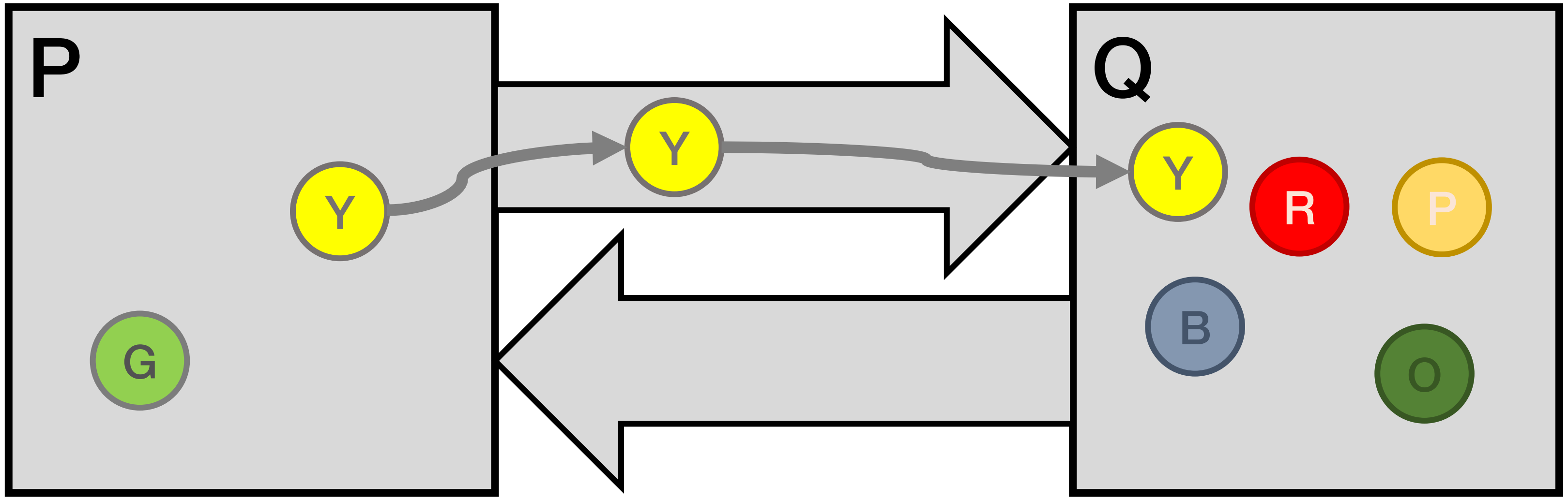
P = { G }

Q = { R, P }

Problem: Duplicated tokens

- P snapshots, then sends Y
- Q receives Y, then snapshots

This snapshot duplicates the Y token



P = { G, Y }

Q = { Y, R, P, B, O }

Idea: “Marker” messages

- What went wrong? We should have captured the state of the channels as well

- Let’s send a marker message ▲ to track this state
  - Distinct from other messages
  - Channels deliver marker and other messages FIFO

Chandy-Lamport algorithm: Overview

- We'll designate one node (say P) to start the snapshot
  - Without any steps in between, P:
    1. Records its local state ("snapshots")
    2. Sends a marker on each outbound channel

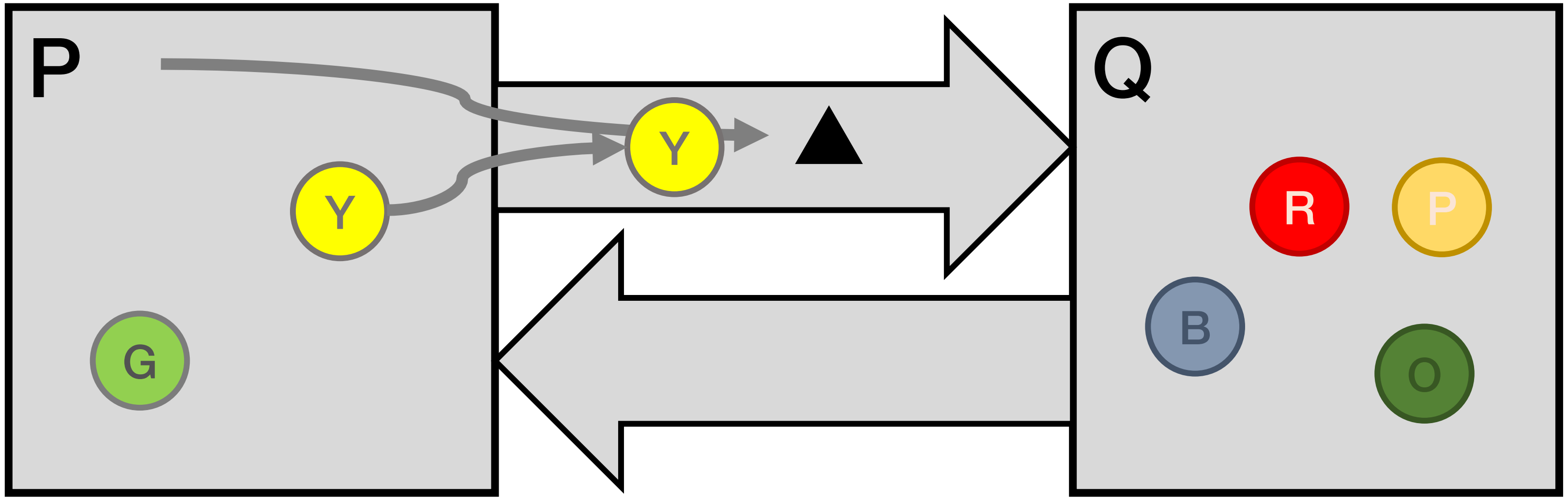
- Nodes remember whether they have snapshotted

- On receiving a marker, a non-snapshotted node performs steps (1) and (2) above

Chandy-Lamport: Sending process

- P snapshots and sends marker, then sends Y

- **Send Rule:** Send marker on all outgoing channels
  - Immediately after snapshot
  - Before sending any further messages

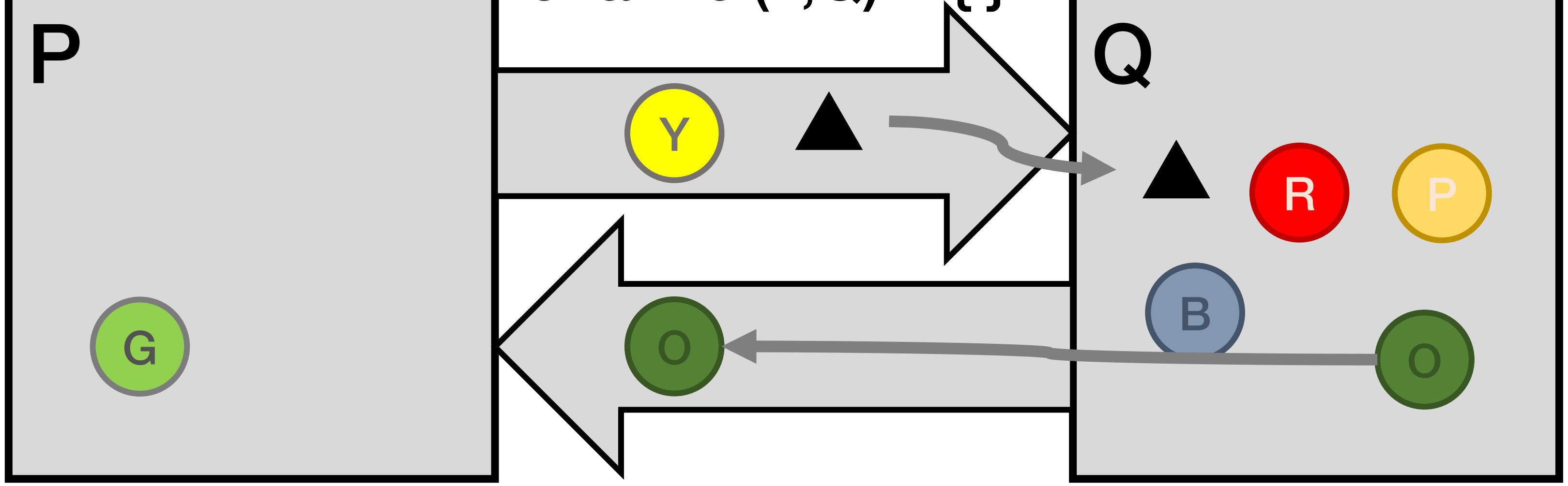


snap: P = { G, Y }

Chandy-Lamport: Receiving process (1/2)

- At the same time, Q sends orange token O
- Then, Q receives marker ▲
- Receive Rule (if not yet snapshotted)
  - On receiving marker on channel c record c's state as empty

channel(P,Q) = { }

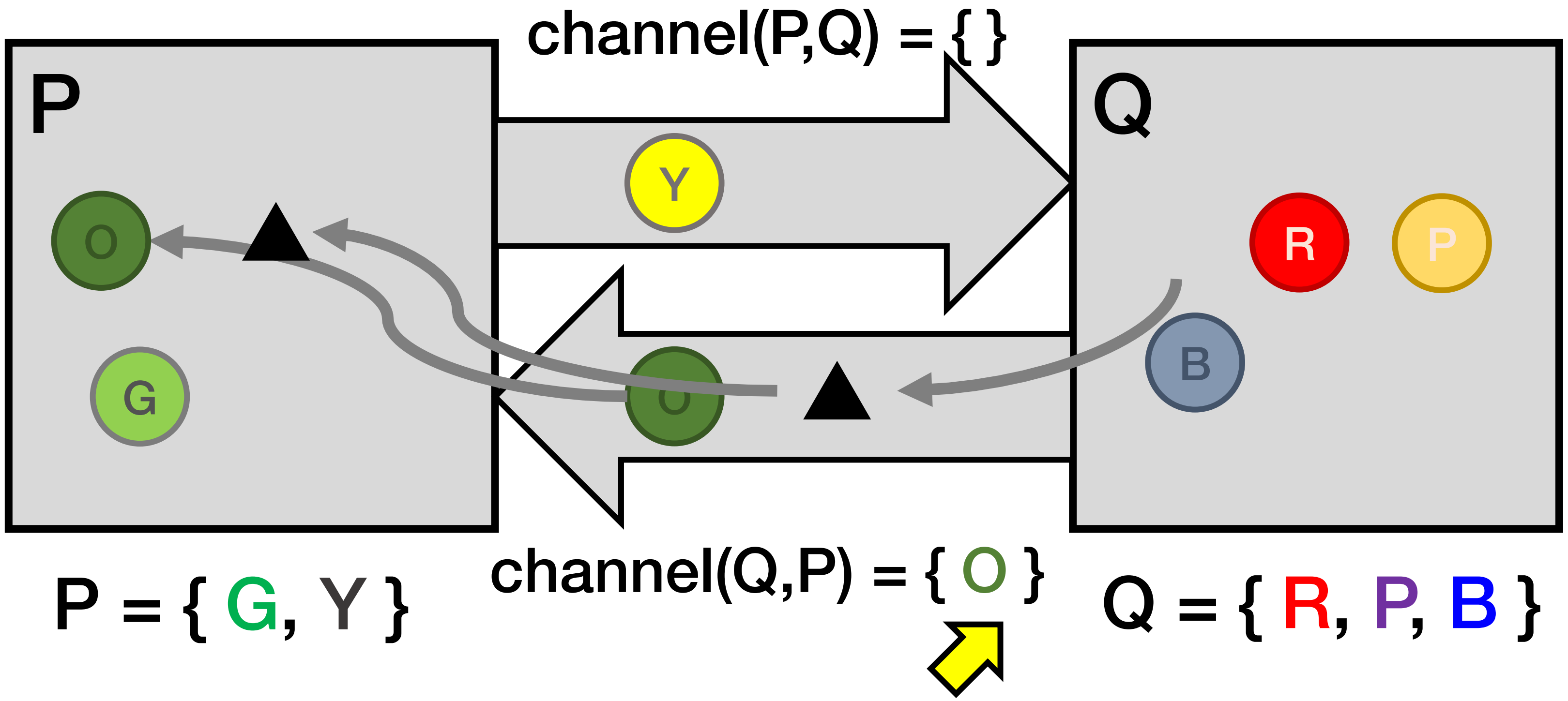


P = { G, Y }

Q = { R, P, B }

Chandy-Lamport: Receiving process (2/2)

- Q sends marker to P
- P receives orange token O, then marker ▲
- Receive Rule (if already snapshotted):
  - On receiving marker on c record c's state: all msgs from c since snapshot



Terminating a snapshot

- Distributed algorithm: No one process decides when it terminates
- Eventually, all processes have received a marker (and recorded their own state)
- All processes have received a marker on all the N–1 incoming channels (and recorded their states)
- Later, a central server can gather the local states to build a global snapshot

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    - Reasoning about C-L: Consistent Cuts

Global states and cuts

- Global state is a n-tuple of local states (one per process and channel)

- A cut is a subset of the global history that contains an initial prefix of each local state
  - Therefore every cut is a natural global state
  - Intuitively, a cut partitions the space time diagram along the time axis

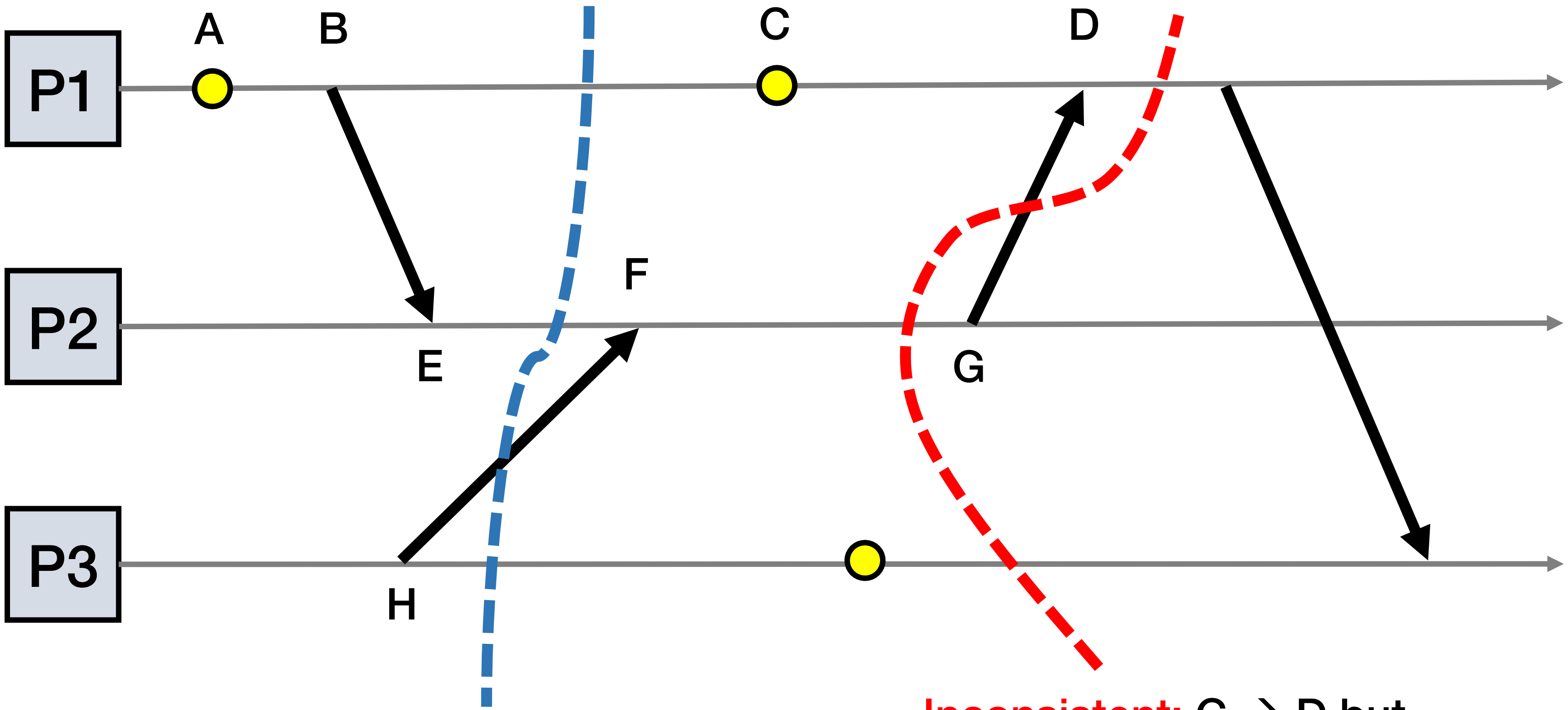
- Cut = { The last event of each process, and message of each channel that is in the cut }

Inconsistent versus consistent cuts

- A consistent cut is a cut that respects causality of events

- A cut C is consistent when:
    - For each pair of events e and f, if:
        1. f is in the cut, and
        2. e → f,
    - then, event e is also in the cut

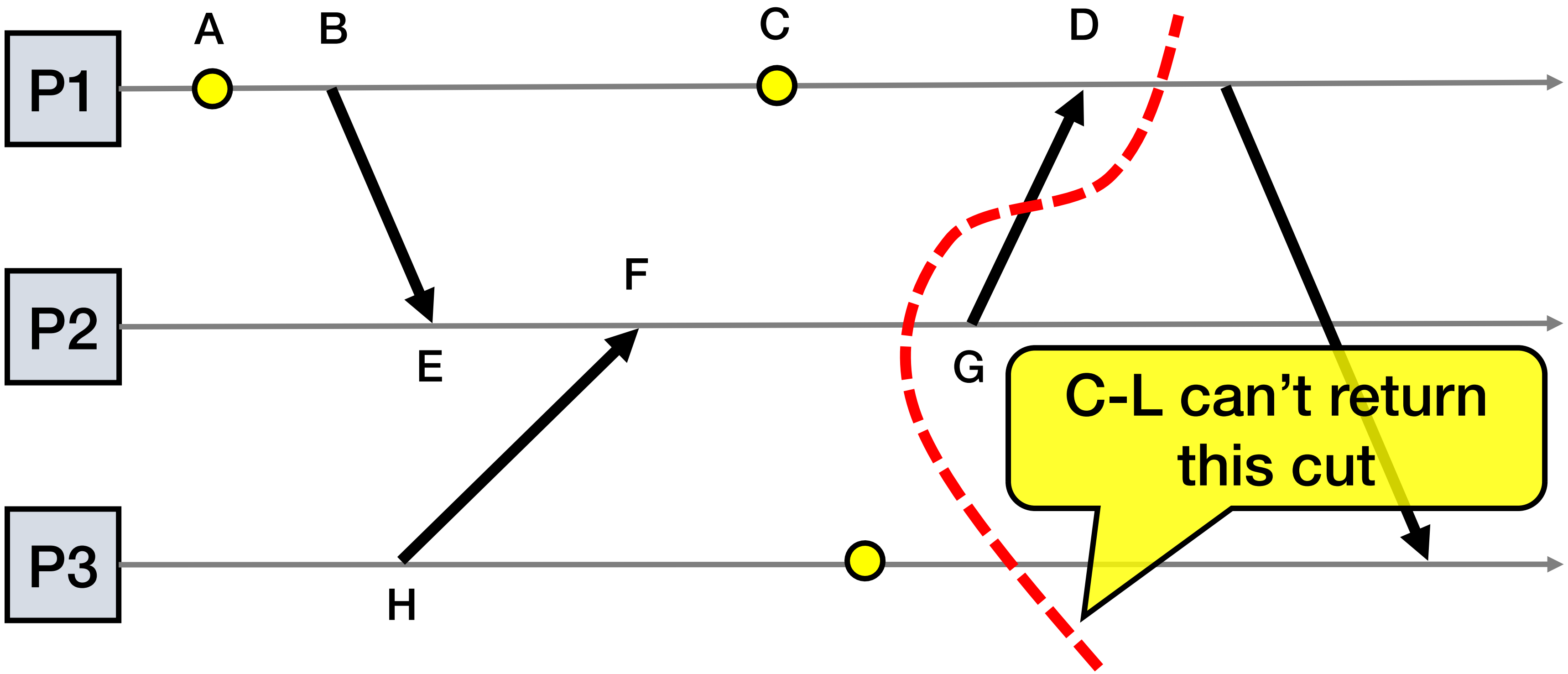
Consistent versus inconsistent cuts



Consistent: H → F
and H in the cut

Inconsistent: G → D but
only D is in the cut

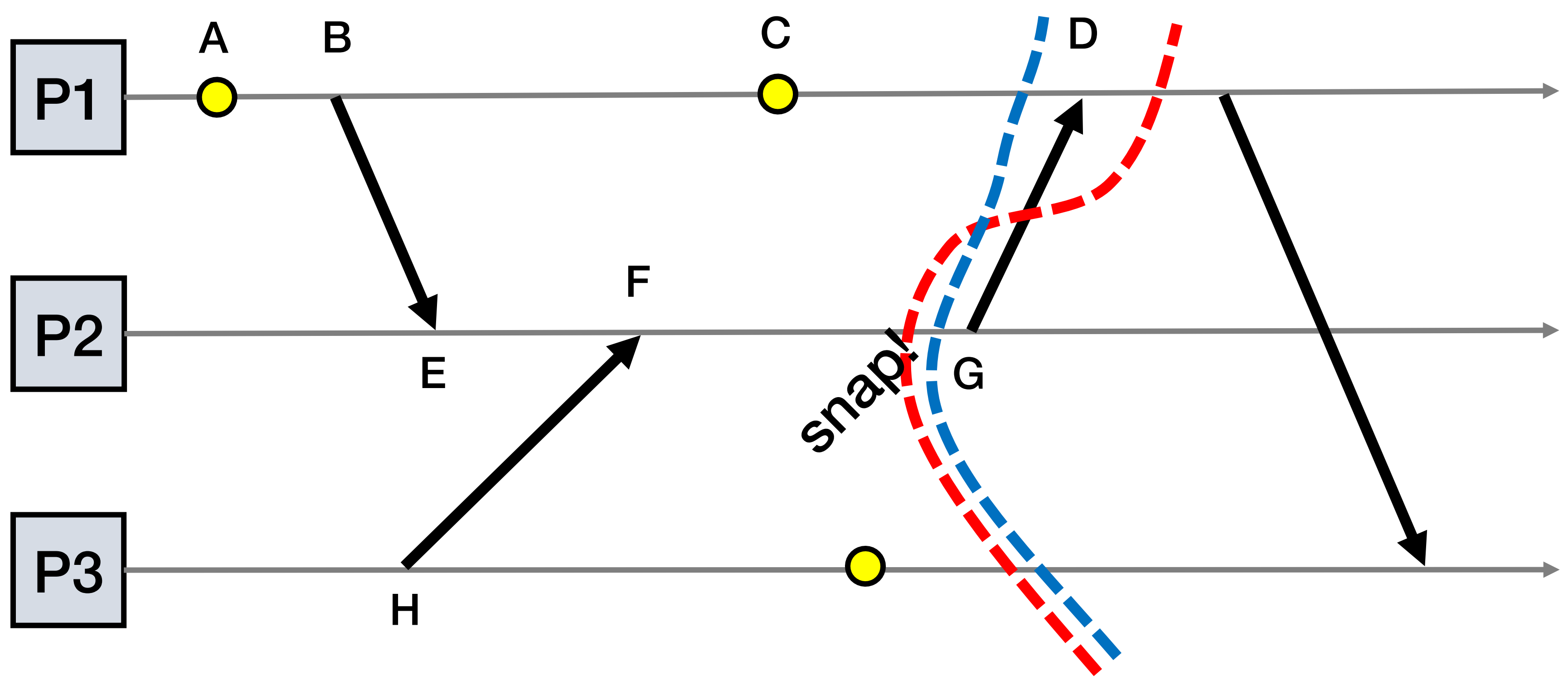
C-L returns a consistent cut



Inconsistent: G → D but only D is in the cut

C-L ensures that if D is in the cut, then G is in the cut

C-L can't return this inconsistent cut



Take-away points

- Vector Clocks: precisely capture happens-before relationship
- Distributed Global Snapshots
  - FIFO Channels: we can do that!
  - Chandy-Lamport algorithm: use marker messages to coordinate
  - Chandy-Lamport provides a consistent cut