Time and Logical Clocks 2 & Distributed Snapshots

CS 240: Computing Systems and Concurrency
Lecture 4

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Lamport Clocks Review

- Happens-Before relationship
  - Event **a** ***happens before*** event **b (a → b)**
  - **c, d** not related by → so ***concurrent,*** written as **c** || **d**
- Lamport clocks is a logical clock construction to capture the order of events in a distributed systems (disregarding the precise clock time)
  - Tag every event **a** by C(**a**)
  - If **a** → **b**, then ?
  - If *C*(**a**) < *C*(**b**), then ?
  - If **a** **||** **b**, then ?

Lamport Clocks Review

- Happens-Before relationship
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- Lamport clocks is a logical clock construction to capture the order of events in a distributed systems (disregarding the precise clock time)
  - Tag every event **a** by C(**a**)
  - If **a** → **b**, then *C*(**a**) < *C*(**b**)
  - If *C*(**a**) < *C*(**b**), then **NOT b → a** (**a → b** or **a || b**)
  - If **a || b**, then nothing

Lamport Clocks and causality

- Lamport clock timestamps **don't capture causality**

- Given two timestamps C(**a**) and C(**z**), want to know whether there's a chain of events linking them:

$$\mathbf{a} \rightarrow b \rightarrow \ldots \rightarrow y \rightarrow \mathbf{z}$$

Take-away points: Lamport clocks

- Can **totally-order** events in a distributed system: that's useful!
  - We saw an application of Lamport clocks for totally-ordered multicast

- **But:** while by construction, **a** → **b** implies C(**a**) < C(**b**),
  - The converse is not necessarily true:
    - C(**a**) < C(**b**) does not imply **a** → **b** (possibly, **a** || **b**)

Can't use Lamport clock timestamps to infer causal relationships between events

Today

1. **Logical Time: Vector clocks**
2. Safety and Liveness Properties
3. Distributed Snapshots

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 $VC(\mathbf{e}) = [c_1, c_2 \ldots, c_n]$
    - Each entry $\boldsymbol{c_k}$ is a **count of events** in process $\boldsymbol{k}$ that **causally precede** **e**

Vector clock: Update rules

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

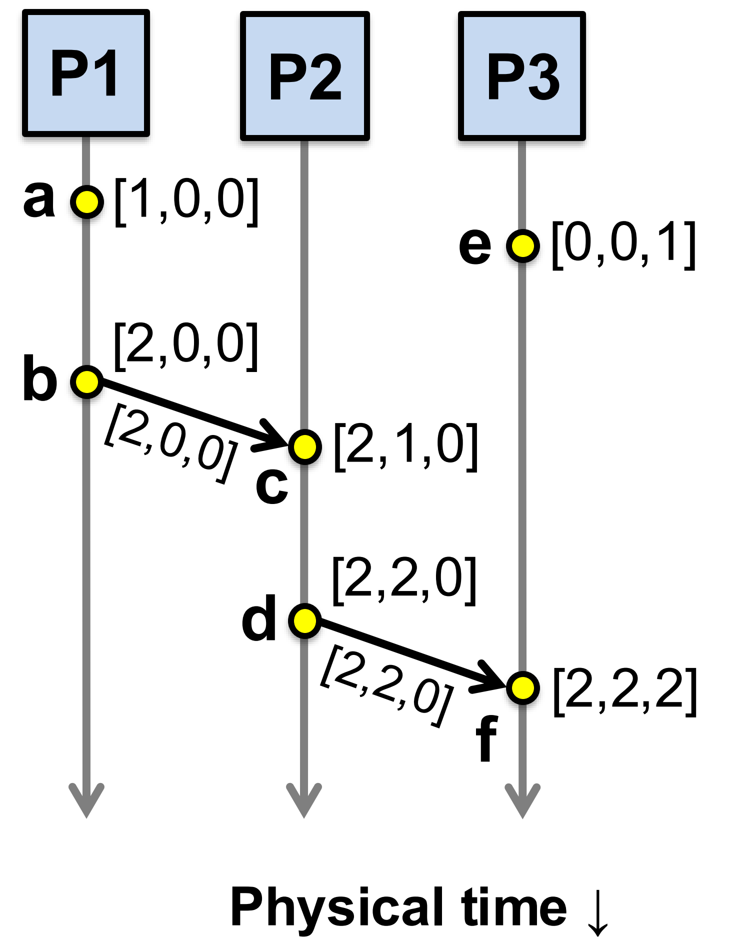
- Two **update rules:**

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 $c_k = \max\{c_k, d_k\}$, for $k = 1 \ldots n$
   - 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

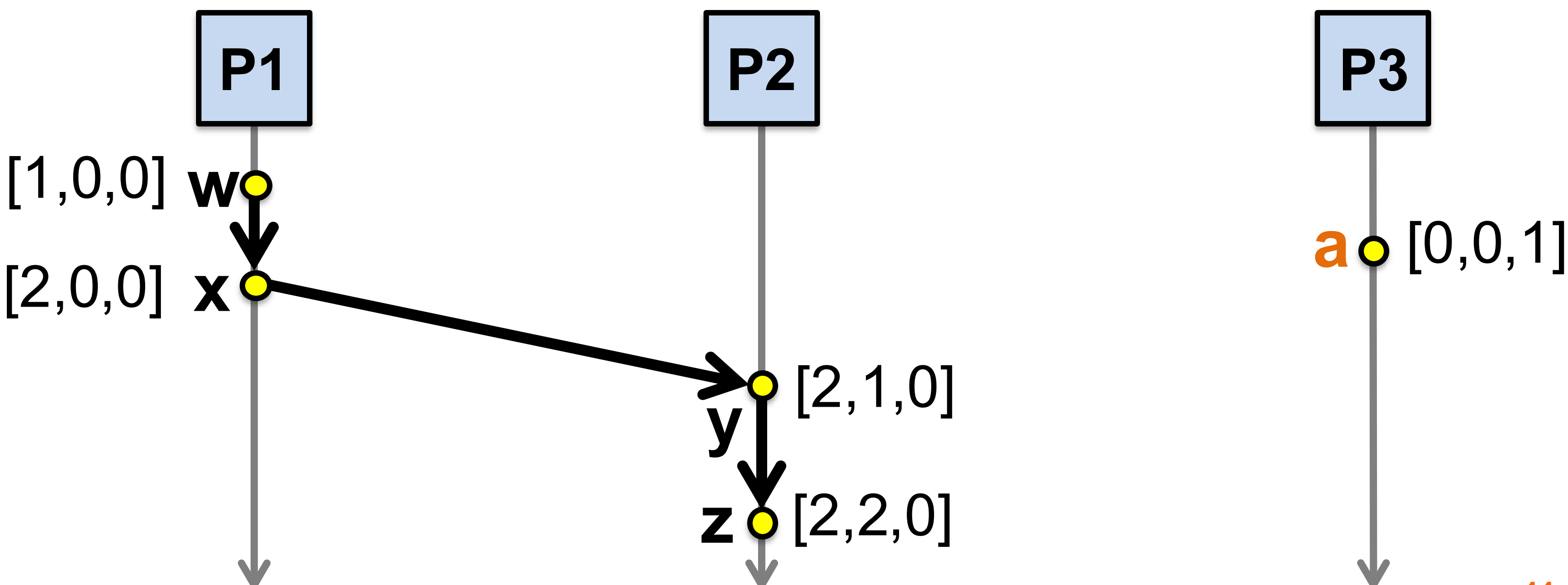
- Rule for comparing vector timestamps:
  - V(**a**) = V(**b**) when $\mathbf{a}_k = \mathbf{b}_k$ for all k
  - V(**a**) < V(**b**) when $\mathbf{a}_k \leq \mathbf{b}_k$ for all k and V(**a**) ≠ V(**b**)

- Concurrency:
  - ***a*** || ***b*** if $\mathbf{a}_i < \mathbf{b}_i$ and $\mathbf{a}_j > \mathbf{b}_j$, some i, j

Vector clocks capture causality

- V(**w**) < V(**z**) **then** there is a chain of events linked by Happens-Before (→) between **w** and **z**

- If 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: NOT z → a (either a → z or a || z)

Vector clocks: V(a) < V(z)
Conclusion: **a → z**

Vector clock timestamps precisely capture Happens-Before relationship (potential causality)

Disadvantage of vector timestamps

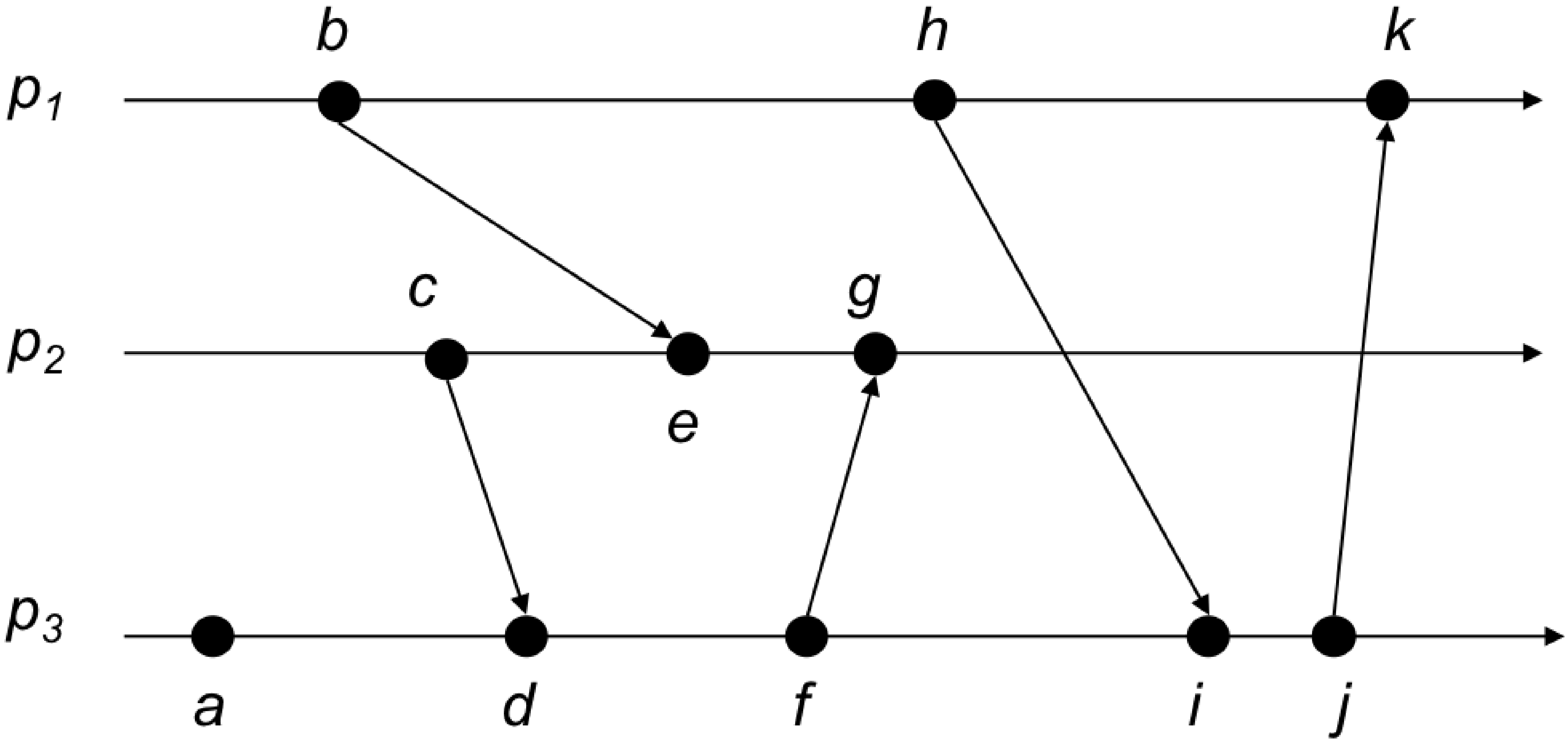
- Compared to Lamport timestamps,
  vector timestamps O(n) overhead for storage and communication, n = no. of processes

Take-away points

- Vector Clocks
  - Precisely capture happens-before relationship

VC Quiz

- Suppose these processes maintain vector clocks. Write the vector clock of each event starting from clock time 0.



Today

1. Logical Time: Vector clocks
2. **Safety and Liveness Properties**
3. Distributed Snapshots

Reasoning about fault tolerance

- This is hard!
  - How do we design fault-tolerant systems?
  - How do we know if we're successful?
- Often use "properties" that hold true for every possible execution
- We focus on **safety** and **liveness** properties

Properties

- **Property**: a predicate that is evaluated over a run of the system
  - "every message that is received was previously sent"
- Not everything you may want to say about a system is a property:
  - "the program sends an average of 50 messages in a run"

Safety properties

- “Bad things” don’t happen, ever
  - No more than k processes are simultaneously in the critical section
  - Messages that are delivered are delivered in causal order
- A safety property is “prefix closed”:
  - if it holds in a run, it holds in every prefix

Liveness properties

- "Good things" eventually happen
  - A process that wishes to enter the critical section eventually does so
  - Some message is eventually delivered
  - Eventual consistency: if a value doesn't change, two servers will eventually agree on its value
- Every run can be extended to satisfy a liveness property
  - If it does not hold in a prefix of a run, it does not mean it may not hold eventually

Often a trade-off

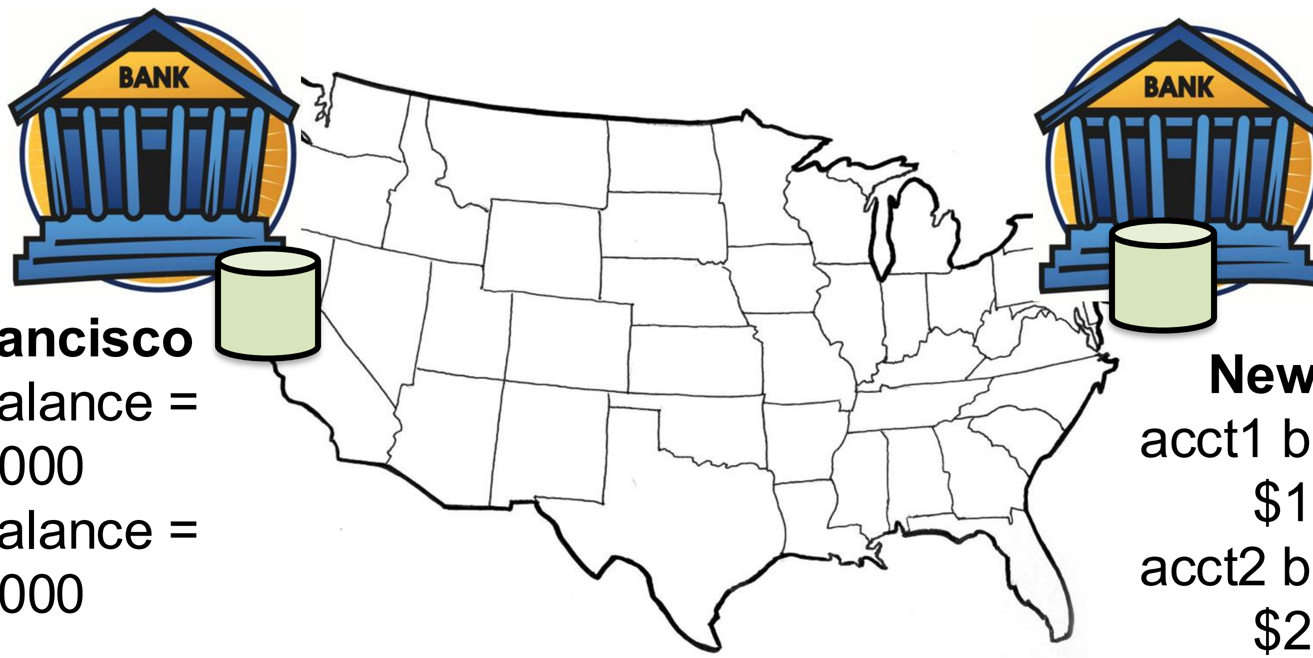
- “Good” and “bad” are application-specific
- Safety is very important in banking transactions
  - May take some time to confirm a transaction
- Liveness is very important in social networking sites
  - See updates right away

Today

1. Logical Time: Vector clocks
2. Safety and Liveness Properties
3. **Distributed Snapshots**
   - 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)**
  – All messages sent on channels arrive intact, unduplicated, in order
  – The channel has **state,** too: the set of messages inside

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 system 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

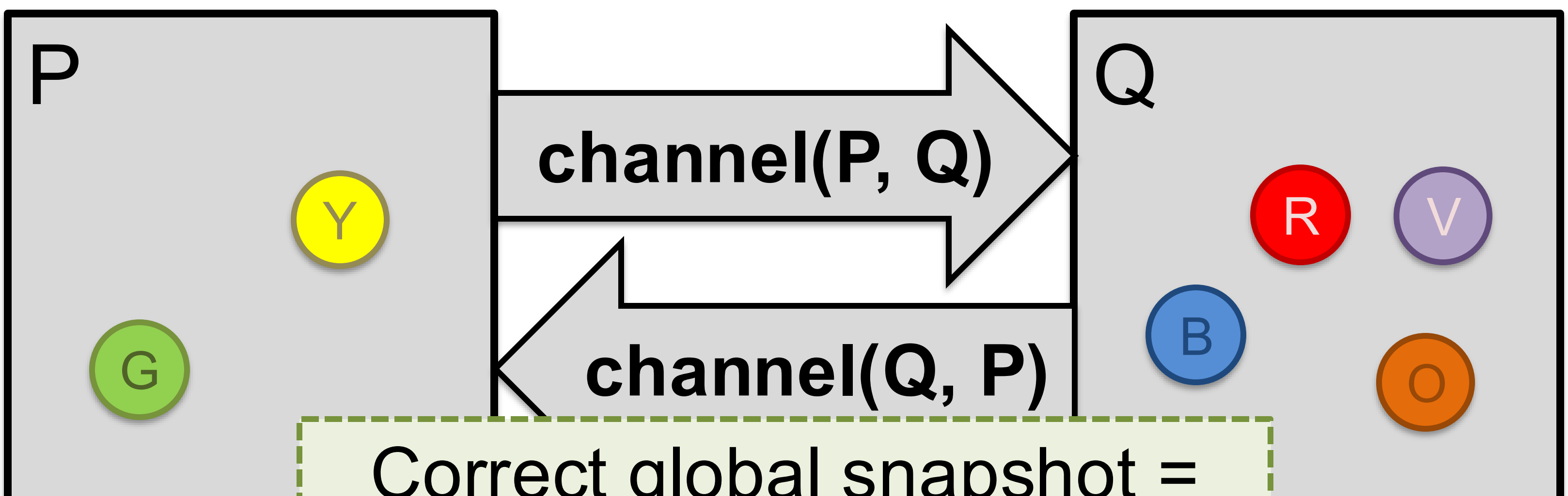
  2. The state of **each communication channel**

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

Why do we need snapshots?

- **Checkpointing:** Restart if the application fails
- **Collecting garbage:** Remove objects that don't have any references
- **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?

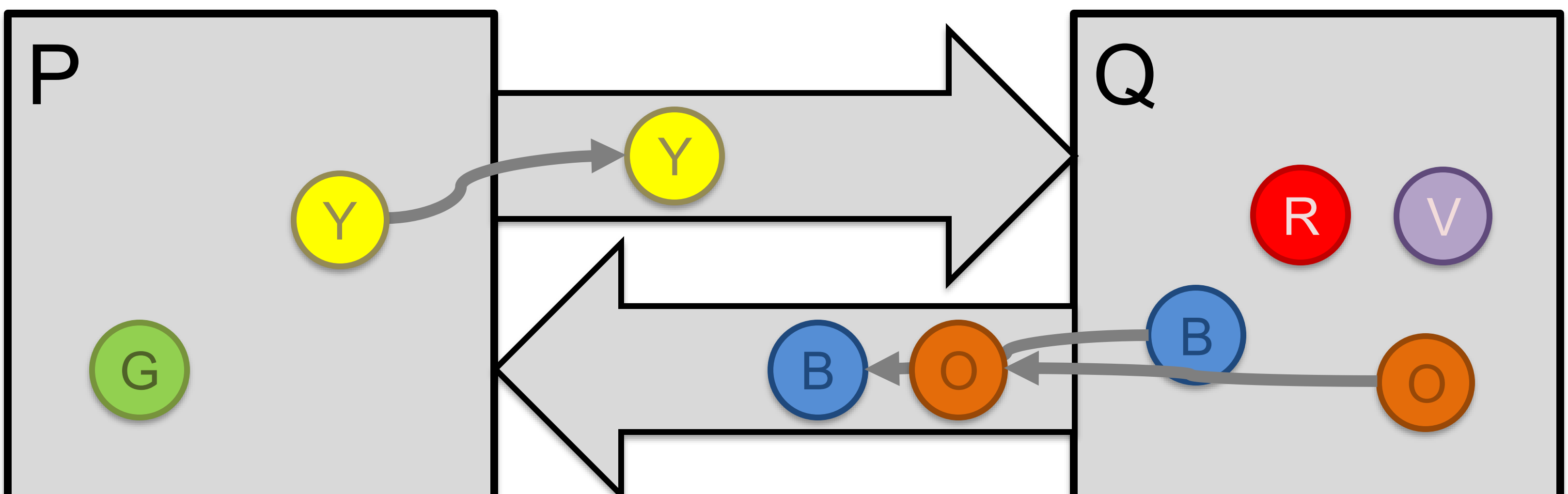
When is inconsistency possible?

- 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



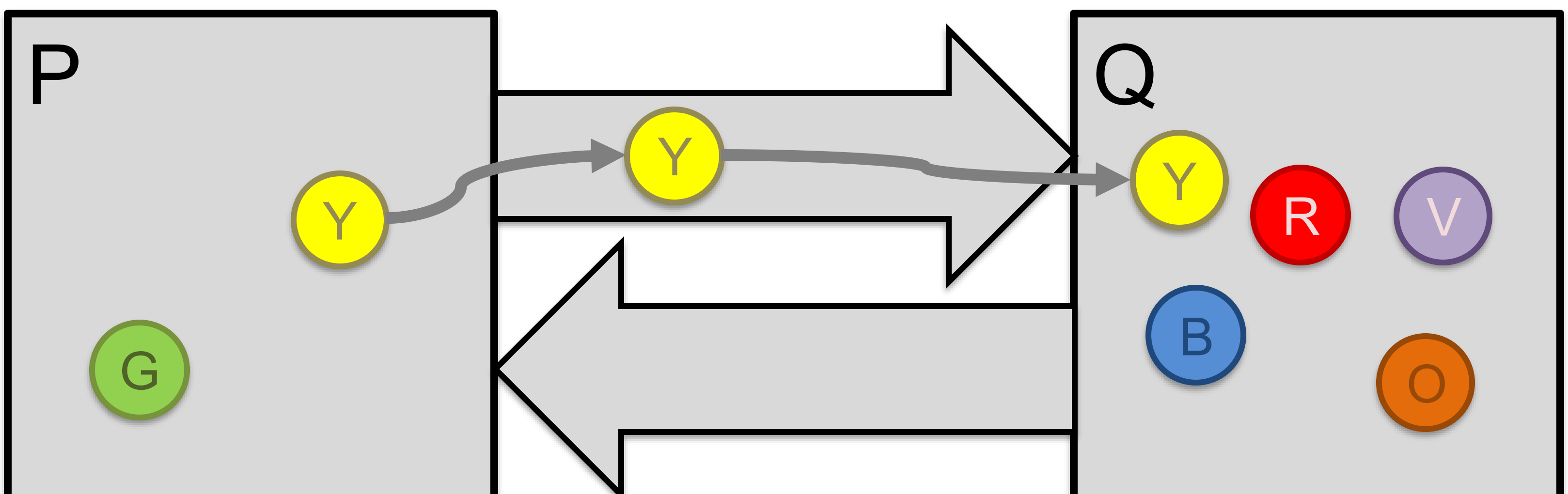
P = { G }

Q = { R, V }

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, V, 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
  - Not an application message, does not interfere with other application messages
  - Channels deliver marker and other messages FIFO

Today

1. Logical Time: Vector clocks
2. Safety and Liveness Properties
3. Distributed Snapshots
   – **Chandy-Lamport algorithm**
   – Reasoning about C-L: Consistent Cuts

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

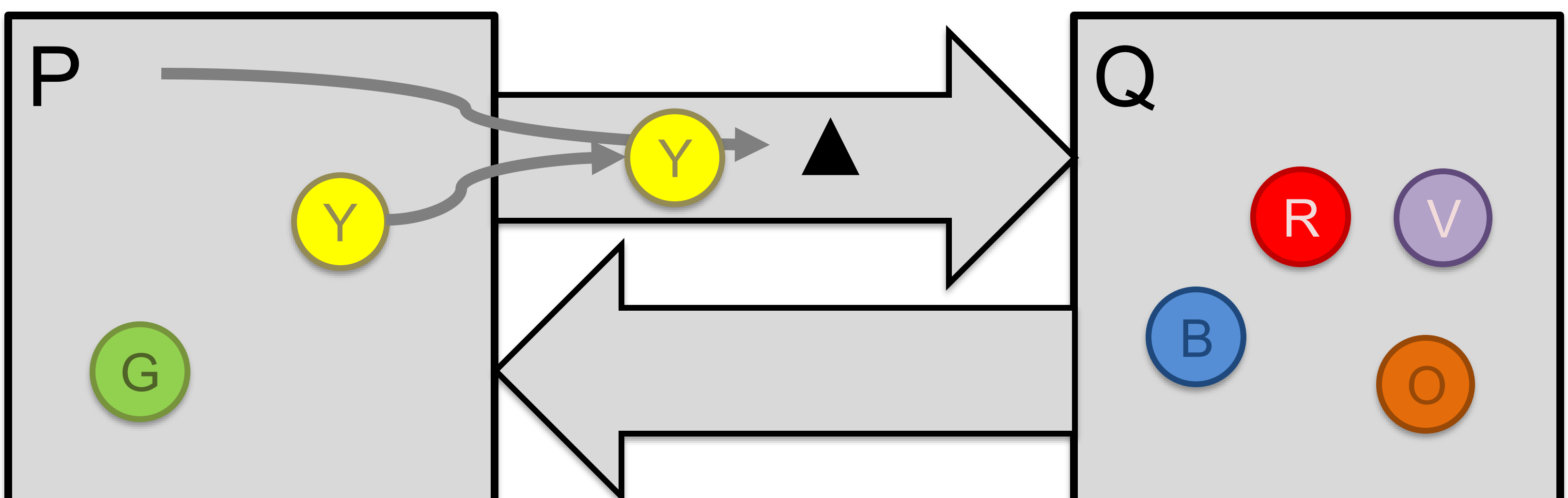
- Nodes remember **whether they have snapshotted**

- **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**

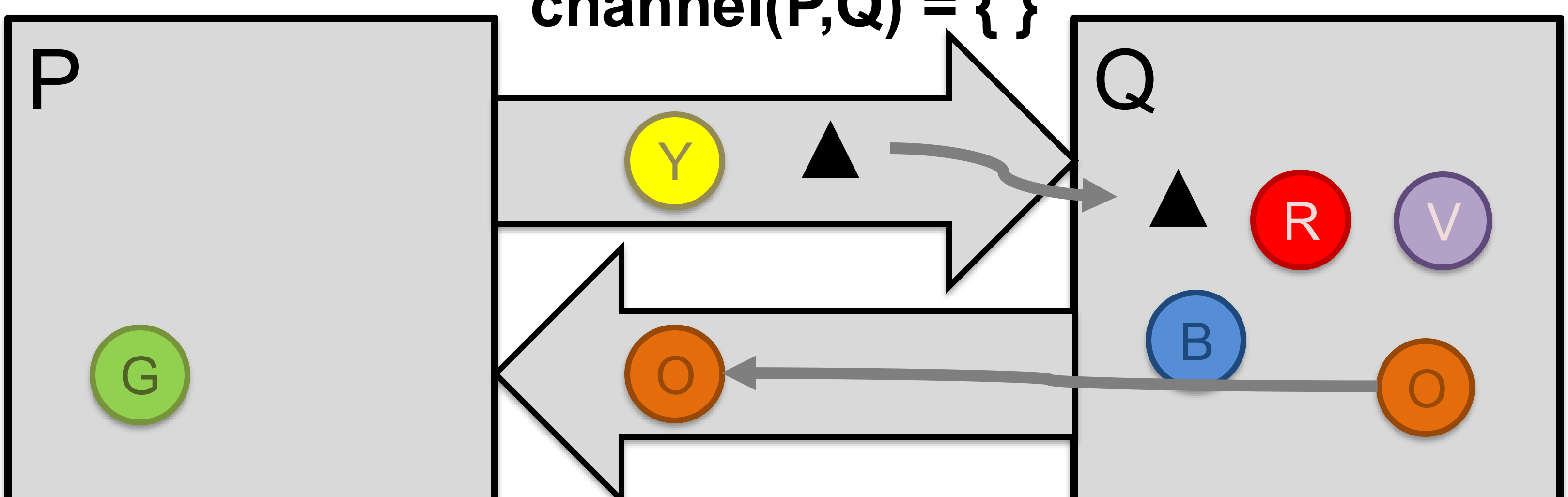


snap: P = { G, Y }

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) = { }

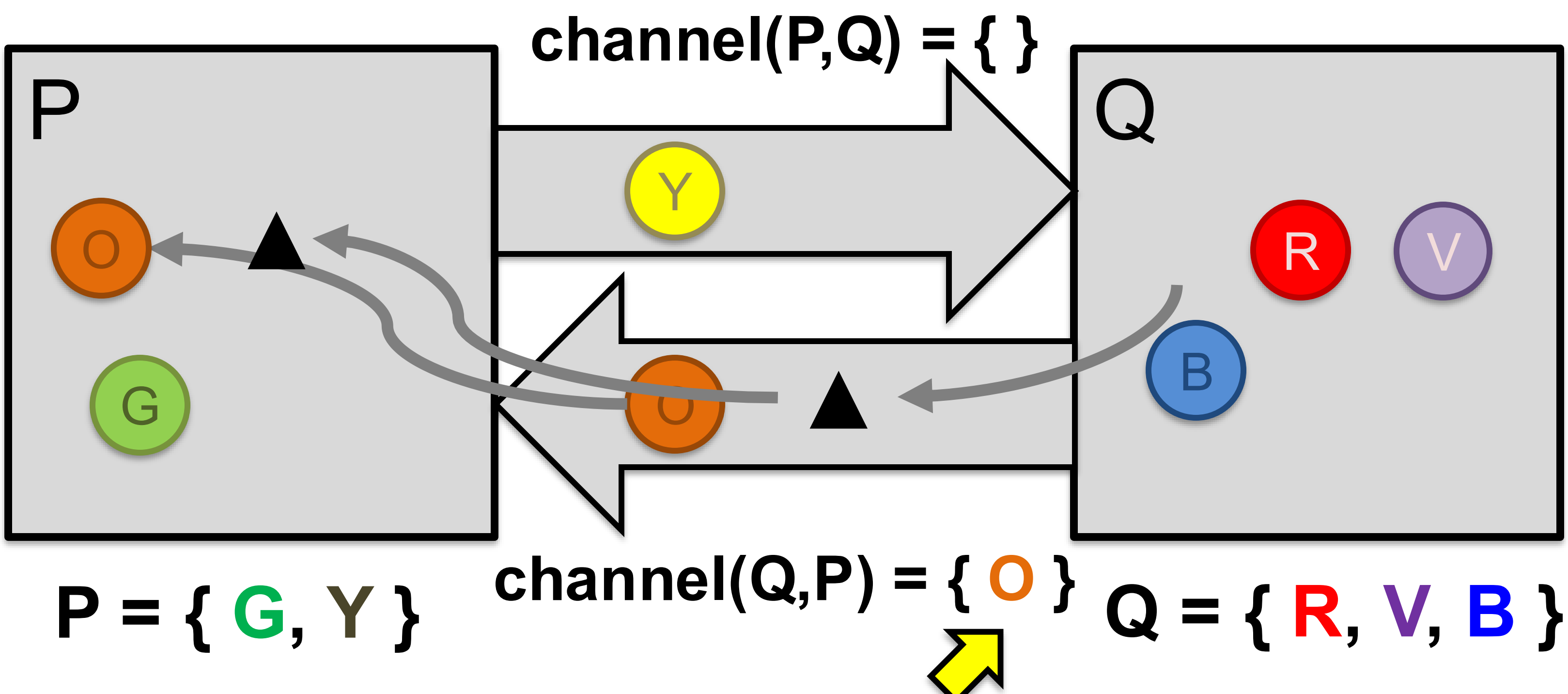


P = { G, Y }

Q = { R, V, 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 single 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

C-L Global Snapshot Algorithm (1/2)

- **First: Initiator P*i* records its own state**

- **for *j=1 to N* except *i***
  - P*i* sends out a **Marker** message on outgoing channel $C_{i,j}$
  - (*N-1*) channels
- Starts recording the incoming messages on each of the incoming channels at P*i*: $C_{j,i}$ (for *j=1 to N* except *i*)

CL Global Snapshot Algorithm (2/2)

Whenever a process P*i* receives a Marker message on an incoming channel $C_{k,i}$

- **if** (this is the first Marker P*i* is seeing)
  - P*i* records its own state first
  - Marks the state of channel $C_{k,i}$ as "empty"
  - for *j=1 to N* except *i*
    - P*i* sends out a Marker message on outgoing channel $C_{i,j}$
  - Starts recording the incoming messages on each of the incoming channels at P*i*: $C_{j,i}$ (for *j=1 to N* except *i* and *k*)
- **else** /* already seen a Marker message */
  - Mark the state of channel $C_{k,i}$ as all the messages that have arrived on it since recording was turned on for $C_{k,i}$

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1. Logical Time: Vector clocks
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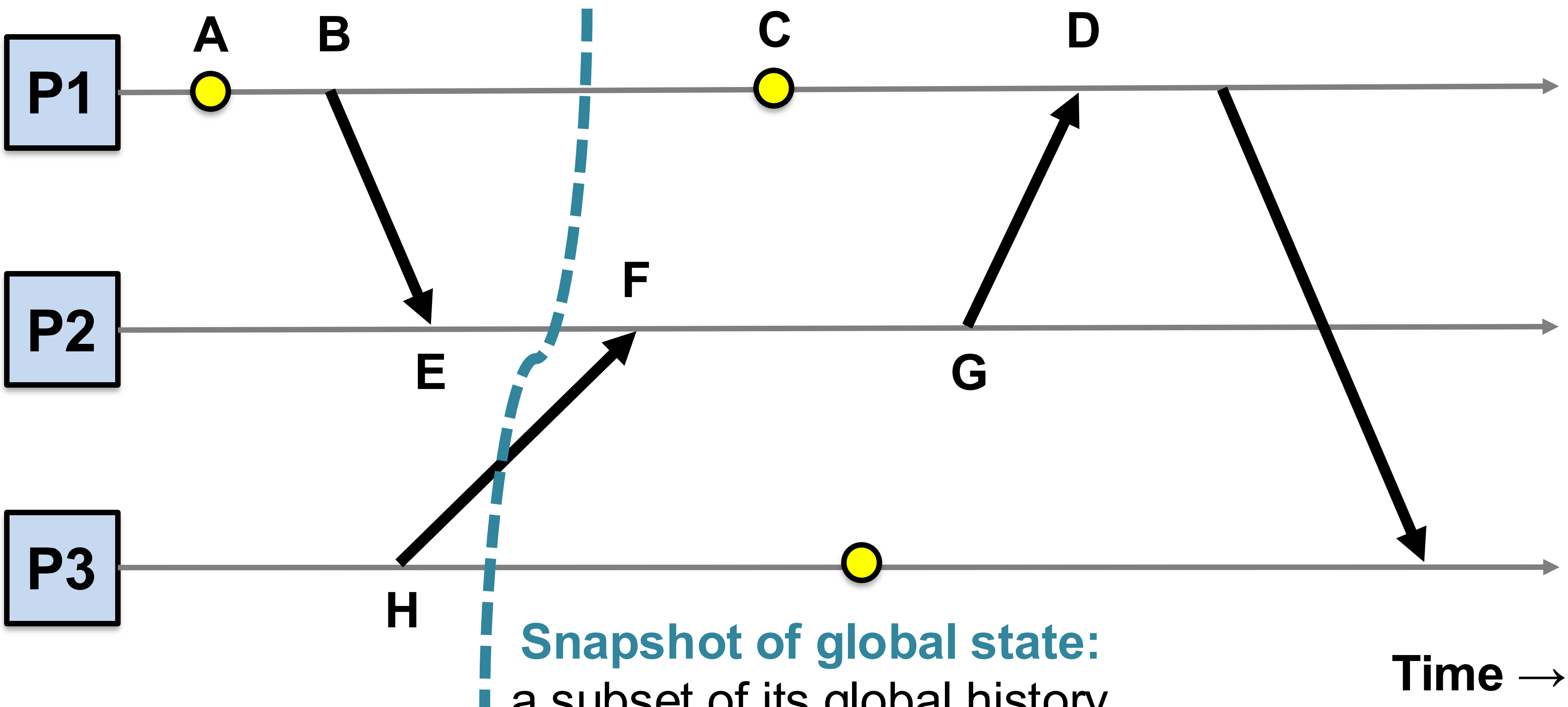
3. Distributed Snapshots
   – Chandy-Lamport algorithm
   – **Reasoning about C-L: Consistent Cuts**

Global state as cut of system's execution



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

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

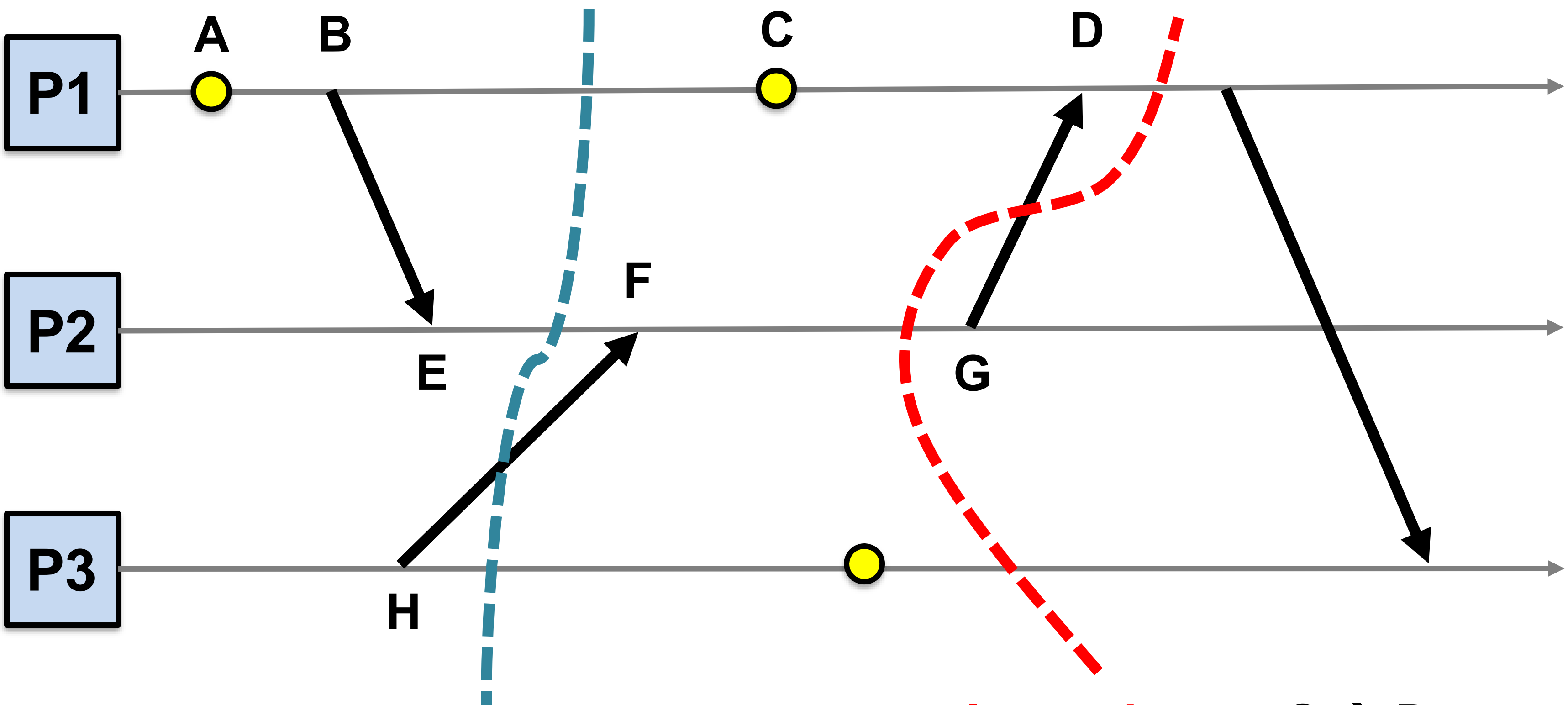
- ***Cut*** = { The last **event** of each **process,** and **message** of each **channel** that is in the cut }

Consistent versus inconsistent cuts

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

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

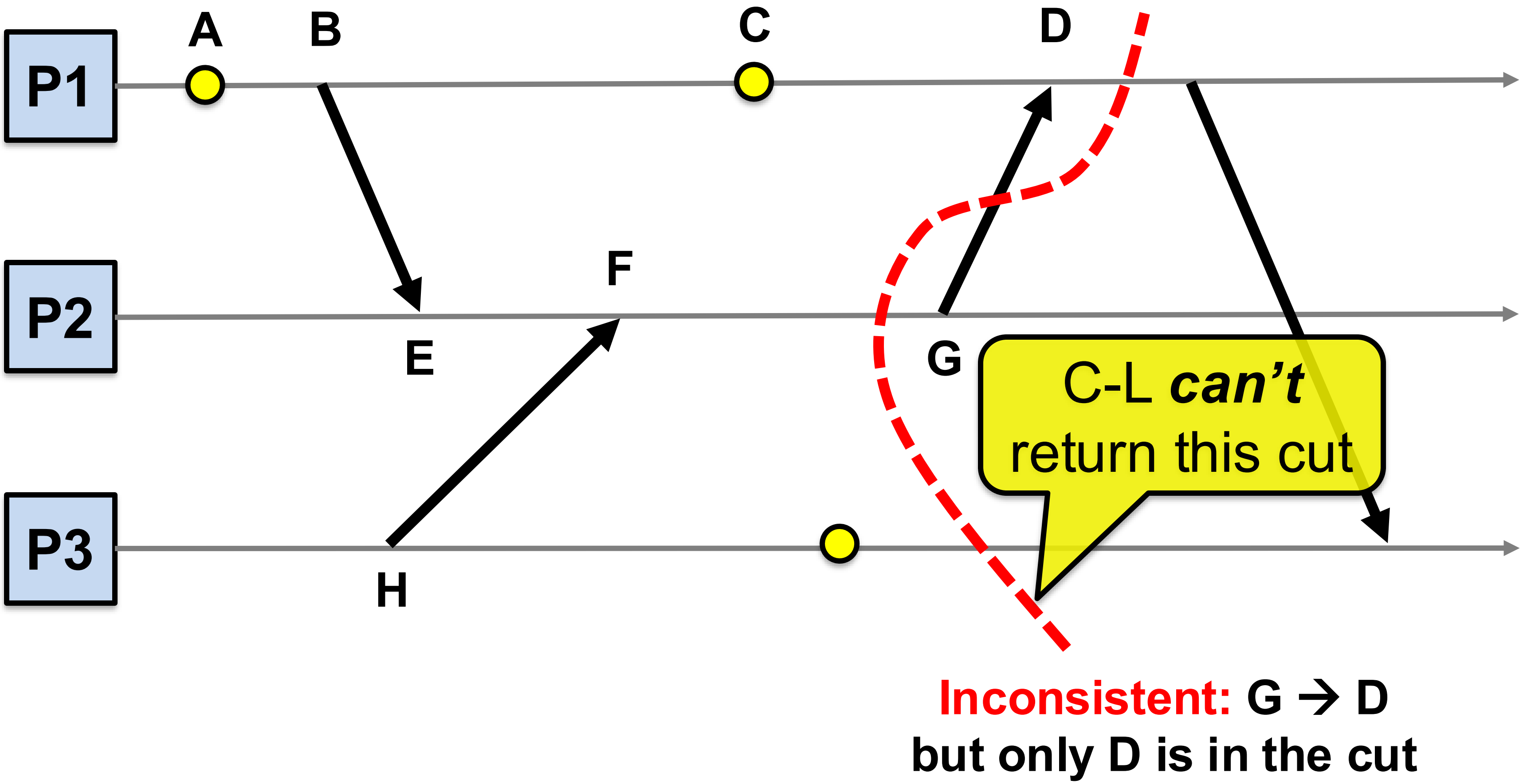
Consistent versus inconsistent cuts



Consistent: H → F
and H in the cut

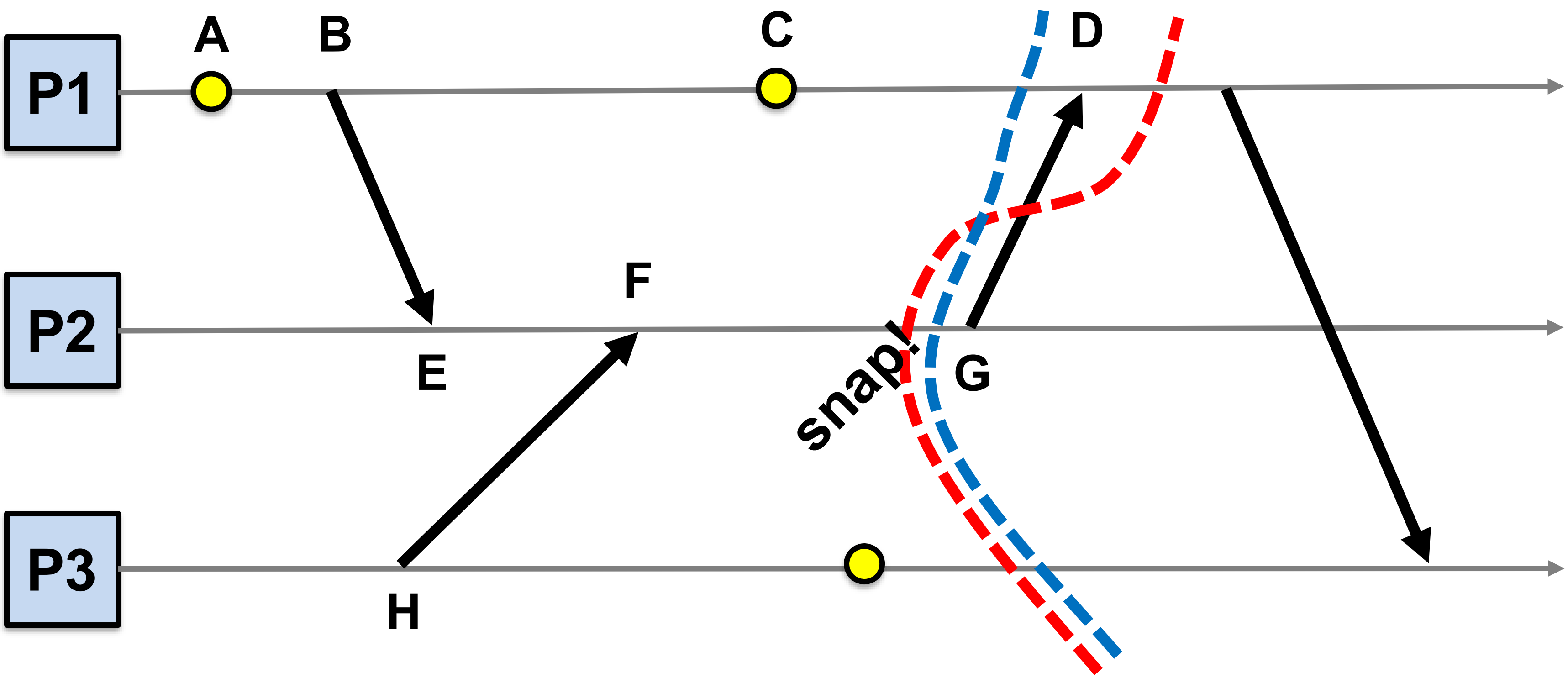
Inconsistent: G → D
but only D is in the cut

C-L returns a consistent cut



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

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

- Distributed Global Snapshots
  - FIFO Channels: we can realize them and build on guarantees
  - Chandy-Lamport algorithm: use marker messages to coordinate
  - Chandy-Lamport provides a consistent cut

Chandy-Lamport Puzzle #1

Is this snapshot possible? And if so, how?

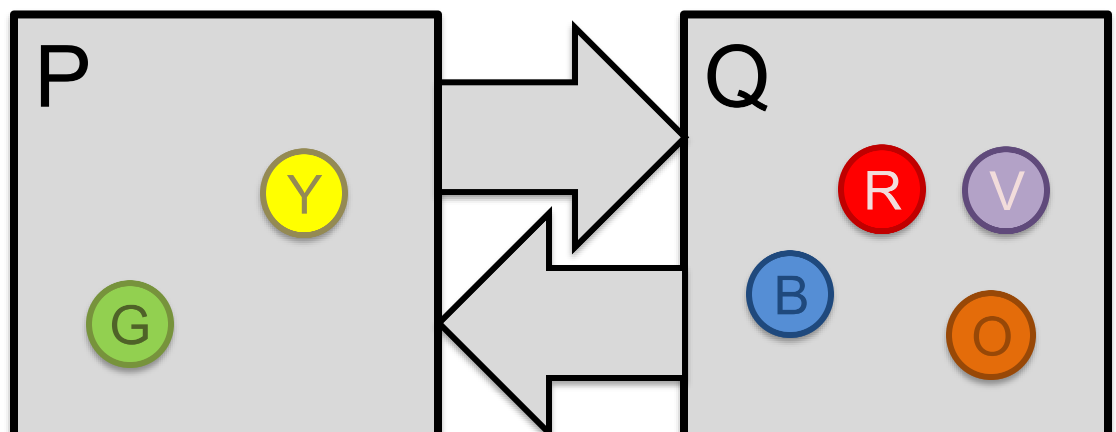
P = { G }

chan(P, Q) = { Y }

Q = { R, V }

chan(Q, P)= { B, O }

Either P or Q starts CL from the current state



Chandy-Lamport Puzzle #2

Is this snapshot possible? And if so, how?

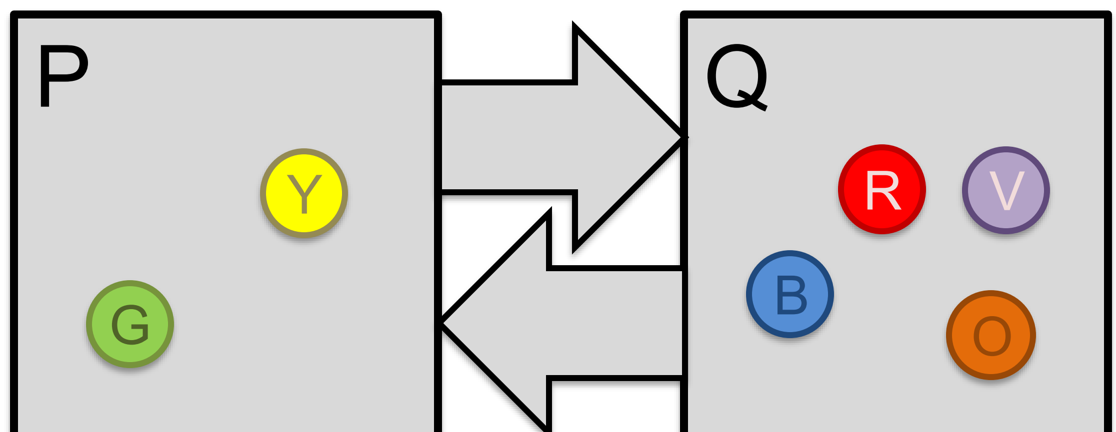
P = { G, Y, R, V, B, O }

chan(P, Q) = { }

Q = { }

chan(Q, P)= { }

Either P or Q starts CL from the current state



Chandy-Lamport Puzzle #3

Is this snapshot possible? And if so, how?

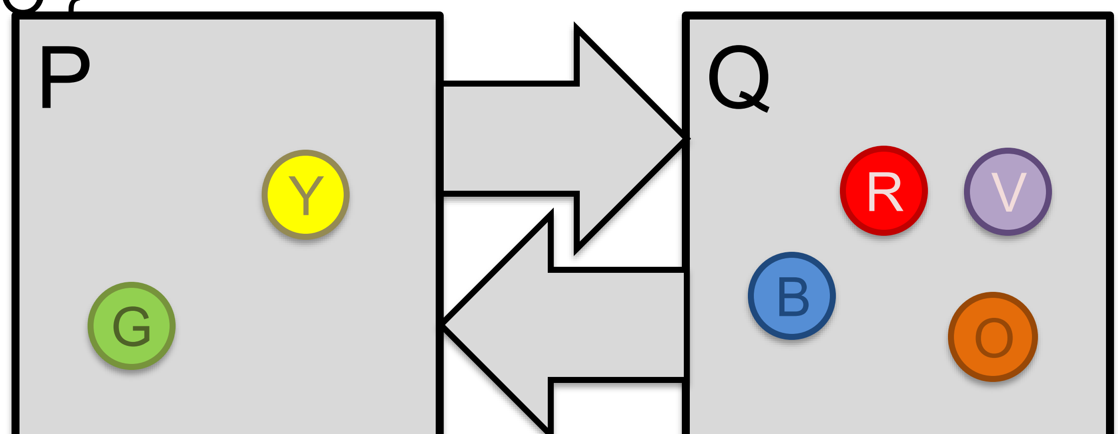
P = { }

chan(P, Q) = { }

Q = { }

chan(Q, P)= {G, Y, R, V, B, O }

Either P or Q starts CL from the current state



Chandy-Lamport Puzzle #4

Is this snapshot possible? And if so, how?

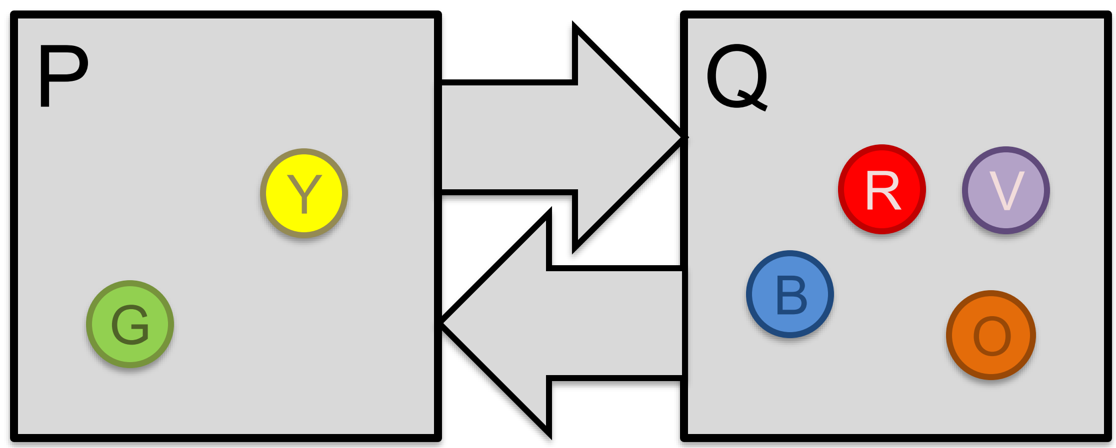
P = { G, Y }

chan(P, Q) = { R }

Q = { B, O }

chan(Q, P)= { V }

Either P or Q starts CL from the current state



Puzzle #4: How are you thinking?

Is this snapshot possible? And if so, how?

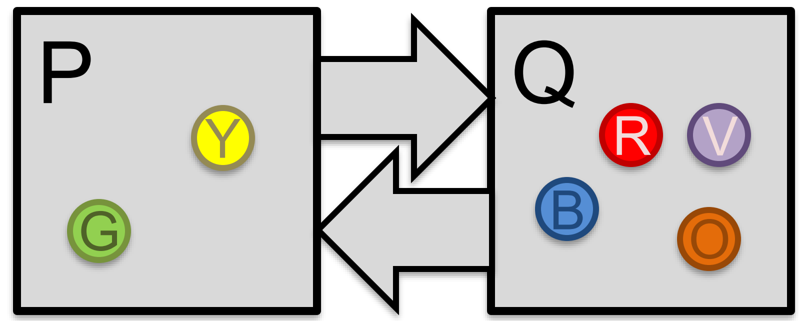
P = { G, Y }

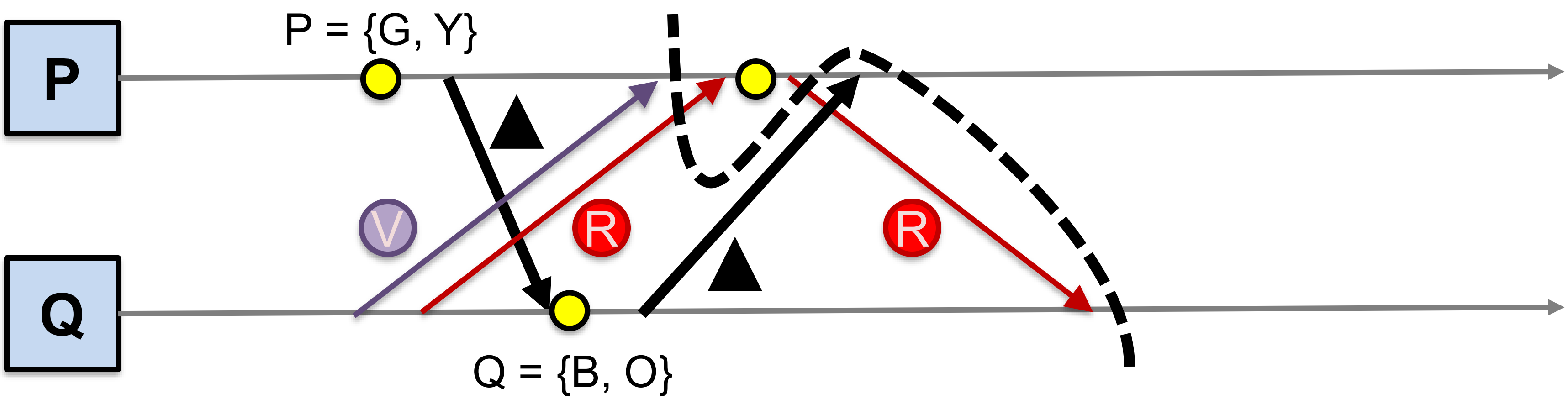
chan(P, Q) = { R }

Q = { B, O }

chan(Q, P) = { V }

Either P or Q starts CL from the current state





Chandy-Lamport Puzzle #5

Is this snapshot possible? And if so, how?

P = { G, Y }

chan(P, Q) = { }

chan(P, T) = { }

Q = { B, O }

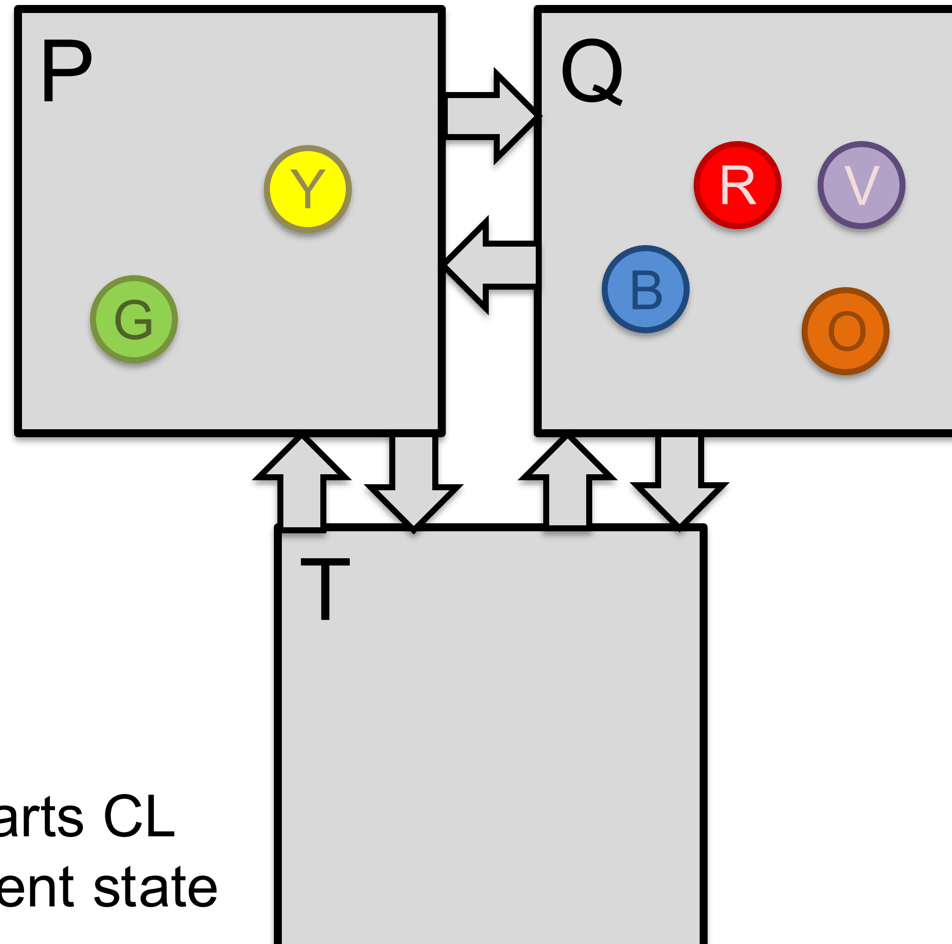
chan(Q, P) = { V }

chan(Q, T) = { R }

T = { }

chan(T, P) = { }

chan(T, Q) = { }



Assume P starts CL from the current state

Chandy-Lamport Puzzle #6

Is this snapshot possible? And if so, how?

P = { G, Y }

chan(P, Q) = { }

chan(P, T) = { }

Q = { B }

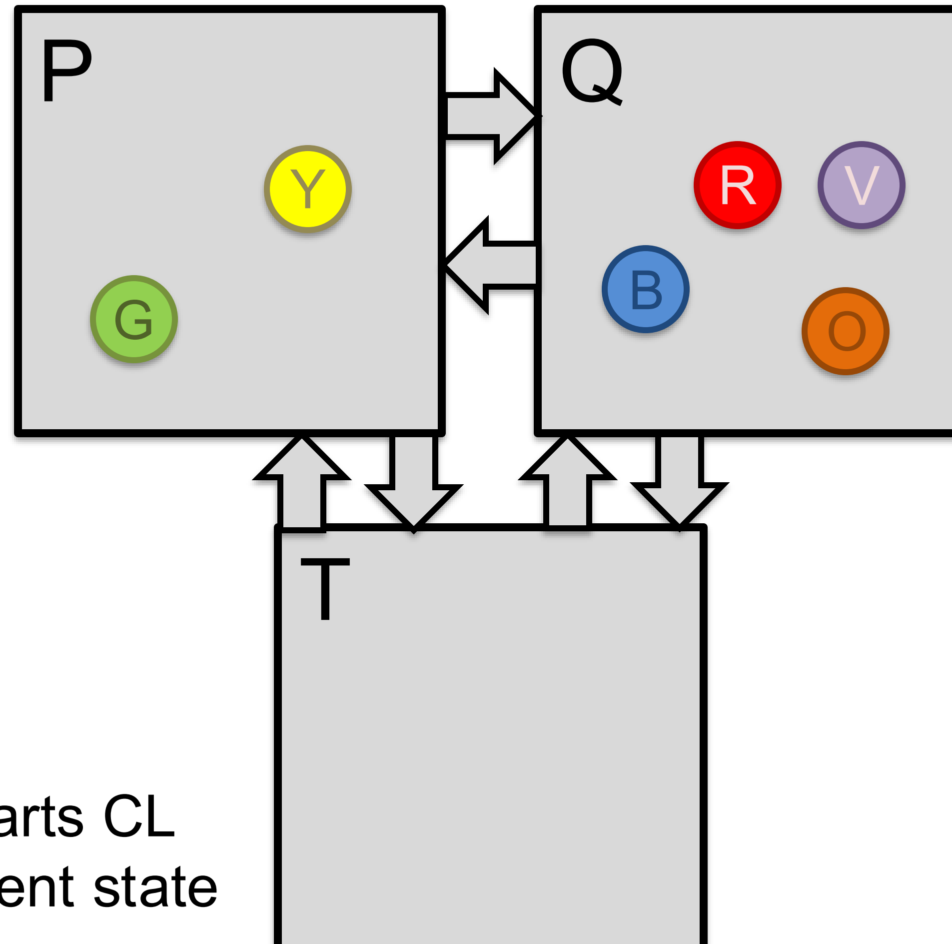
chan(Q, P) = { V }

chan(Q, T) = { R }

T = { O }

chan(T, P) = { }

chan(T, Q) = { }



Assume P starts CL from the current state