Ordering and Consistent Cuts

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Time, Clocks, and the Ordering of Events in a Distributed System

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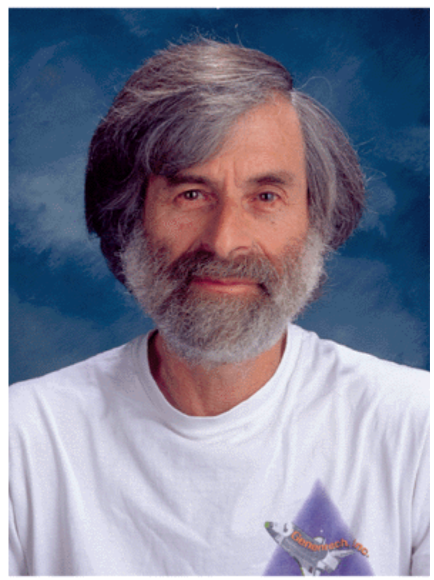
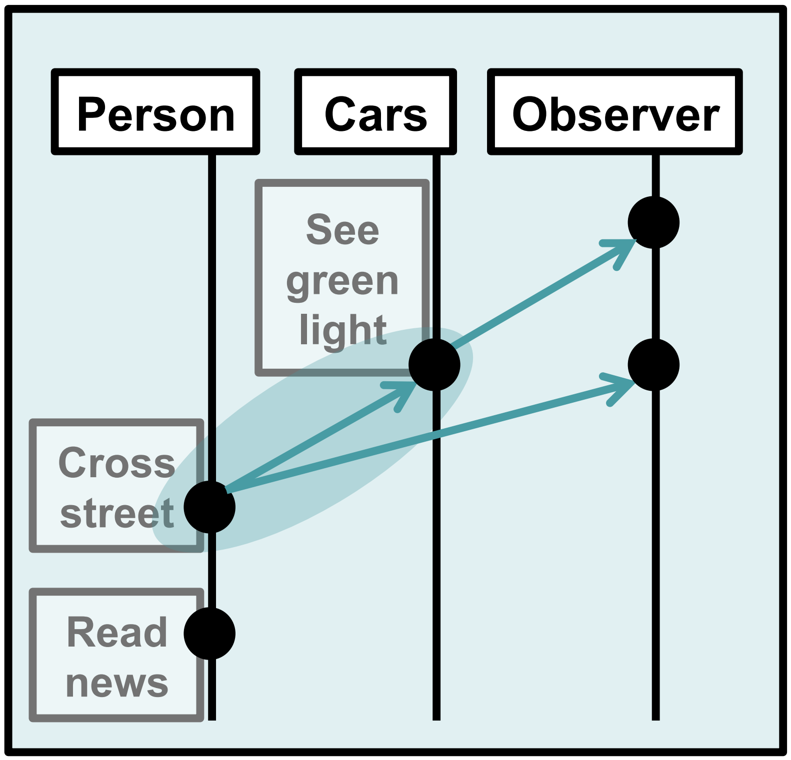
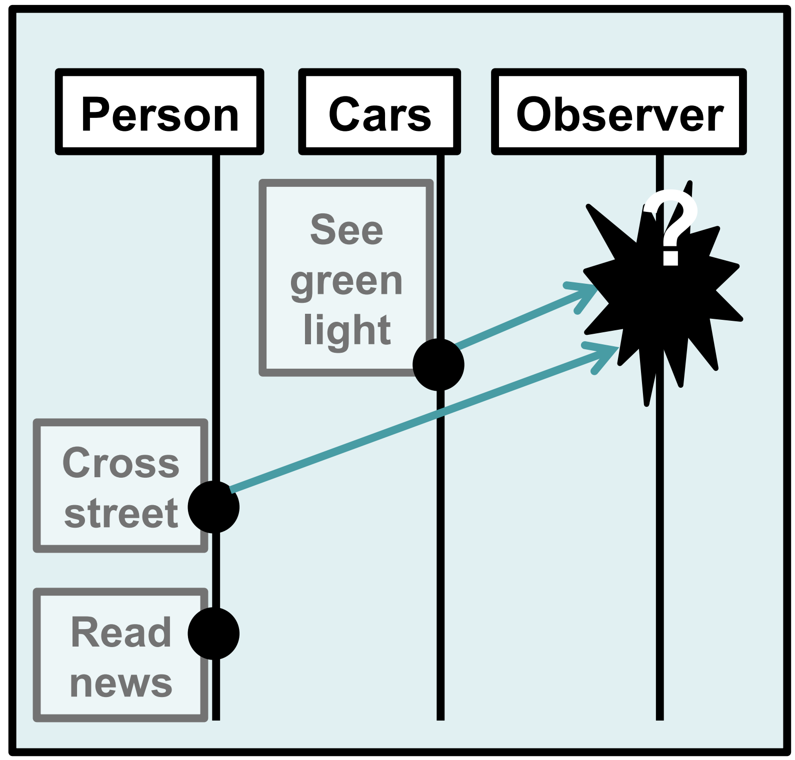


Time, Clocks, and the Ordering of Events in a Distributed System

Introduction

- Our concept of time
- Distributed system's concept of time





Time, Clocks, and the Ordering of Events in a Distributed System

Introduction

- Coordination of Distributed Systems
- Lack of Understanding
- Partial Ordering of Events
- Total Ordering of Events

Outline

- **Partial Ordering of Events**
- Logical Clocks
- Total Ordering of Events
- Anomalous Behavior
- Physical Clocks

Partial Ordering of Events

- **System Definition**
  - **System** contains spatially separated processes
  - **Process** contains a sequence of events
  - **Event** manifestation is arbitrary, but must include message sending and message receiving

Partial Ordering of Events

- **Mathematical Properties**
  - **Asymmetric**
    - If **a\<b**, then **b<a**
    - If **a\<b** and **b\<a**, then **a=b**
  - **Transitive**
    - If **a\<b** and **b\<c**, then **a\<c**
  - **Reflexive**
    - **a\<a**

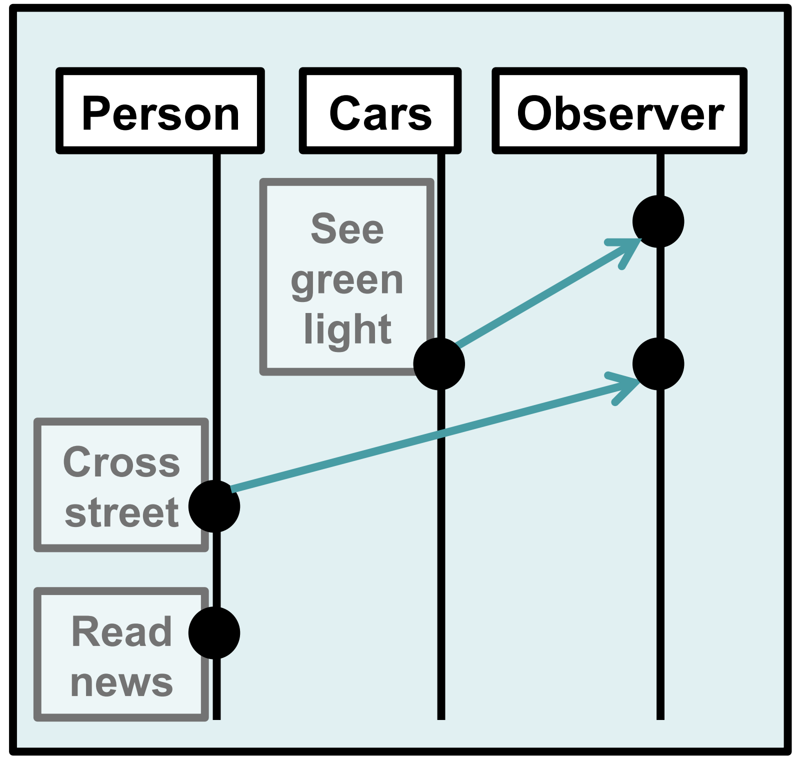
Partial Ordering of Events

- **“Happened Before” Relation (→)**
  - **Asymmetric:** If **a→b**, then **b\→a**
    - If **a** and **b** are in same process
      - **a→b** if **a** occurs before **b**
    - If **a** and **b** are in different processes
      - **a→b** if **a** is sending of message and **b** is receipt of message
    - If **a** is **concurrent** with **b**
      - **a\→b** and **b\→a**
  - **Transitive:** If **a→b** and **b→c**, then **a→c**
  - **Reflexive:** **a\→a**

Time, Clocks, and the Ordering of Events in a Distributed System

Partial Ordering of Events

- **Typical Space-Time Diagram for a Distributed System**



Outline

- Partial Ordering of Events
- **Logical Clocks**
- Total Ordering of Events
- Anomalous Behavior
- Physical Clocks

Logical Clocks

- **Process Clock C_i**
  - Clock assigns number to event to represent time
    - Assigns $\mathbf{C_i(a)}$ to each event **a** within $\mathbf{P_i}$
    - Belongs to one process $\mathbf{P_i}$
- **System Clock C**
  - Clock $\mathbf{C(a) = C_i(a)}$

Logical Clocks

- **Clock Condition**: If **a→b**, then **C(a) < C(b)**
  - If events **a** and **b** are in the same process $\mathbf{P_i}$
    - $\mathbf{C_i(a)<C_i(b)}$
      - if **a** occurs before **b**
  - If events **a** and **b** are in processes $\mathbf{P_i}$ and $\mathbf{P_j}$
    - $\mathbf{C_i(a)<C_j(b)}$
      - **a** is the sending of a message
      - **b** is the receipt of the message

Outline

- Partial Ordering of Events
- Logical Clocks
- **Total Ordering of Events**
- Anomalous Behavior
- Physical Clocks

Total Ordering of Events

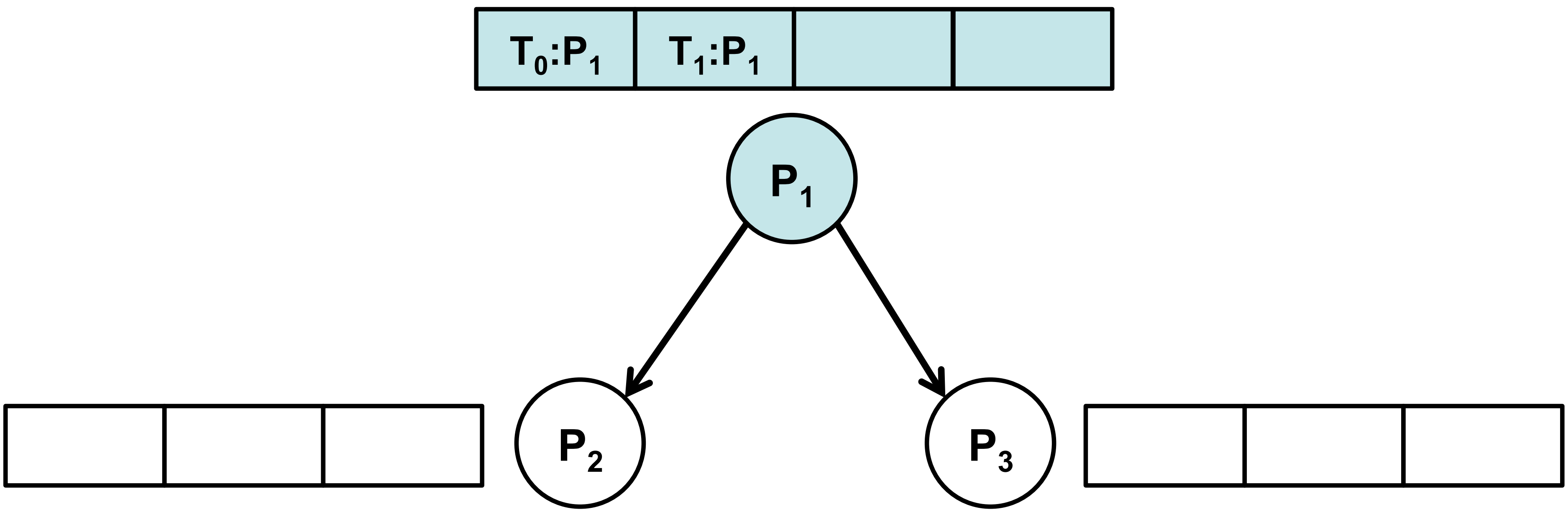
- **Total ordering eliminates concurrency**
- **Identify message with event sending it**
- **Following Example**
  - Multiple processes compete for resource
  - Told from point of view of one process P_i

Total Ordering of Events

- **Process P_i is granted resource**
  - **Request T_m:P_i**
    - In **P_i**'s request queue
    - Time-stamped before other requests in the queue
  - **Acknowledge T_m:P_i**
    - Received from **P_j**
    - Time-stamped later than **Request T_m:P_i**

Total Ordering of Events

- **Step 1: P_i Sends Request Resource**
  - **P_i** sends **Request T_m:P_i** to **P_j**
  - **P_i** puts **Request T_m:P_i** on its request queue



Total Ordering of Events

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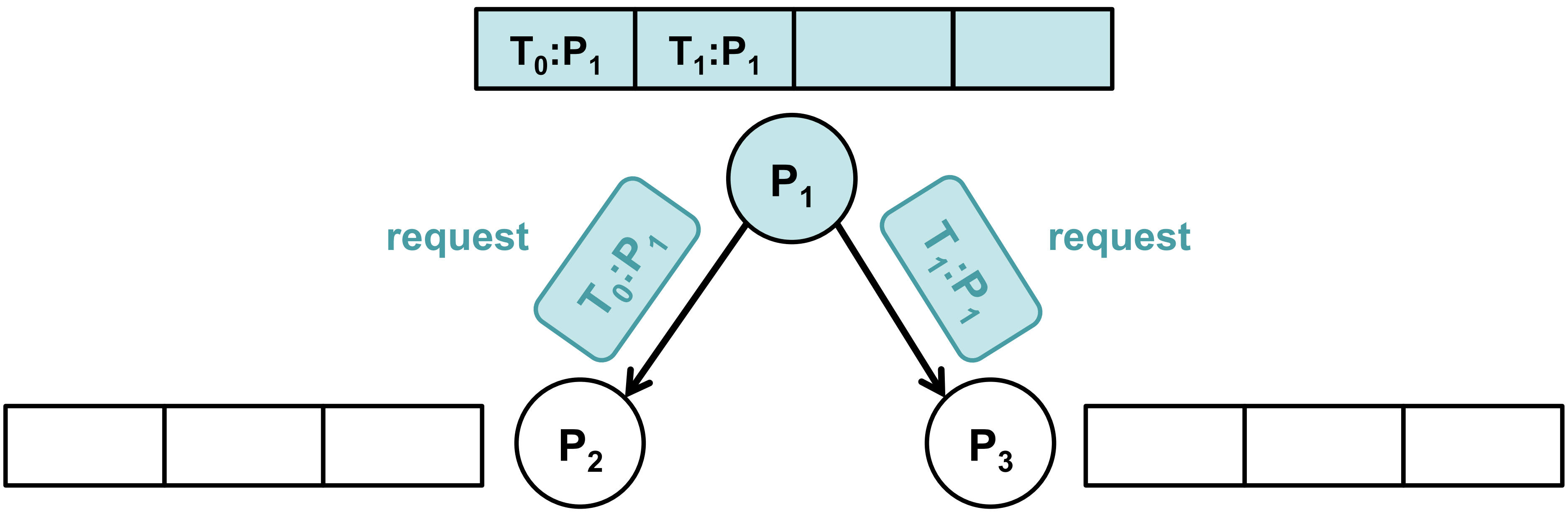
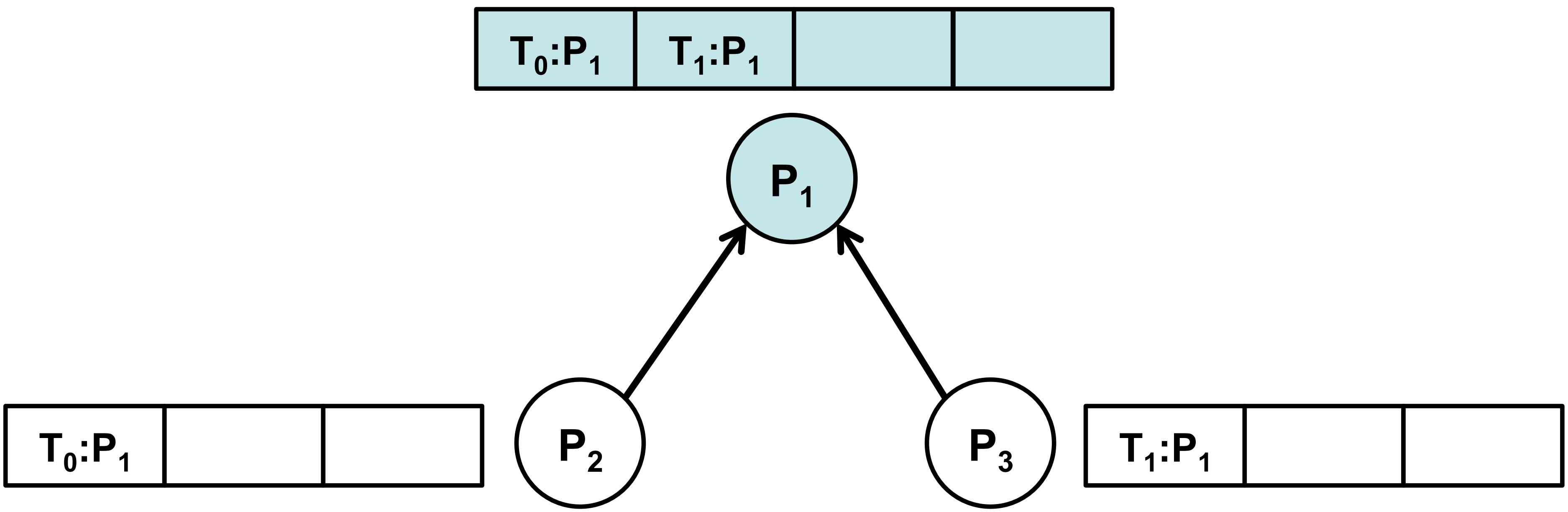
  - P_i sends **Request T_m:P_i** to P_j
  - P_i puts **Request T_m:P_i** on its request queue



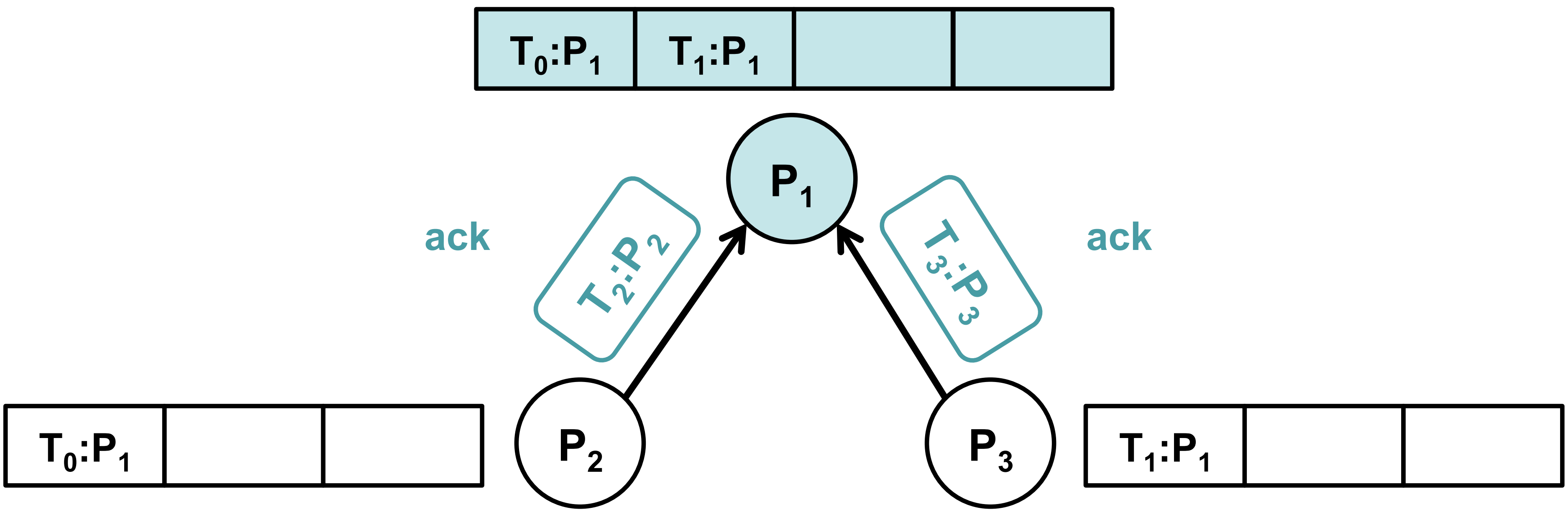
Total Ordering of Events

- **Step 2: P_j Adds Message**
  - **P_j** puts **Request T_m:P_i** on its request queue
  - **P_j** sends **Acknowledgement T_m:P_j** to **P_i**



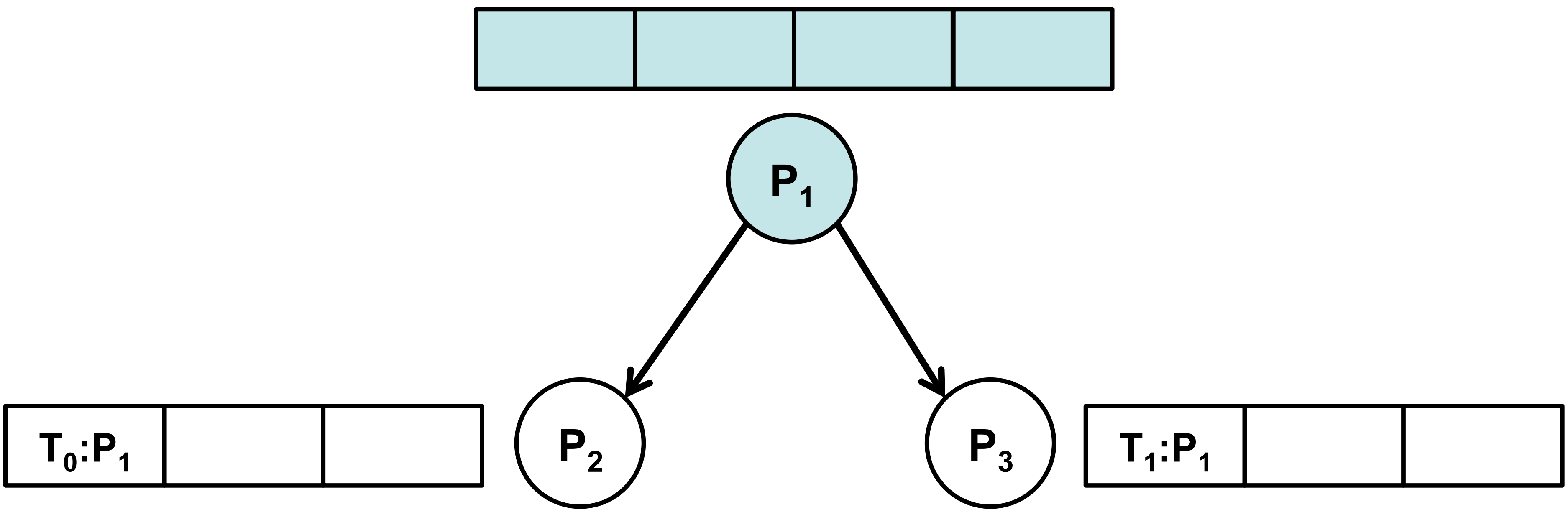
Total Ordering of Events

- **Step 2: P_j Adds Message**
  - P_j puts **Request T_m:P_i** on its request queue
  - P_j sends **Acknowledgement T_m:P_j** to P_i



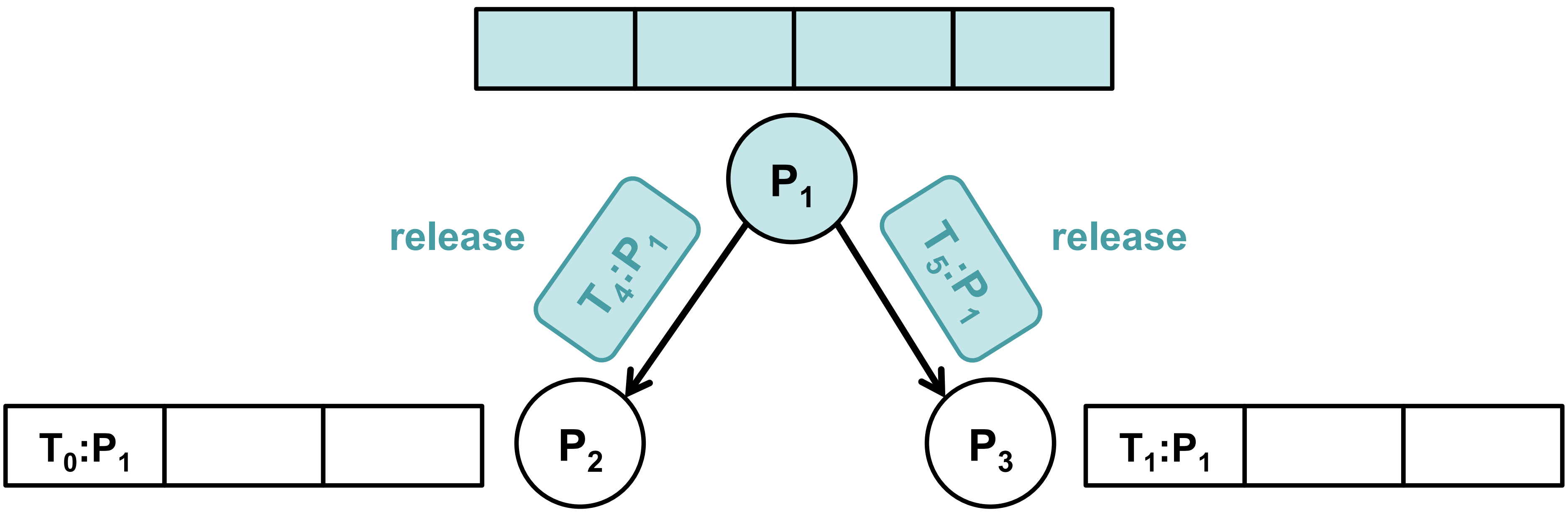
Total Ordering of Events

- **Step 3: P_i Sends Release Resource**
  - **P_i** removes **Request T_m:P_i** from request queue
  - **P_i** sends **Release T_m:P_i** to each **P_j**



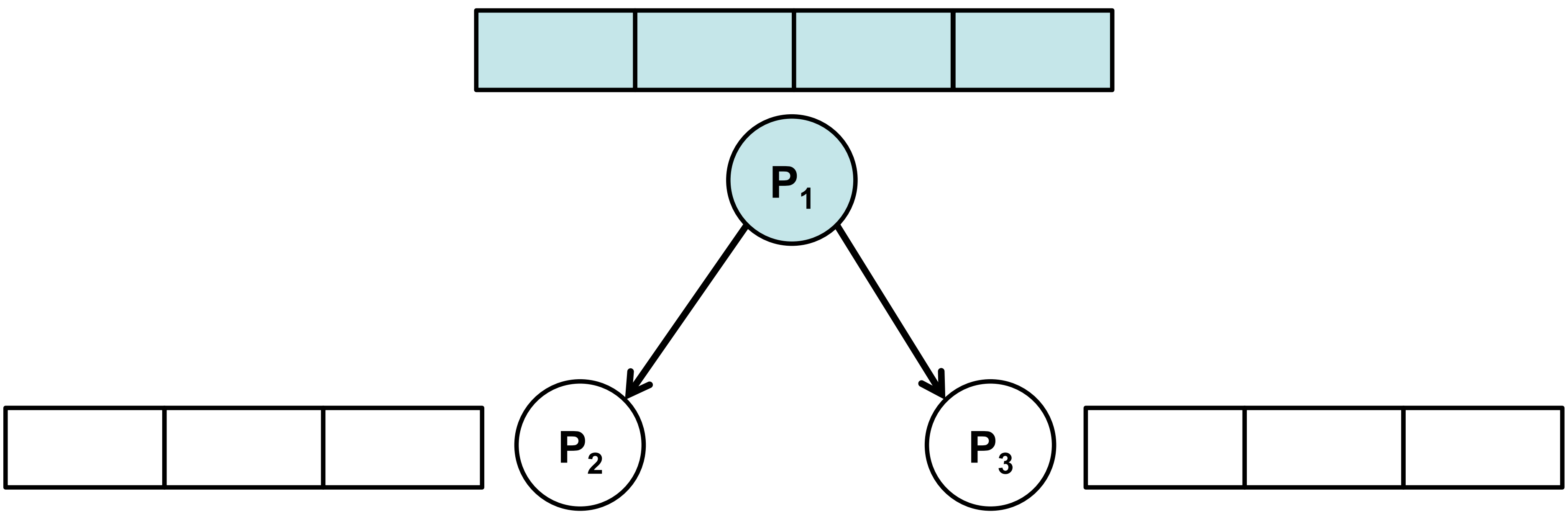
Total Ordering of Events

- **Step 3: P_i Sends Release Resource**
  - P_i removes **Request T_m:P_i** from request queue
  - P_i sends **Release T_m:P_i** to each P_j



Total Ordering of Events

- **Step 4: P_j Removes Message**
  - P_j receives **Release T_m:P_i** from **P_i**
  - P_j removes **Request T_m:P_i** from request queue



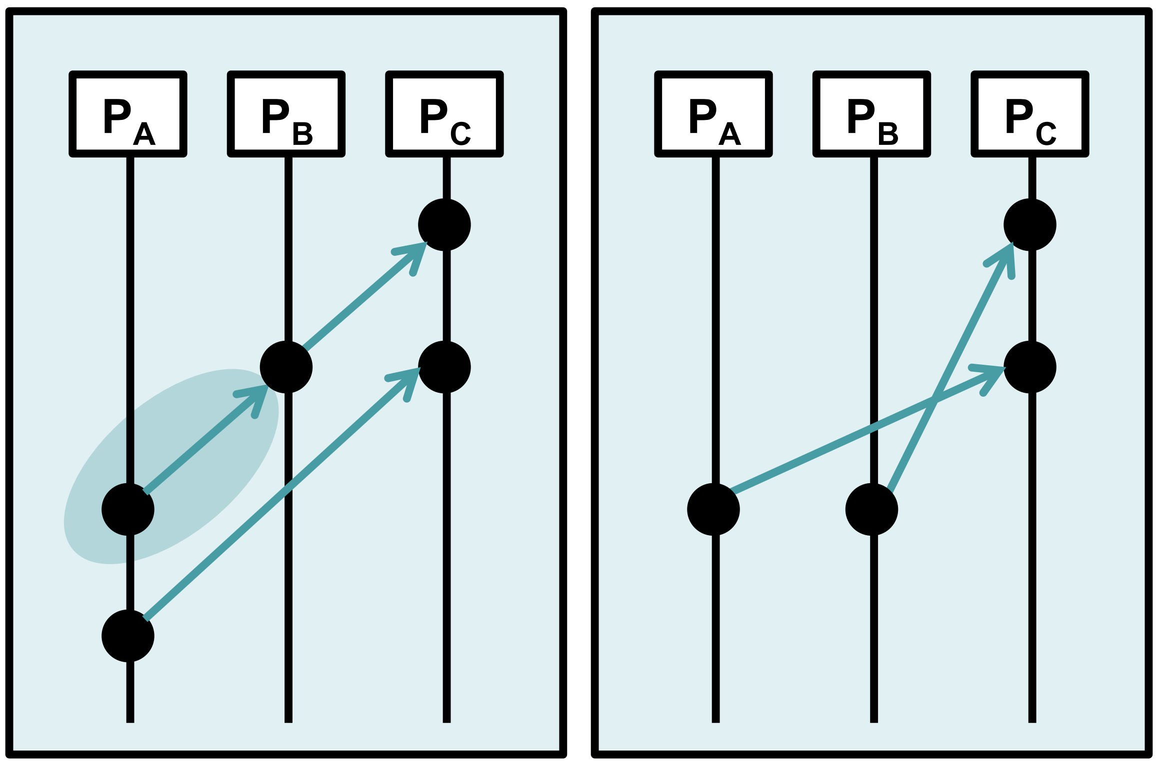
Outline

- Partial Ordering of Events
- Logical Clocks
- Total Ordering of Events
- **Anomalous Behavior**
- Physical Clocks

Anomalous Behavior

- **Discrepancy between universe/system**
  - Event sets and "happens before" relations

Universal
Event Set
S: **a→b**



System
Event Set
S: **a\→b**
and **b\→a**

Time, Clocks, and the Ordering of Events in a Distributed System

Anomalous Behavior

- **Strong Clock Condition**
  - For events **a** and **b** in system event set **S**
  - If **a➔b**, Then **C(a)<C(b)**
  - Attainable via physical clocks

Outline

- Partial Ordering of Events
- Logical Clocks
- Total Ordering of Events
- Anomalous Behavior
- **Physical Clocks**

Physical Clocks

- **Physical Clock $C_i(t)$**
  - **PC1**
    - **$\kappa \ll 1$** for all i: **$| dC_i(t)/dt - 1 | < \kappa$**
  - **PC2**
    - **ϵ** for all i,j: **$| C_i(t) - C_j(t) | < \epsilon$**
  - **Also**
    - **$\mu <$** smallest transmission time

Physical Clocks

- **Prevent anomalous behavior**
  - Must ensure that $\mathbf{C_j(t) < C_i(t+\mu)}$
  - How small must κ and ϵ be? $\boldsymbol{\epsilon/(1-\kappa) < \mu}$

Discussion

- **Partial ordering**
- **Total ordering**
- **Anomalous Behavior**
- **Physical clocks**

Conclusions

- **Coordination of Distributed Systems**
- **Partial Ordering of Events**
- **Total Ordering of Events**

Distributed Snapshots: Determining Global States of Distributed Systems

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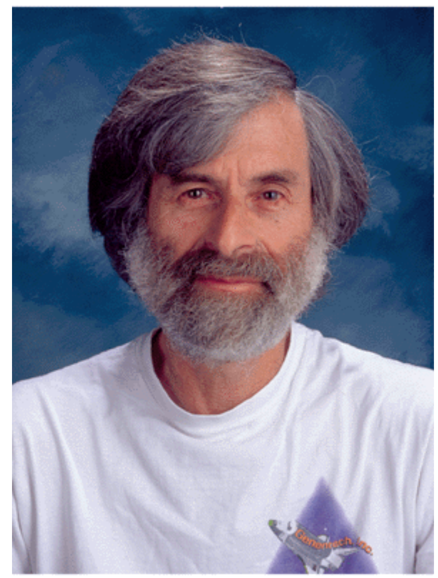


Introduction

- **Panoramic dynamic scene**
  – Cannot capture with single snapshot
  – Must piece together multiple snapshots
- **Questions**
  – How should snapshots be taken?
  – What criteria must overall picture satisfy?

Introduction

- **Process can record its own state**
- **States of all processes form global state**
- **Record valid global system state**
- **Detect stable properties**
  - **y(S) = true** implies
  - **y(**all states reachable from **S) = true**

Outline

- **Distributed System Model**
- Global State Detection Algorithm
- Recorded Global State Properties
- Stability Detection

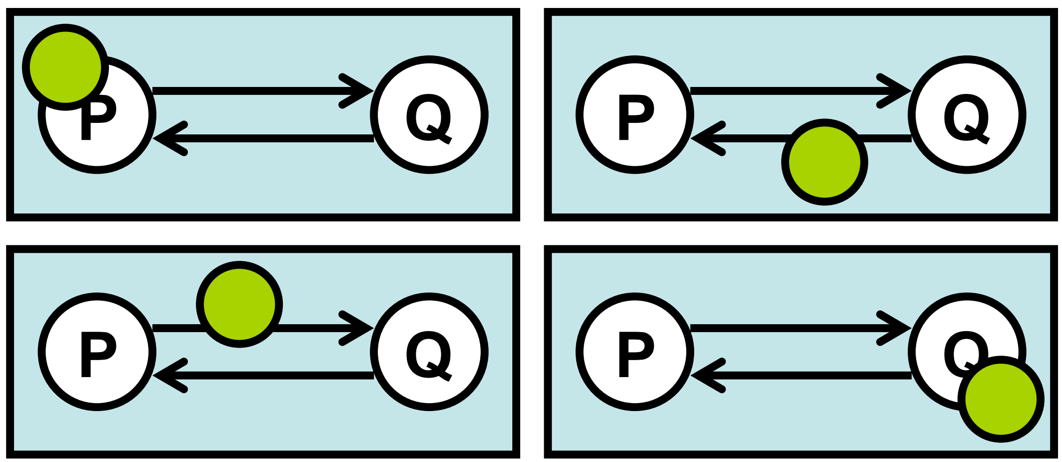
Distributed System Model

- **Process**
  - State(t)
  - Event(t)
- **Channel**
  - MessagesSent(t)
  - Event(t)
- **Event**
  - Process P
    - State S before
    - State S' after
  - Channel C (incoming or outgoing from P)
    - Messages (received by P or sent from P)

Distributed System Model

- **Example 1: Single Token System**

States
Global: in-P
P : sI
C : empty
C': empty
Q : sO



States
Global: in-C'
P : sO
C : empty
C': token
Q : sO

Event
P sends

States
Global: in-C
P : sO
C : token
C': empty
Q : sO

Event
Q sends

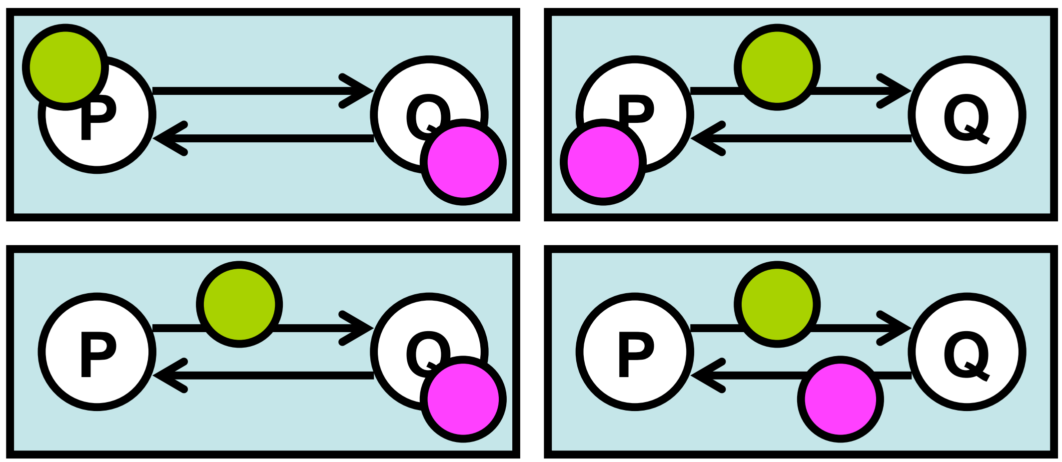
States
Global: in-Q
P : sO
C : empty
C': empty
Q : sI

Event
Q receives

Distributed System Model

- **Example 2: Nondeterministic System**

States
Global: S0
P : sI
C : empty
C’: empty
Q : sI



States
Global: S3
P : sI
C : M
C’: empty
Q : sO

Event
P sends
M

States
Global: S1
P : sO
C : M
C’: empty
Q : sI

Event
Q sends
M’

States
Global: S2
P : sO
C : M
C’: M’
Q : sO

Event
P receives
M’

Outline

- Distributed System Model
- **Global State Detection Algorithm**
- Recorded Global State Properties
- Stability Detection

Algorithm

- **Marker Sending Rule**
  - P records its state
  - P sends marker along each outgoing channel C
- **Marker Receiving Rule**
  - Q receives a marker along incoming channel C
  - If Q has not recorded its state
    - Q records its state
  - Else
    - Q records C's state as a sequence of messages

Algorithm

- **Example: Process P Obtains Global State from Process Q**
  - Q receives P's marker along channel C
  - Q records its state
  - Computation
  - Q receives P's marker along channel C
  - Q records C's state

Outline

- Distributed System Model
- Global State Detection Algorithm
- **Recorded Global State Properties**
- Stability Detection

Recorded Global State Properties

- **Markers produce concurrent subsequence**
  - S* may not actually exist
  - S* from combination of concurrent events
- **No effect on preceding/following events**
  - S* reachable from S_i
  - S_o reachable from S*

Recorded Global State Properties

- **Theorem 1: Exists Computation $\{e_0' \ldots e_n'\}$**
  - **Events**
    - $\{ e_0' \ldots e_i -1' \}$ is equivalent to $\{ e_0 \ldots e_i -1 \}$
    - $\{ e_i' \ldots e_o -1' \}$ is a permutation of $\{ e_i \ldots e_o -1 \}$
    - $\{ e_o' \ldots e_n' \}$ is equivalent to $\{ e_o \ldots en \}$
  - **States**
    - $\{ S_0' \ldots S_i' \}$ is equivalent to $\{ S_0 \ldots S_i \}$
    - For some k, where $i<k<o$, $S_k' = S^*$
    - $\{ S_o' \ldots S_n' \}$ is equivalent to $\{ S_o \ldots S_n \}$

Outline

- Distributed System Model
- Global State Detection Algorithm
- Recorded Global State Properties
- **Stability Detection**

Stability Detection

- **Algorithm**
  - **Initialize:** definite=false, $y(S_i)$=definite
  - **Repeat:** record S*, definite=y(S*)
- **Implications of "definite"**
  - **definite == false:** no stable property at start
  - **definite == true:** stable property at termination
- **Correctness**
  - S_i can lead to S*, S* can lead to S_o
  - for all j: $y(S_j) = y(S_j+1)$

Discussion

- Partial Ordering
- Recorded Global State
- Global State Detection Algorithm
- Stable Property Detection

Conclusions

- **Processes form recorded global state**
  – Record its own state
  – Piece together multiple records
- **Questions addressed**
  – How should the snapshots be taken?
  – What criteria must overall picture satisfy?