Distributed System Fundamentals

Jingzhu He

Agenda

I. Synchronous versus Asynchronous systems
II. Lamport clocks and vector clocks
III. Global Snapshots
IV. Impossibility of Consensus proof

Two Different System Models

- *Synchronous* Distributed System
  - Each message is received within bounded time
  - Drift of each process' local clock has a known bound
  - Each step in a process takes lb < time < ub
  - *Ex:A collection of processors connected by a communication bus, e.g., a Cray supercomputer*
- *Asynchronous* Distributed System
  - No bounds on process execution
  - The drift rate of a clock is arbitrary
  - No bounds on message transmission delays
  - *Ex: The Internet is an asynchronous distributed system*
- *This is a more <u>powerful</u> model than the synchronous system model. A protocol for an asynchronous system will also work for a synchronous system (though not vice-versa)*
- It would be ***im***possible to accurately synchronize the clocks of two communicating processes in an asynchronous system

Two Different Clocks

- Physical clocks
  - Time-of-day clocks: time since a fixed date (e.g., 1 January 1970 epoch)
  - Monotonic clocks: time since arbitrary point (e.g., when machine booted up)

- Logic clocks
  - Lamport clocks
  - vector clocks

- *Why do we need clocks in distributed systems?*

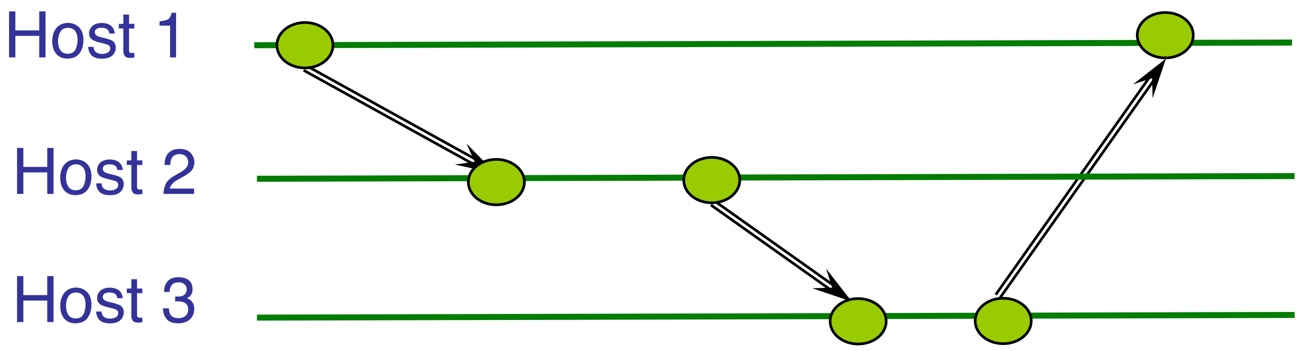
Logic Clocks

- But is accurate (or approximate) clock sync. even required?
- Wouldn't a **logical ordering** among events at processes suffice?
- Lamport's **happens-before** ($\rightarrow$) among **events**:
  - On the same process: $a \rightarrow b$, if $time(a) < time(b)$
  - If p1 sends *m* to p2: $send(m) \rightarrow receive(m)$
  - If $a \rightarrow b$ *and* $b \rightarrow c$ then $a \rightarrow c$ (can we say $a \rightarrow a$?)
- Lamport's **logical timestamps** preserve causality:
  - All processes use a **local counter** (logical clock) with initial value of zero
  - Just before each **event**, the local counter is incremented by 1 and assigned to the event as its timestamp
  - A *send (message)* event carries its timestamp
  - For a *receive (message)* event, the counter is updated by

    max(receiver's-local-counter, message-timestamp) + 1

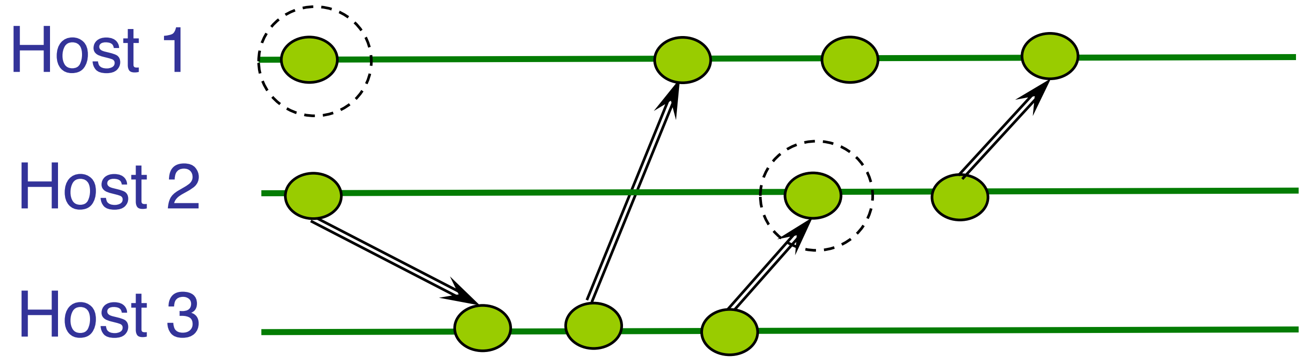
Lamport Timestamps

- *Logical timestamps preserve causality of events,*
  i.e., $a \rightarrow b \implies TS(a) < TS(b)$
- *Can be used instead of physical timestamps*



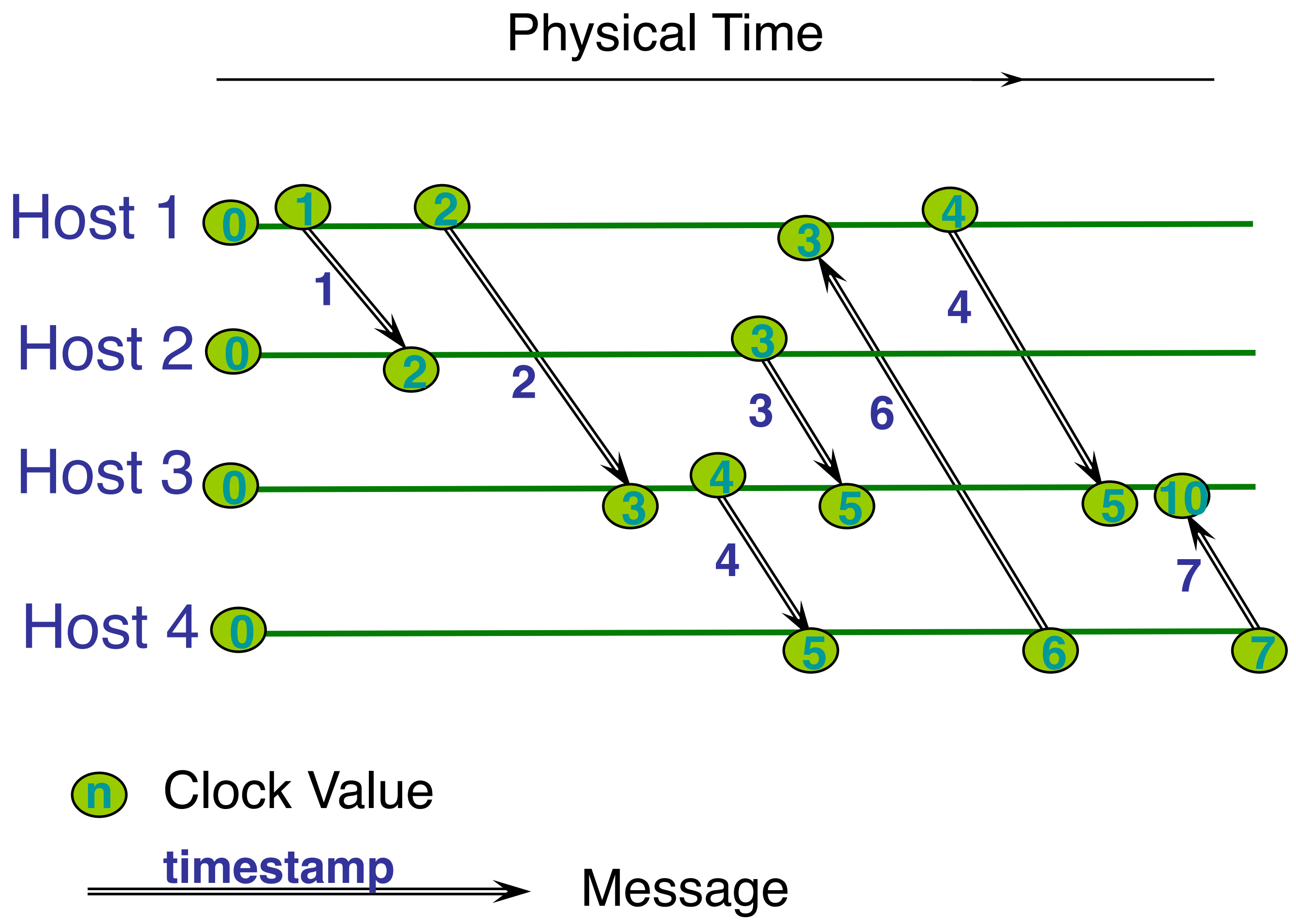
Lamport Timestamps

- $a \rightarrow b \implies TS(a) < TS(b)$
- Does $TS(a) < TS(b) \implies a \rightarrow b$ hold?

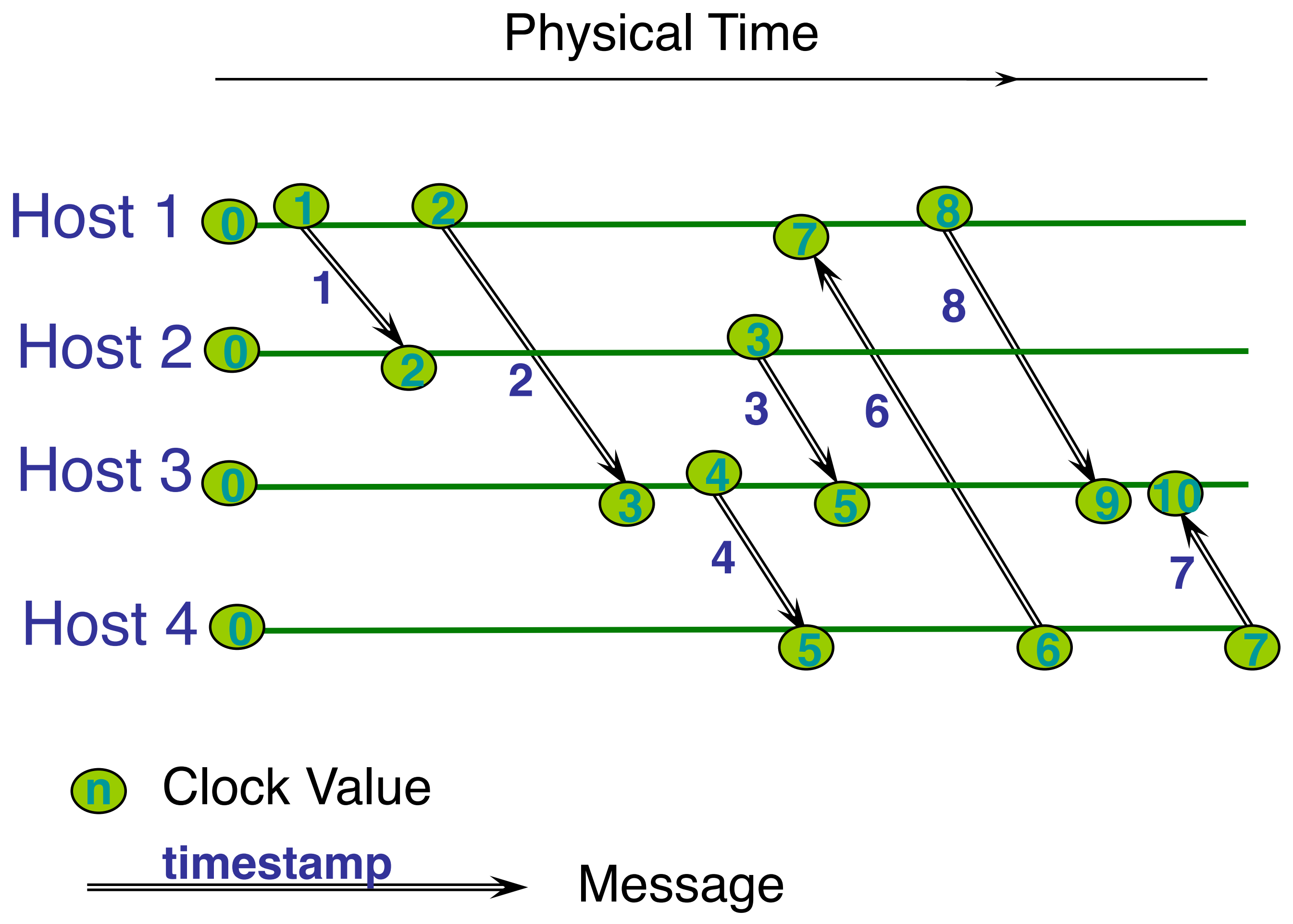


- $TS(a) \geq TS(b) \implies a \nrightarrow b$

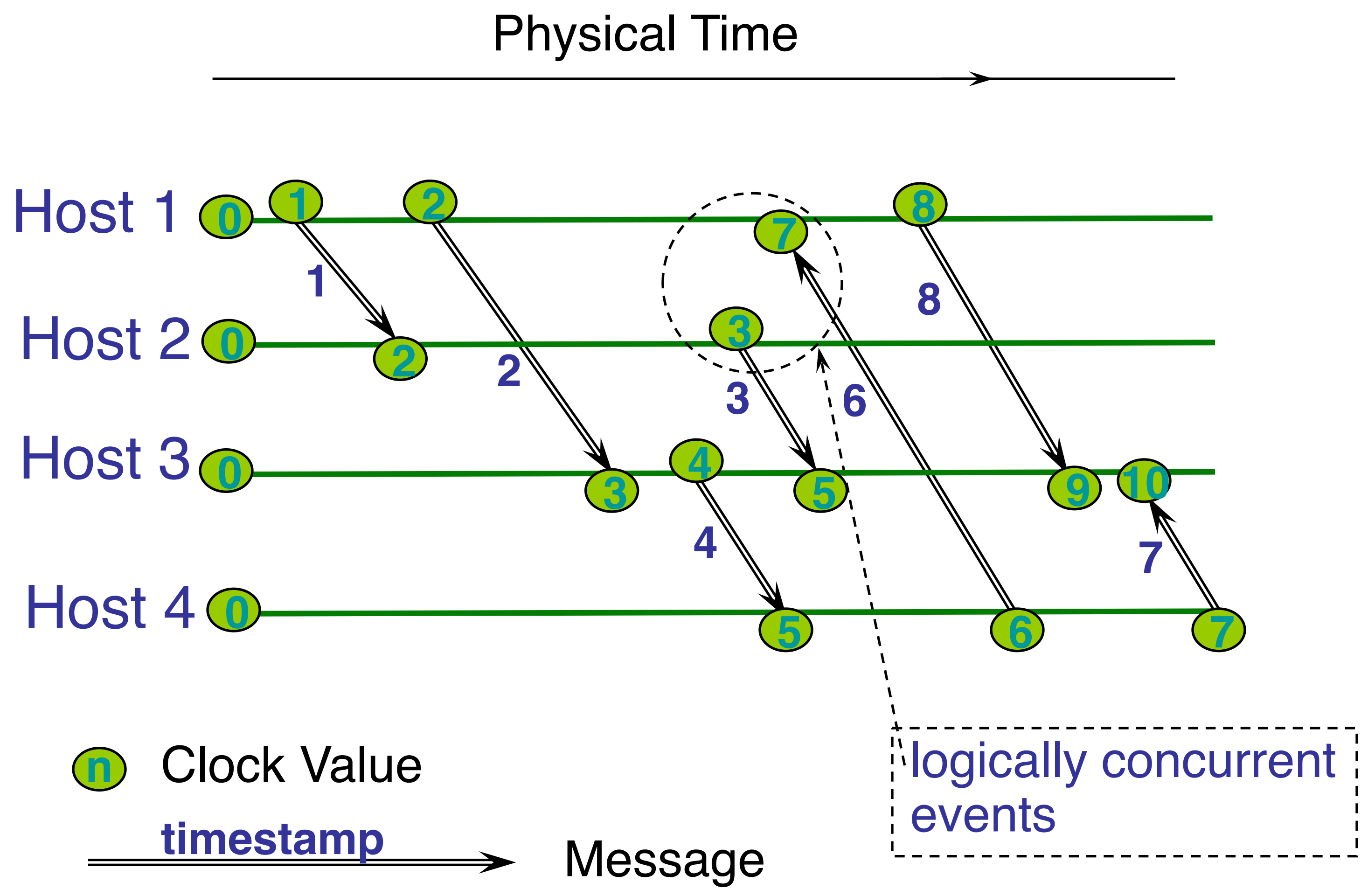
Spot the Mistake



Corrected Example: Lamport Logical Time



Corrected Example: Lamport Logical Time



•$a \rightarrow b \implies TS(a) < TS(b)$ *but not the other way around*

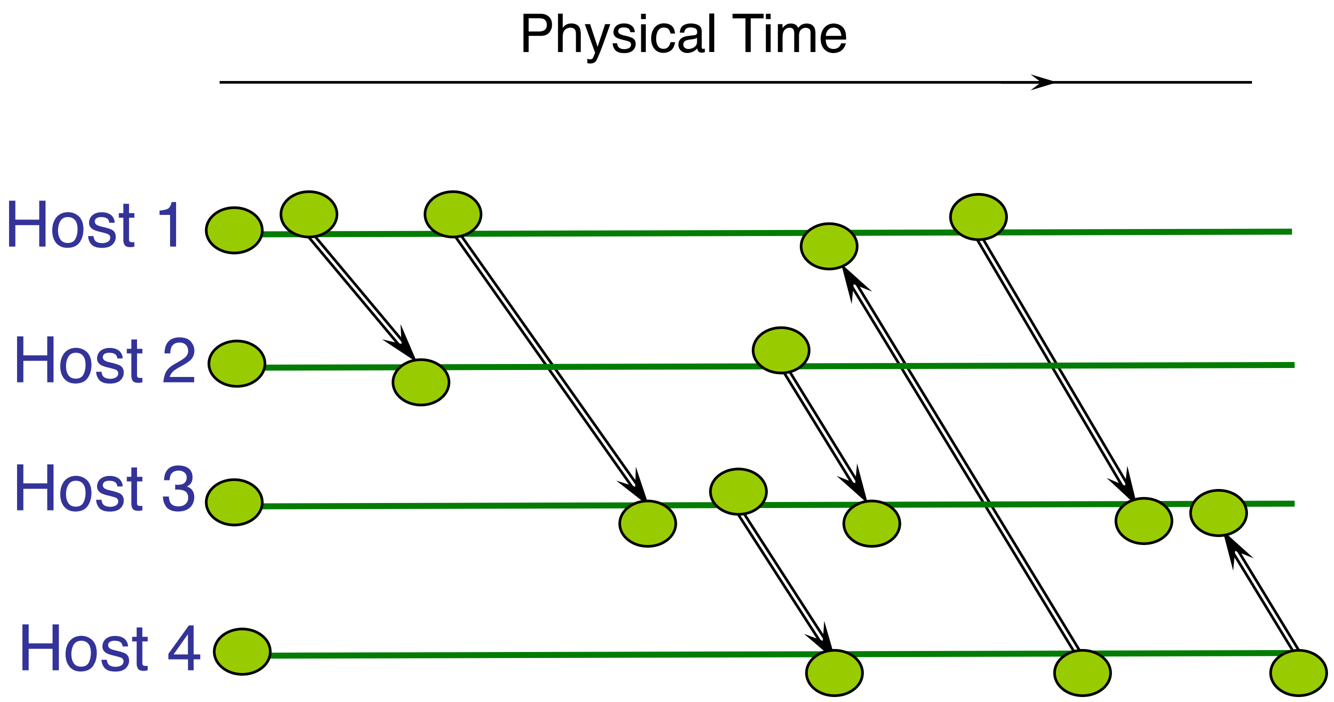
•*Logical time does not account for out-of-band messages*

Vector Clocks

- Lamport clock:
  - $a \rightarrow b ==> TS(a) < TS(b)$
  - Only **one** integer

- Vector clock:
  - $a \rightarrow b <==> VC(a) < VC(b)$
  - All processes use a **vector of integers** (vector size equal to number of processes) with all elements initialized to zeroes
  - Just before each **event**, a process increments its own position by 1 in its vector clock
  - A *send (message)* event carries its current vector clock
  - For a *receive (message)* event, a process increments its own position by 1 and updates its vector clock to max(receiver's-local-counter, message-clock)

Vector Clock Example



Message

- $VC(a) < VC(b) \Longleftrightarrow a \rightarrow b$
- $VC(a) \nless VC(b) \Longleftrightarrow a \mathbin{?} b$

III. Global Snapshot Algorithm

- Can you capture (record) the states of all processes and communication channels at exactly 10:04:50 am?
- Is it necessary to take such an exact snapshot?
- Chandy and Lamport snapshot algorithm: records a *logical (or causal)* snapshot of the system.
- *System Model:*
  - No failures, all messages arrive intact, exactly once, eventually
  - Communication channels are unidirectional and FIFO-ordered
  - There is a communication path between every process pair

Chandy and Lamport Snapshot Algorithm

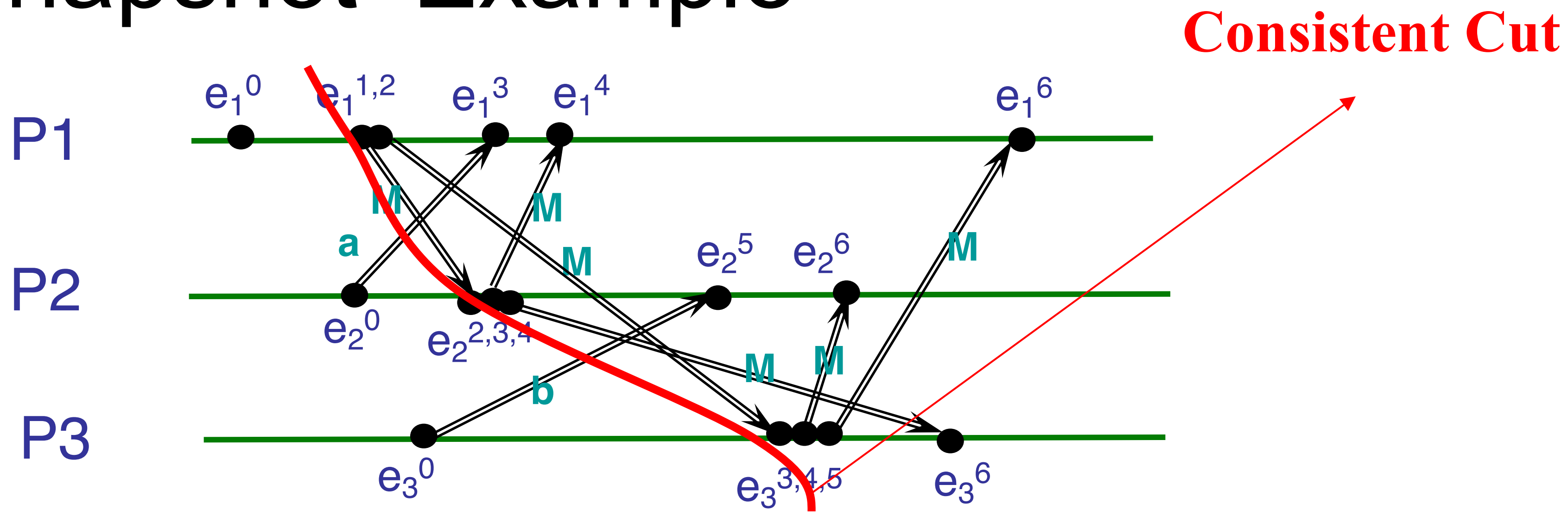
1. *Marker (token message) sending rule for initiator process P_0*
   - After P_0 has recorded its state
     - for each outgoing channel C, send a marker on C
     - turn on recording of messages on each incoming channel

2. *Marker receiving rule for a process P_k :*

   On receipt of a marker over channel C
   - *if this is first marker being received at P_k*
     - record P_k's state
     - record the state of C as "empty"
     - turn on recording of messages over all other incoming channels
     - for each outgoing channel C, send a marker on C
   - *else*
     - turn off recording messages only on channel C, and mark state of C as all the messages recorded over C

- Protocol terminates when every process has received a marker from every other process

Snapshot Example



1- P1 initiates snapshot: records its state (S1); sends Markers to P2 & P3; turns on recording for channels C21 and C31

2- P2 receives Marker over C12, records its state (S2), sets state(C12) = {} sends Marker to P1 & P3; turns on recording for channel C32

3- P1 receives Marker over C21, sets state(C21) = {a}

4- P3 receives Marker over C13, records its state (S3), sets state(C13) = {} sends Marker to P1 & P2; turns on recording for channel C23

5- P2 receives Marker over C32, sets state(C32) = {b}

6- P3 receives Marker over C23, sets state(C23) = {}

7- P1 receives Marker over C31, sets state(C31) = {}

Consistent Cut =time-cut across processors and channels so no event after the cut "happens-before" an event before the cut

Centralized vs. Decentralized Algorithm

1. Do multiple initiators work using the algorithm?

2. Is the algorithm centralized or decentralized?

3. Decentralized algorithm:
   - multiple initiators (e.g., Chandy-Lamport, Paxos)

4. Centralized algorithm:
   - Exact one initiator

IV. Give it a thought

Have you ever wondered why distributed server vendors always only offer solutions that promise five-9's reliability, seven-9's reliability, but never 100% reliable?

The fault lies in the impossibility of consensus

What is Consensus?

- N processes
- Each process p has
  - input variable xp : initially either 0 or 1
  - output variable yp : initially b
- Consensus problem: design a protocol so that either
  - all processes set their output variables to 0
  - Or all processes set their output variables to 1
  - There is at least one initial state that leads to each outcome above

Why is Consensus Important

- Many problems in distributed systems are equivalent to *(or harder than)* consensus!
  - Agreement (harder than consensus, since it can be used to solve consensus)
  - Leader election (select exactly one leader, and every alive process knows about it)
  - Failure Detection
- Consensus using leader election

  Choose 0 or 1 based on the last bit of the identity of the elected leader.

Properties of Consensus

- **Termination**: each non-faulty process eventually decides a value
- **Agreement**: all non-faulty processes decide on the same value
- **Validity**: the agreed-upon value must be one of the proposed value

Let’s Try to Solve Consensus!

- Uh, what’s the **model**? (assumptions!)
- Synchronous system: bounds on
  - Message delays
  - Max time for each process step

  e.g., multiprocessor (common clock across processors)
- Asynchronous system: no such bounds!

  e.g., The Internet! The Web!
- Processes can fail by stopping (crash-stop failures)

Consensus in a Synchronous System

[Fischer, Lynch 82]

Possible to achieve!

- For a system with at most *f* processes crashing
  - All processes are synchronized and operate in "rounds" of time
  - the algorithm proceeds in $f+1$ rounds (with timeout), using reliable communication to all members - $Values^r_i$: the set of proposed values known to P_i at the beginning of round r.

```
- Initially $Values^0_i = \{\}$ ; $Values^1_i = \{v_i\}$
    for round = 1 to f+1 do
        multicast ($Values^r_i - Values^{r-1}_i$)
        $Values^{r+1}_i \leftarrow Values^r_i$
        for each $v_j$ received
            $Values^{r+1}_i = Values^{r+1}_i \cup v_j$
        end
    end
  $d_i = \text{minimum}(Values^{f+1}_i)$
```

Why does the Algorithm Work?

- Proof by contradiction.
- Assume that two non-faulty processes, say p_i and p_j , differ in their final set of values (i.e., after $f+1$ rounds)
- Assume that p_i possesses a value v that p_j does not possess.
  - → p_i must have received v in the last round (why?)
  - → A third process, p_k, sent v to p_i, and crashed before sending v to p_j.
  - → Similarly, a fourth process sending v in the last-but-one round must have crashed; otherwise, both p_k and p_j should have received v.
  - → Proceeding in this way, we infer at least one (unique) crash in each of the preceding rounds.
  - → But we have assumed at most f crashes can occur and there are $f+1$ rounds → contradiction.

Intuition of the Consensus Algorithm

- If there is NO failure, consensus can be reached after 1st round
- Only one complication: a failed process may send its value to just a subset of the intended recipients.
- If there is a failure-free round, everyone receives all messages and consensus can be reached.
- There is at least one failure-free round in $f+1$ rounds assuming f total failures

Consensus in an Asynchronous System

- Impossible to achieve!
  - even a single failed process is enough to avoid the system from reaching agreement

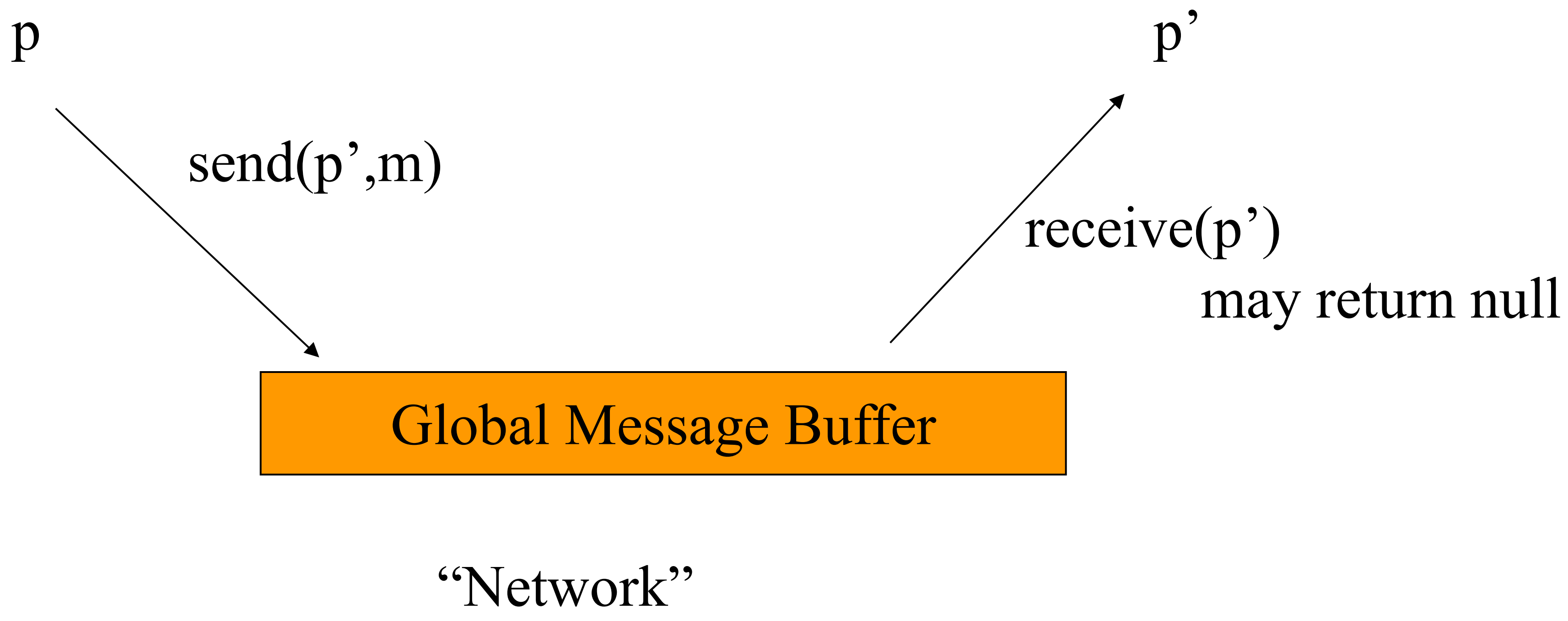
- Proved in a now-famous result by Fischer, Lynch and Patterson, 1983 (FLP) *reference:* *Impossibility of Distributed Consensus with One Faulty Process*
  - Stopped many distributed system designers dead in their tracks
  - A lot of claims of "reliability" vanished overnight

Recall

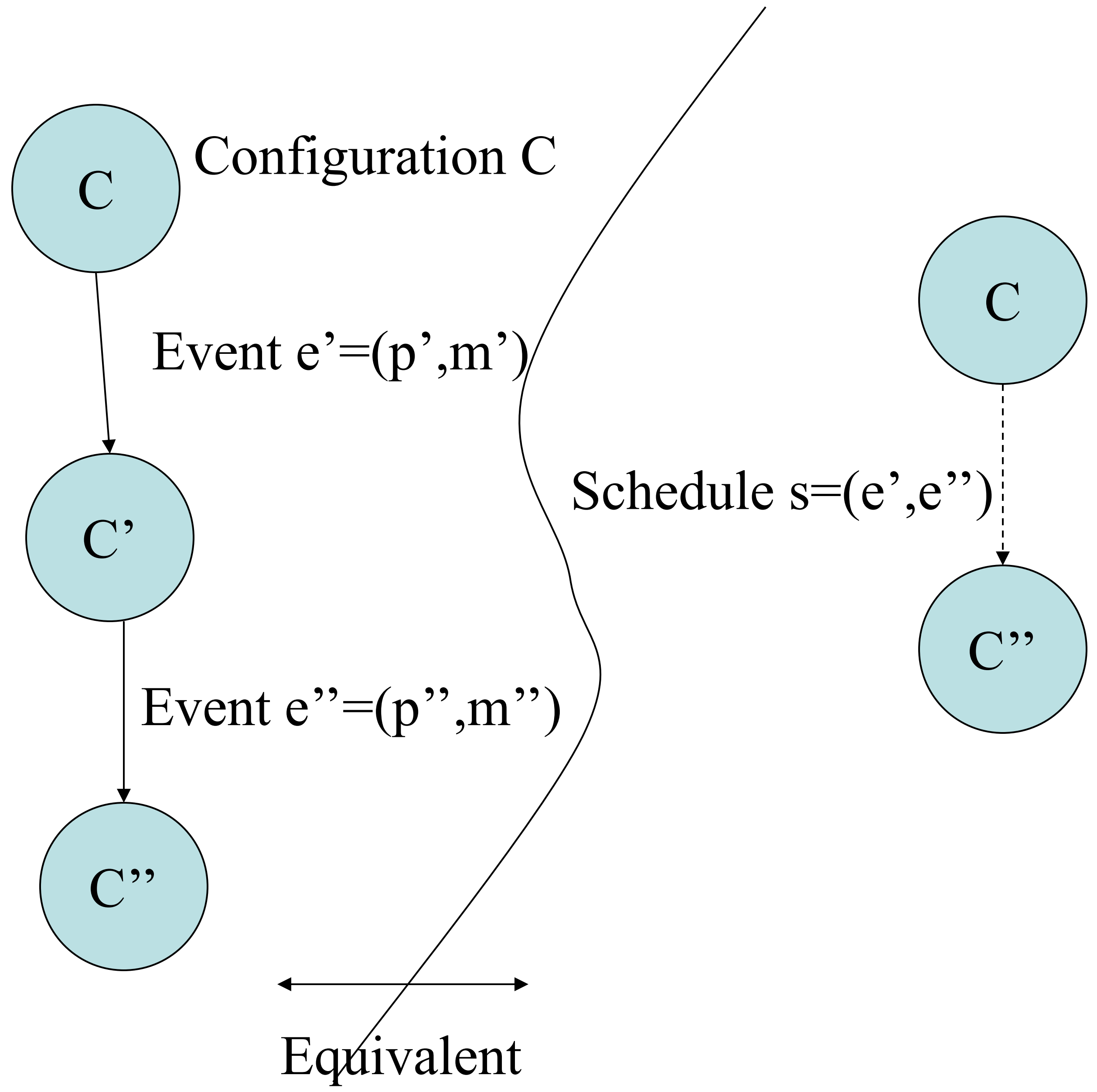
- Each process p has a state
  - program counter, registers, stack, local variables
  - input register xp : initially either 0 or 1
  - output register yp : initially b
- Consensus Problem: design a protocol so that either
  - all processes set their output variables to 0
  - Or all processes set their output variables to 1
- For impossibility proof, OK to consider (i) more restrictive system model, and (ii) easier problem

Consensus Properties in FLP

- Termination: Some non-faulty processes eventually decide values
- Validity: If all processes with 0/1, 0/1 is the only allowed decision
- Agreement: No two processes decide on different values

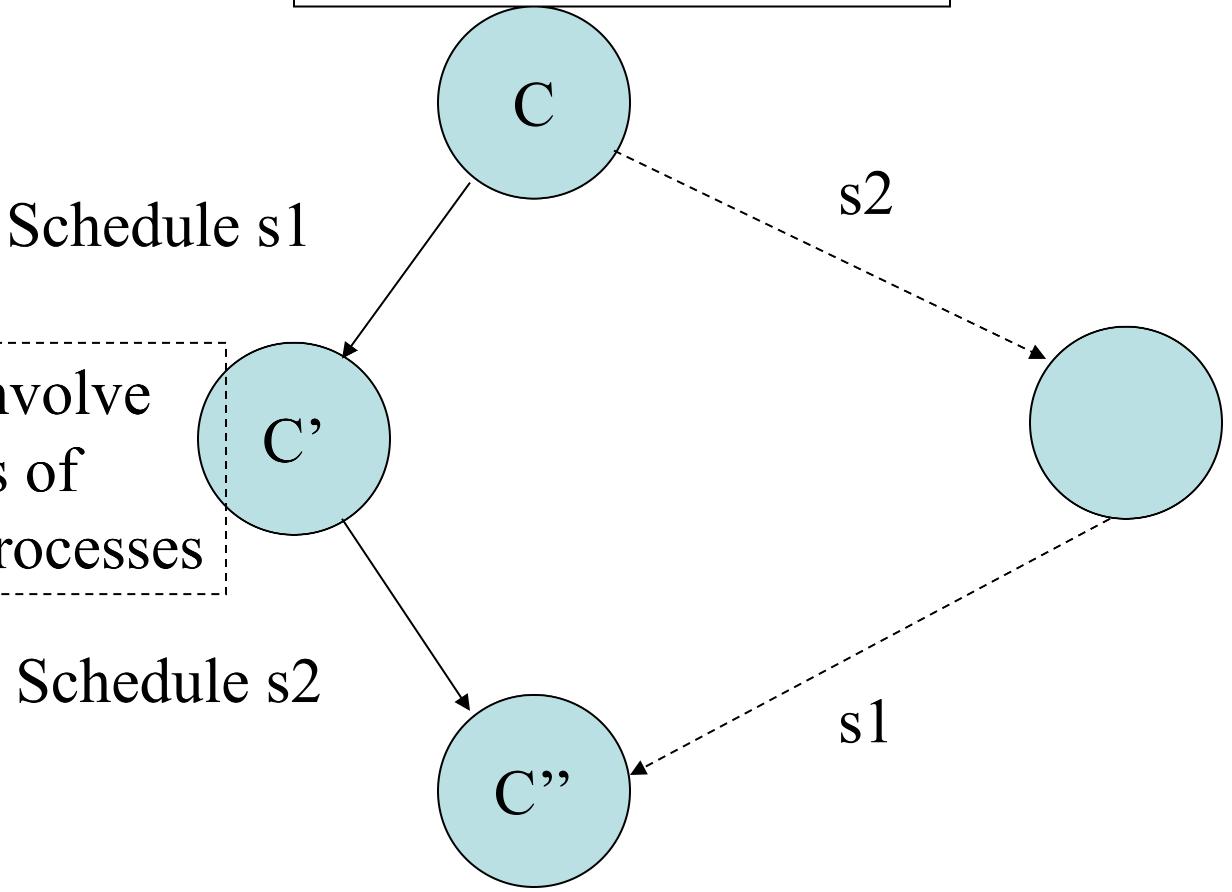

p
p'
send(p',m)
receive(p')
may return null
Global Message Buffer
"Network"

- State of a process
- **Configuration**=global state. Collection of states, one for each process; and state of the global buffer.
- Each Event (<u>different</u> from Lamport events)
  - receipt of a message by a process (say p)
  - processing of message (may change recipient's state)
  - sending out of all necessary messages by p
- Schedule: sequence of events


C
Configuration C
Event e'=(p',m')
C'
Event e''=(p'',m'')
C''
C
Schedule s=(e',e'')
C''
Equivalent

Lemma 1

Disjoint schedules are commutative



s1 and s2 involve <u>disjoint</u> sets of <u>receiving</u> processes

- Let config. C have a set of decision values V reachable from it
  - If |V| = 2, config. C is bivalent
  - If |V| = 1, config. C is 0-valent or 1-valent, as is the case

- Bivalent means outcome is unpredictable

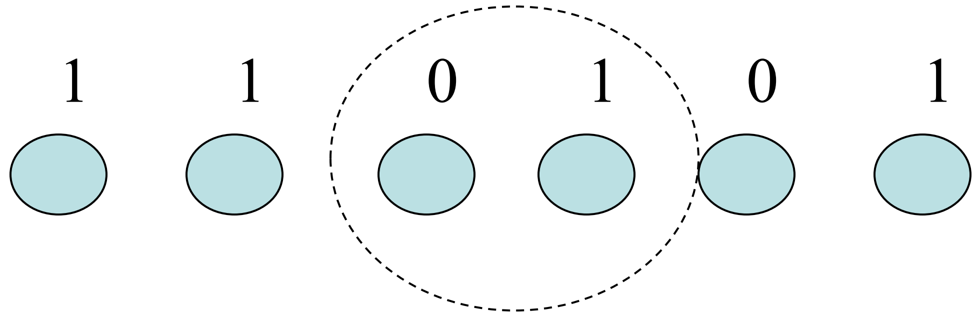
What the FLP Proof Shows

1. There exists an initial configuration that is bivalent
2. Starting from a bivalent config., there is always another bivalent config. that is reachable

Lemma 2

Some initial configuration is bivalent

- Suppose all initial configurations were either 0-valent or 1-valent.
- If there are N processes, there are *2^N* possible initial configurations
- Place all configurations side-by-side (in a lattice), where
  adjacent configurations differ in initial xp value
  for exactly one process.

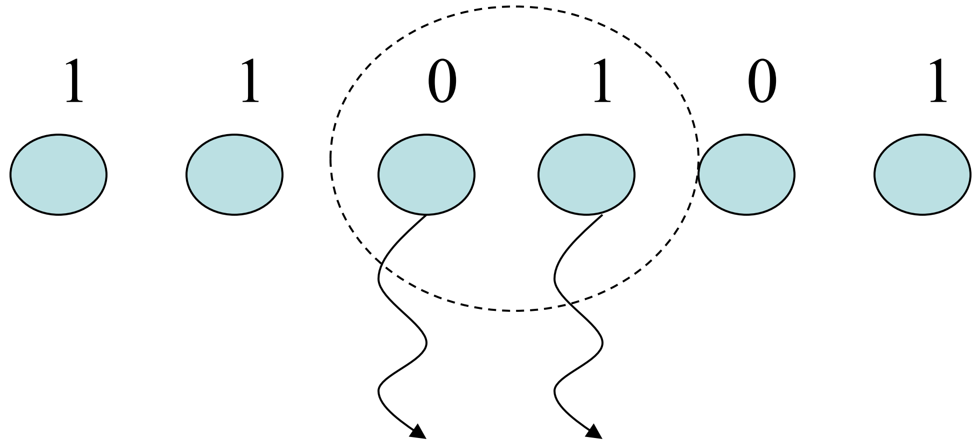


- There has to be some adjacent pair of 1-valent and 0-valent configs.

Lemma 2

Some initial configuration is bivalent

- There has to be some adjacent pair of 1-valent and 0-valent configs.
- Let the process p that has a different state across these two configs. be the process that has crashed (silent throughout)



Both initial configs. will lead to the same config. for the same sequence of events

Therefore, at least one of these initial configs. are bivalent when there is such a failure

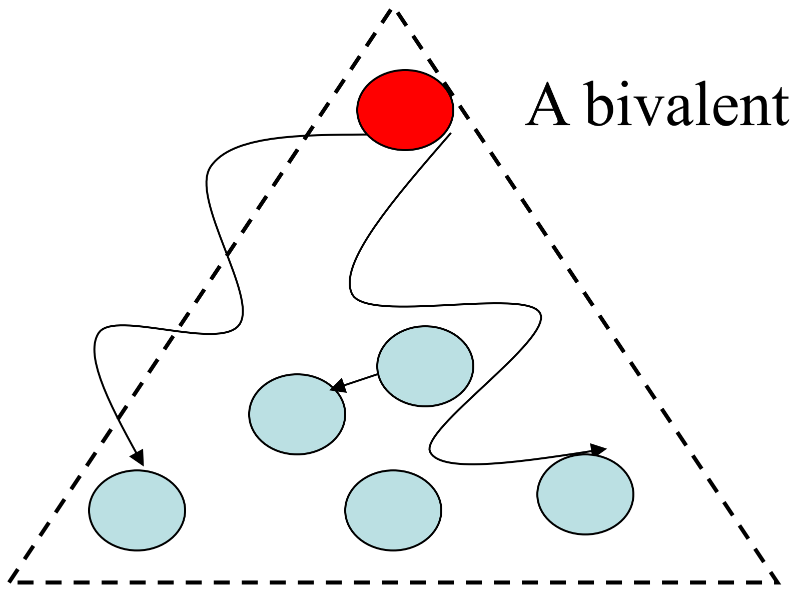
What we'll Show

1. There exists an initial configuration that is bivalent
2. Starting from a bivalent config., there is always another bivalent config. that is reachable

Lemma 3

Starting from a bivalent config., there is always another bivalent config. that is reachable

Lemma 3

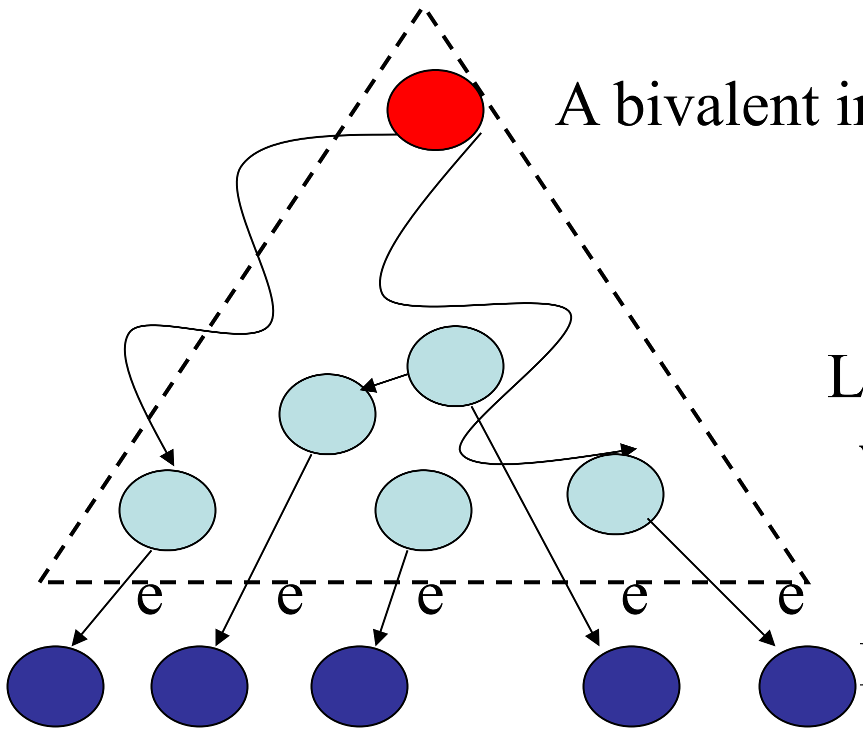


A bivalent initial config.

let e=(p,m) be an applicable event to the initial config.

Let *C* be the set of configs. reachable **without** applying e

Lemma 3



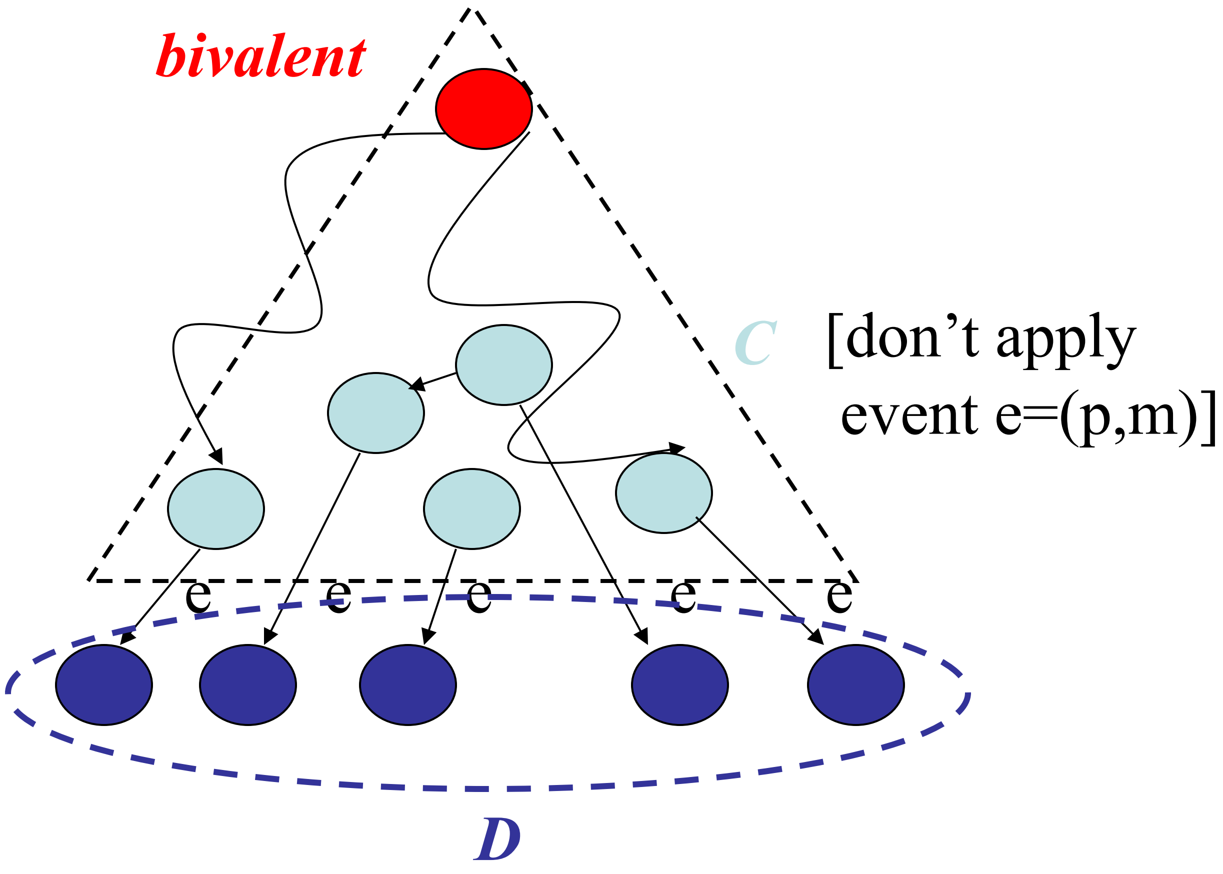
A bivalent initial config.

let e=(p,m) be an applicable event to the initial config.

Let *C* be the set of configs. reachable **without** applying e

Let ***D*** be the set of configs. obtained by **applying e** to some config. in ***C***

Lemma 3

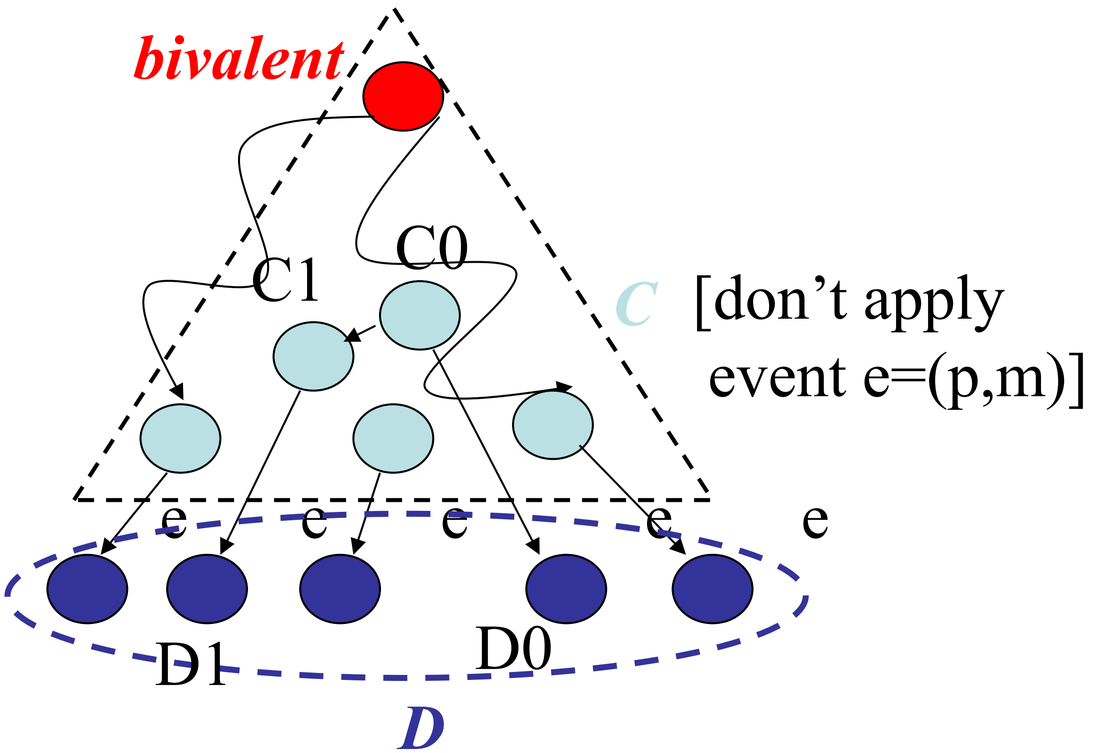


Claim. ***D*** contains a bivalent config.

Proof. By contradiction.

1. ***D*** contains both 0- and 1-valent configurations (why?)

2. There are states C0 and C1 in ***C*** such that
   C1 = C0 followed by some event e'=(**p'**,m')
   and
   – D0 is 0-valent, D1 is 1-valent
   – D0=C0 foll. by e=(p,m)
   – D1=C1 foll. by e=(p,m)

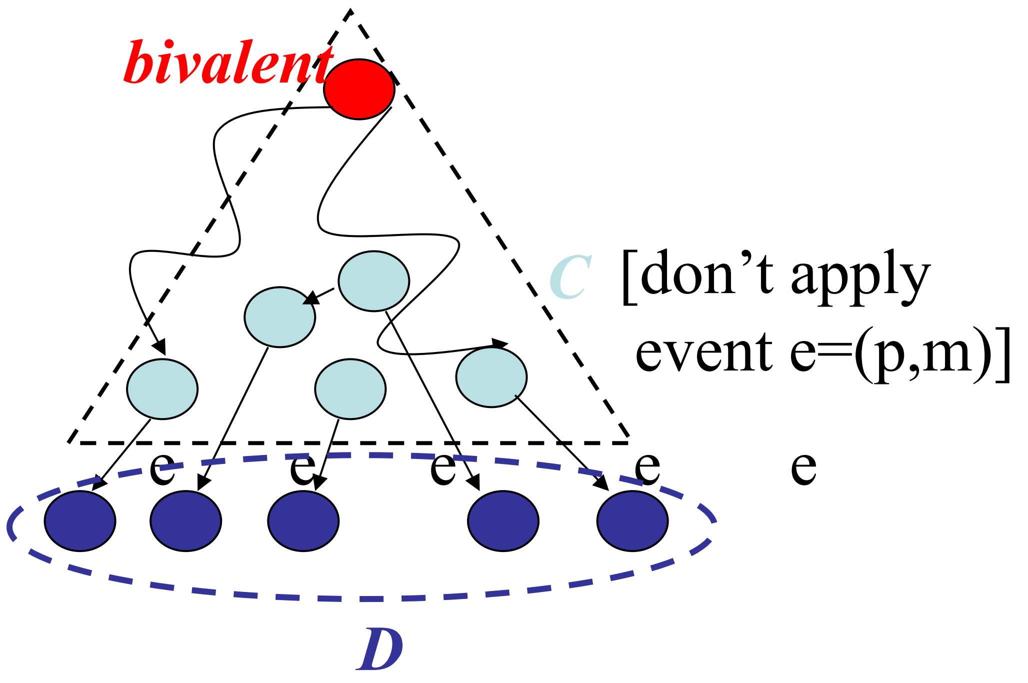


Proof. (contd.)

- Case I: p’ is not p $\longrightarrow$
- Case II: p’ same as p

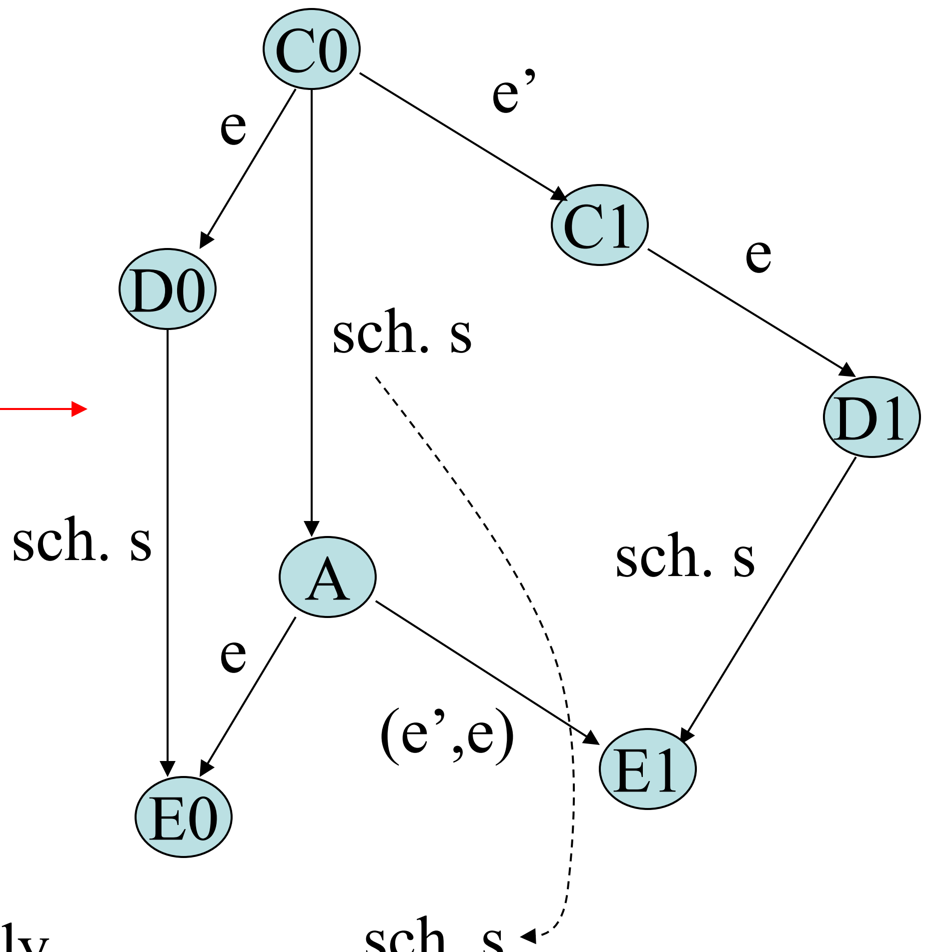
$$\begin{tikzcd}
 & C0 \arrow[dl, "e"'] \arrow[dr, "e'"] & \\
D0 \arrow[dr, "e'"'] & & C1 \arrow[dl, "e"] \\
 & D1 &
\end{tikzcd}$$

Why? (Lemma 1)
But D0 is then bivalent!



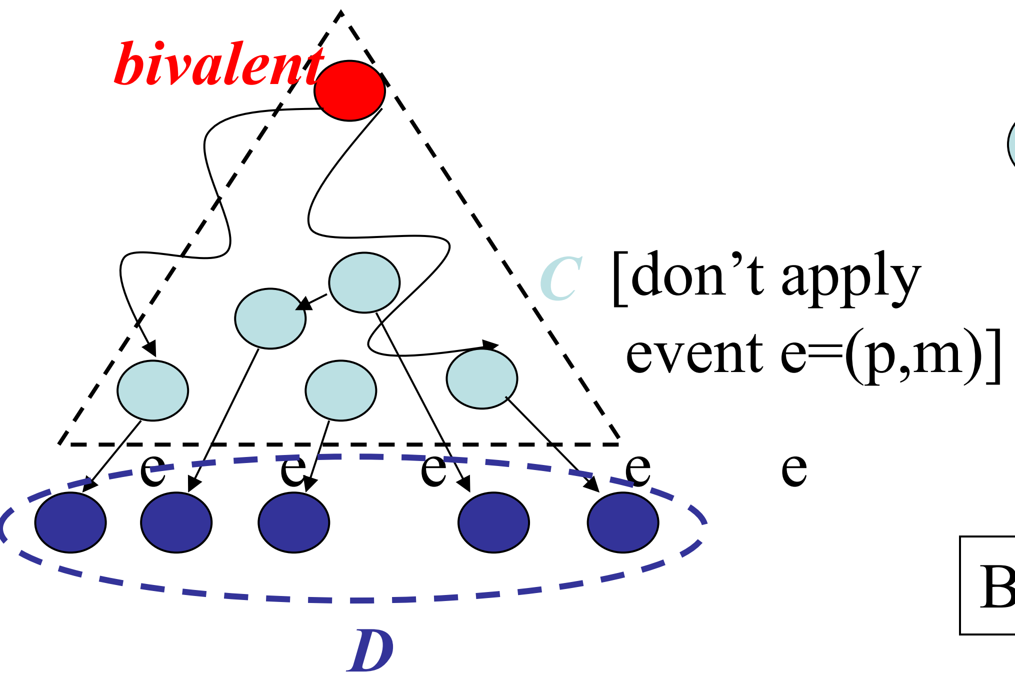
Proof. (contd.)

- Case I: p’ is not p
- Case II: p’ same as p



sch. s
- finite
- **deciding run** from C0
- *p takes no steps*

But A is then bivalent!



Lemma 3

Starting from a bivalent config., there is always another bivalent config. that is reachable

Putting it all Together

- Lemma 2: There exists an initial configuration that is bivalent
- Lemma 3: Starting from a bivalent config., there is always another bivalent config. that is reachable

- Theorem (Impossibility of Consensus): There is always a run of events in an asynchronous distributed system such that the group of processes never reach consensus (i.e., stays bivalent all the time)

Summary

- Consensus Problem
  - agreement in distributed systems
  - Solution exists in synchronous system model (e.g., supercomputer)
  - Impossible to solve in an asynchronous system (e.g., Internet, Web)
    - Key idea: with even one (adversarial) crash-stop process failure, there are always sequences of events for the system to decide any which way
    - Whatever algorithm you choose!
  - FLP impossibility proof