Synchronizing Physical Clock Logical Clock & Vector Clock

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AP/CSE

Reference: 1. Mukesh Singhal & N.G. Shivaratri, Advanced Concepts in Operating Systems,

2. George Coulouris, Jean Dollimore and Tim Kindberg, "Distributed Systems Concepts and Design", Fifth Edition, Pearson Education, 2012

Overview

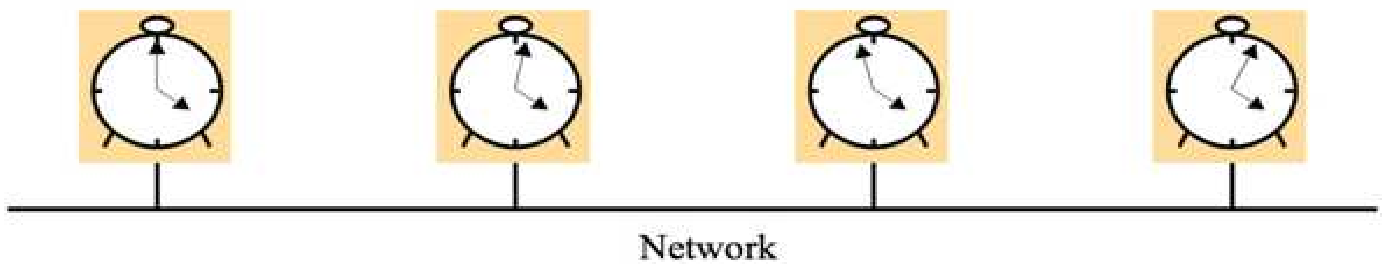
- Physical Clocks
- Synchronizing Physical Clock (Algorithms)
- Problems with Physical Clock
- Lamport's Logical Clock
- Problems with Logical Clock
- Vector Clock

Clock Synchronization

- Temporal ordering of events produced by concurrent processes
- Synchronization between senders and receivers of messages
- Serialization of concurrent access for shared objects
- **Physical Clock**: It is the internal clock present in a computer. (Time of a day)
- **Logical Clock**: keeps track of event ordering among related (causal) events.

Clock Synchronization

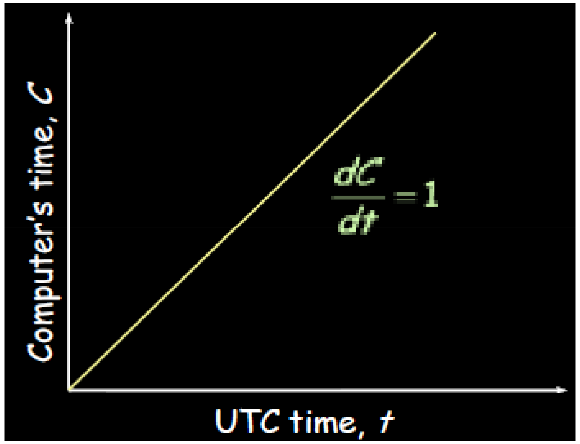
- Getting two systems to agree on time
  - Two clocks hardly ever agree
  - **Quartz oscillators oscillate at slightly different frequencies**
- **Clock Drift :** Clocks tick at different rates. Create ever-widening gap in perceived time
  - Clock drift in ordinary clocks based on quartz crystal is 10^-6 seconds.
  - This creates a difference of 1 sec for every 11.6 days (1,000,000 sec)
  - Clock drift of high precision clock is 10^-7 to 10^-8
- **Clock Skew :** Difference between two clocks at one point in time.

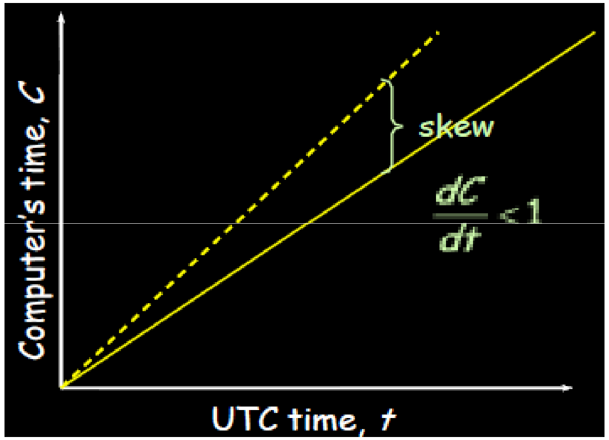


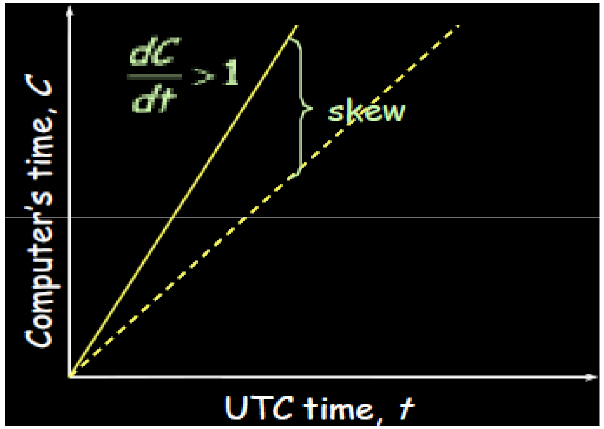
Clock Synchronization

- Dealing with Clock Drift: Go for gradual clock correction

UTC : Universal Coordinated Time







If slow:

Make clock run faster until it Synchronizes

If fast:

Make clock run slower until it Synchronizes

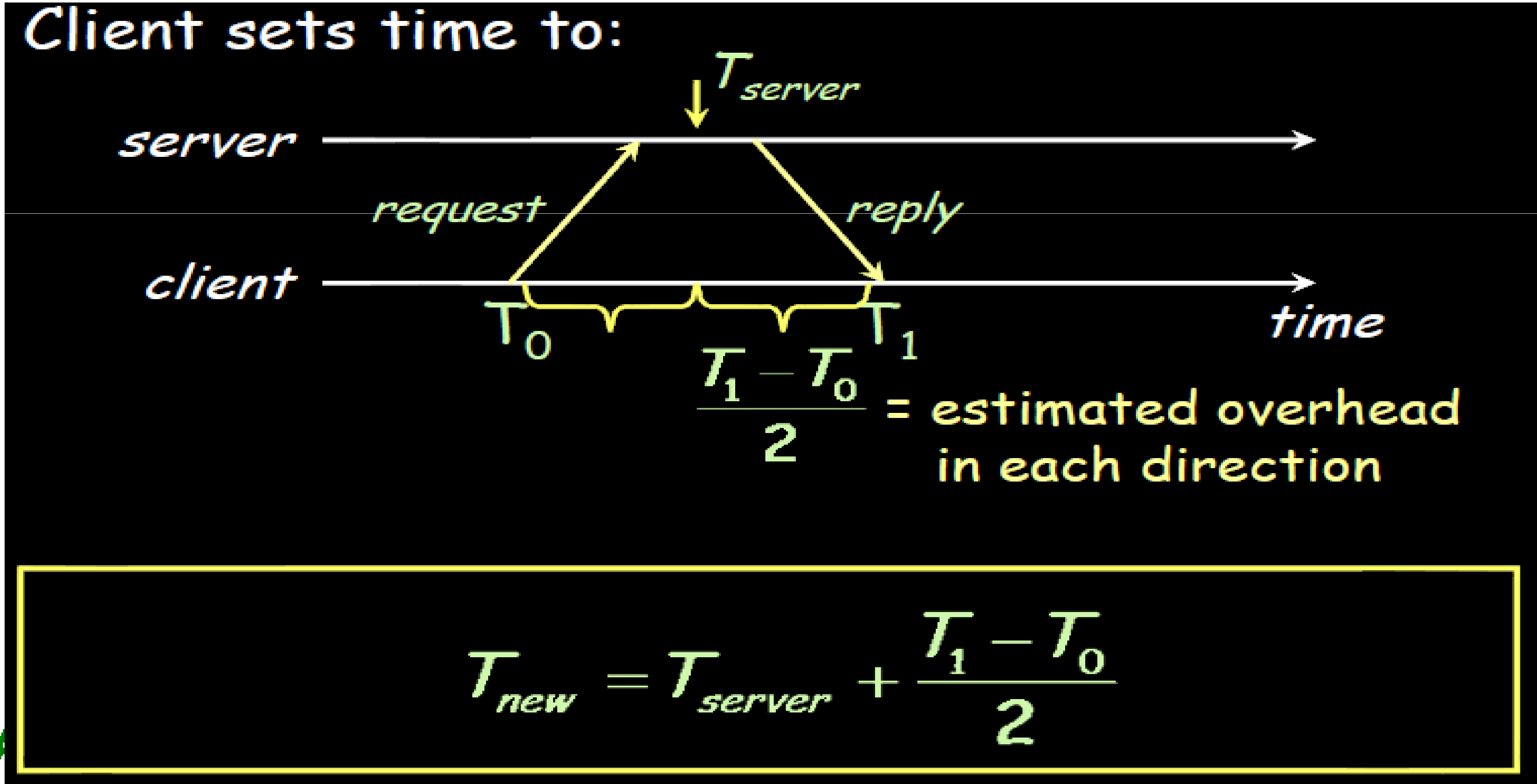
Clock Synchronization

- **External Synchronization** : Clock synchronizes to correct time from external timing elements like Radio / Satellite time.
- **Internal Synchronization** : Clock synchronizes to correct time by getting timings from other computers.
- 3 - Algorithms for Synchronizing Physical Clock
  1. **Cristian's Algorithm**
  2. **Berkeley Algorithm**
  3. **Network Time Protocol (NTP)**

Clock Synchronization

1. Cristian's Algorithm

(T1-T0)/2 is round-trip time



Clock Synchronization

1. Cristian's Algorithm – Example

- Send request at 5:08:15.100 (T0)
- Receive response at 5:08:15.900 (T1)
- Response contains 5:09:25.300 (Tserver)
- Elapsed time is T1 -T0

  5:08:15.900 - 5:08:15.100 = 800 msec
- Best guess: timestamp was generated

  400 msec ago (800/2)
- Set time to Tserver+ elapsed time

  5:09:25.300 + 400 = 5:09.25.700

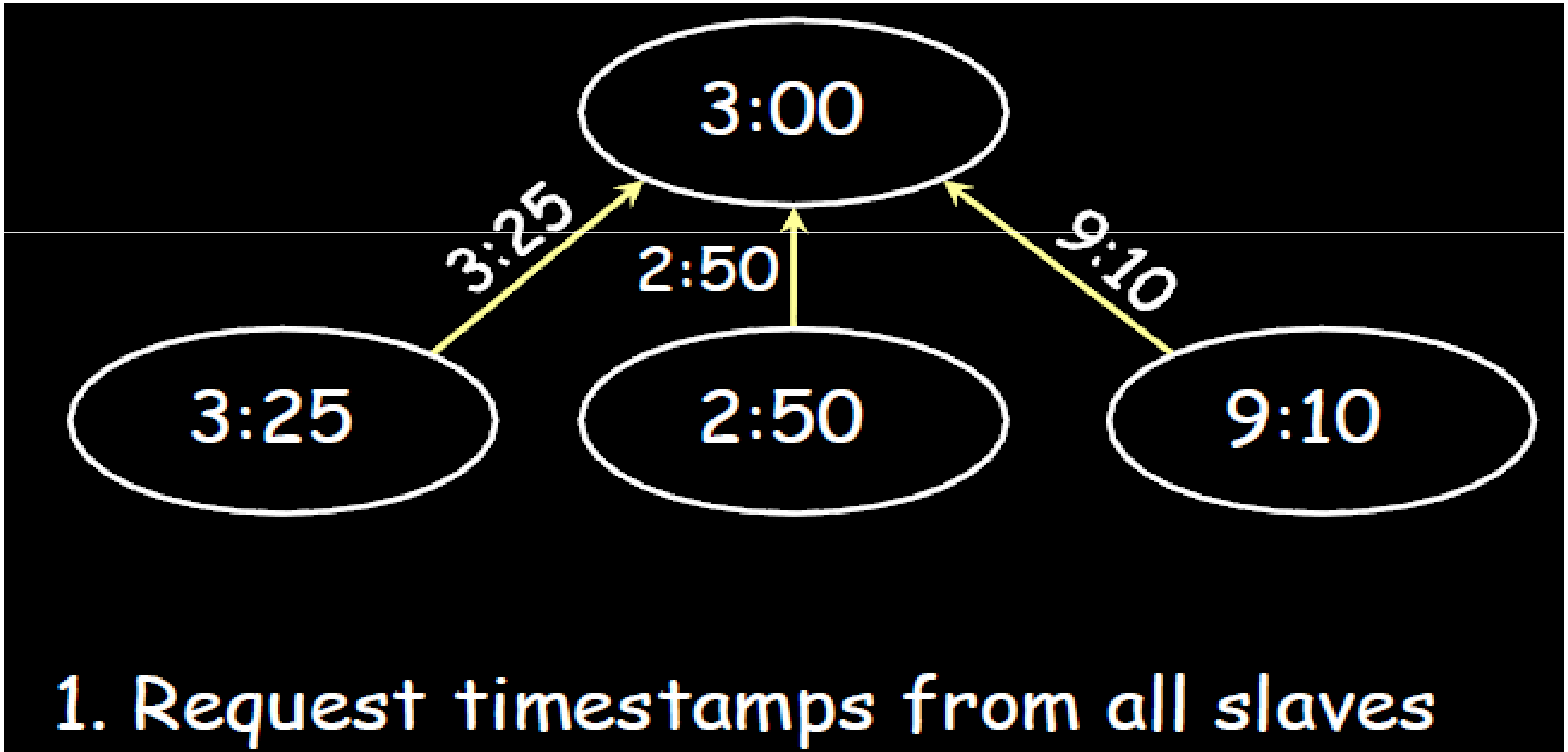
Clock Synchronization

2. Berkeley Algorithm

- Machines run **time dæmon** Process that implements protocol
- One machine is elected (or designated) as the server (**master)** Others are **slaves**
- Master polls each machine periodically and ask each machine for time
- Can use Cristian's algorithm to compensate for network latency
- When results are received, master computes average of times - Including master's time
- **Hope**: Average cancels out individual clock's tendencies to run fast or slow (clock drift)
- Send offset by which each clock needs adjustment to each slave.
- Algorithm has provisions for ignoring readings from clocks whose skew is too great
- Compute a **fault-tolerant average**
- If master fails - any slave can take over

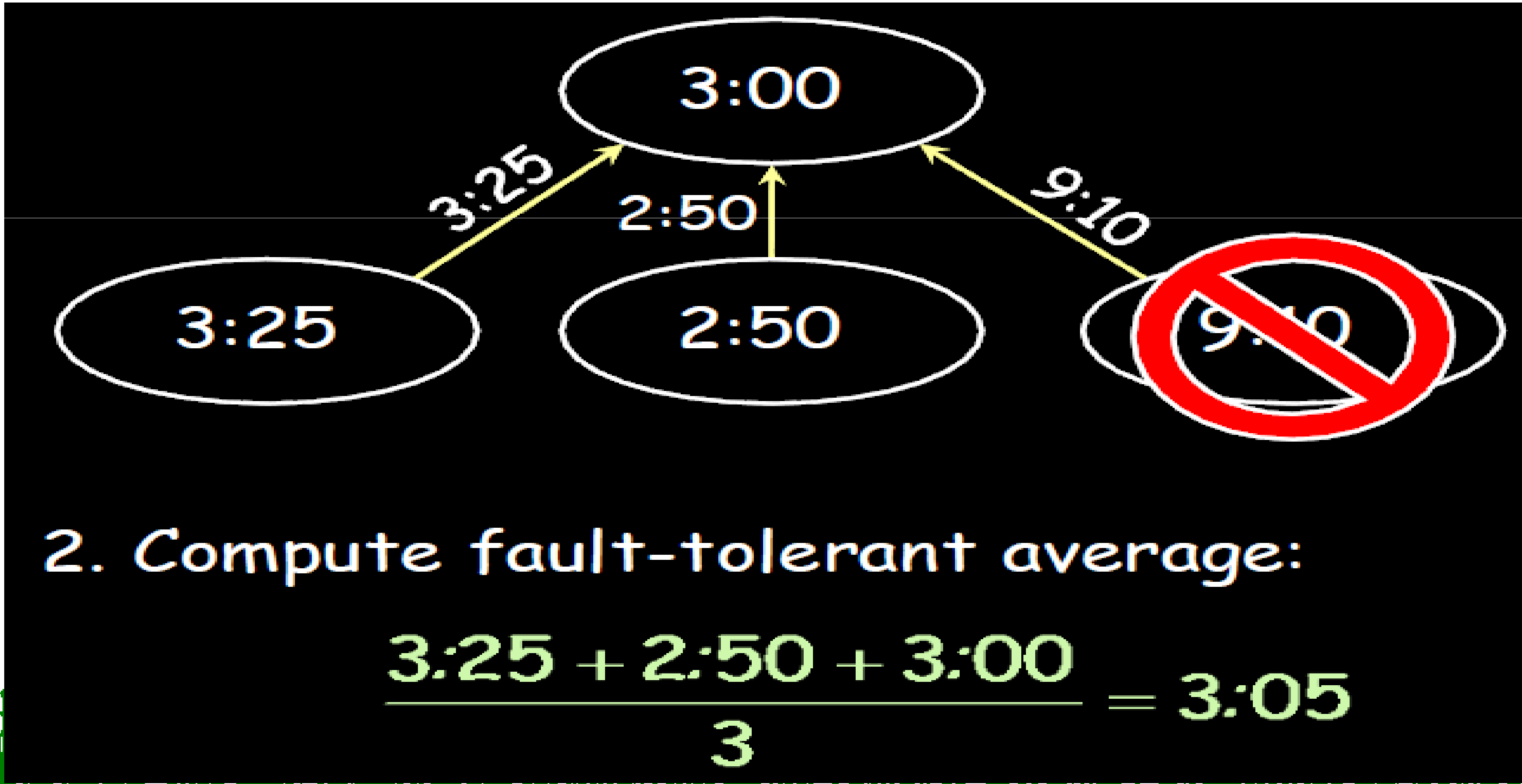
Clock Synchronization

2. Berkeley Algorithm Example



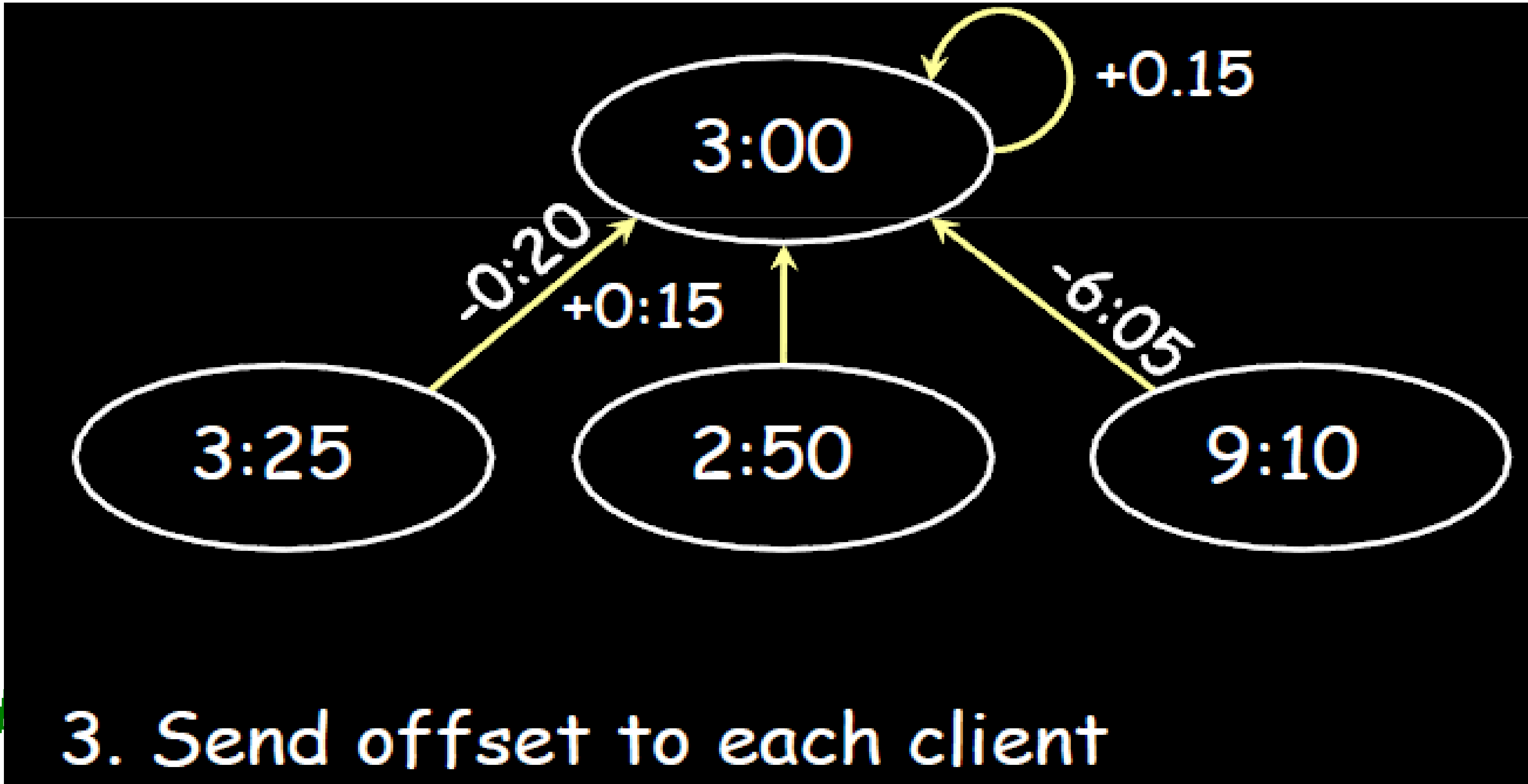
Clock Synchronization

2. Berkeley Algorithm Example



Clock Synchronization

2. Berkeley Algorithm Example



Clock Synchronization

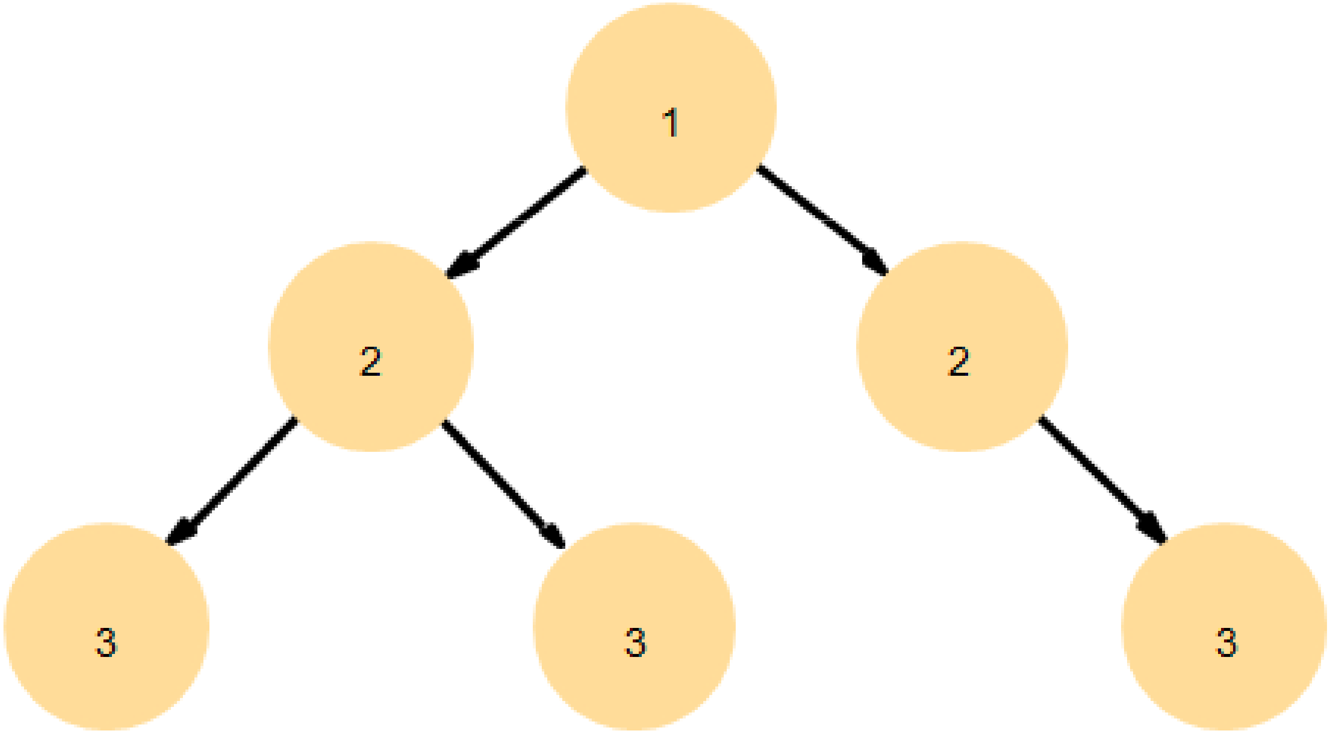
3. Network Time Protocol

- Enable clients across Internet to be accurately synchronized to UTC despite message delays
- Primary servers are connected directly to a time source such as a radio clock receiving UTC; secondary servers are synchronized with primary servers.
- The servers are connected in a logical hierarchy called a **synchronization subnet** whose levels are called **strata**.
- Primary servers occupy stratum 1: they are at the root.
- Stratum 2 servers are secondary servers that are synchronized directly with the primary servers;
- Stratum 3 servers are synchronized with stratum 2 servers, and so on.

Clock Synchronization

3. Network Time Protocol

Arrows denote synchronization control, numbers denote strata.



Clock Synchronization

3. Network Time Protocol (Synchronization Modes)

- **Multicast mode**
  - Every node sends its time to all the other nodes in the LAN
  - For high speed LANs
  - Lower accuracy but efficient
- **Procedure call mode**
  - Similar to Cristian's algorithm
- **Symmetric mode**
  - Intended for master servers
  - Pair of servers exchange messages and retain data to improve synchronization over time

All messages delivered unreliably with UDP

Problems with Physical Clocks

- **Clock Drift :** Clocks tick at different rates. Create ever-widening gap in perceived time
- **Clock Skew :** Difference between two clocks at one point in time.
- For quartz crystal clocks, typical drift rate is about one second every 106 seconds =11.6 days
- Best atomic clocks have drift rate of one second in 1013 seconds = 300,000 years.
- **Quartz clock run at rate of 1.5 microseconds slower for every 35 days.**

Problems with Physical Clocks

8:01:24

Skew = +84 seconds
+84 seconds/35 days
Drift = +2.4 sec/day

Oct 23, 2006
8:00:00

8:01:48

Skew = +108 seconds
+108 seconds/35 days
Drift = +3.1 sec/day

Logical Clocks

Need for Logical Clock

- For many purposes, it is sufficient to know the order in which events occurred.
- Lamport (1978) — introduce logical (*virtual) time,* synchronize *logical clocks.*
- An event may be an instruction execution, may be a function execution, etc.
- Events include message send / receive

Within a single process, or between two processes on the same computer

- The order in which two **events** occur **can** be determined using the **physical clock**

Between two different computers in a distributed system

- The order in which two events occur **cannot** be determined **using local physical clocks**, since those clocks cannot be synchronized perfectly

Happened Before Relation

- Lamport defined the happened before relation (denoted as "→"), which describes a **causal ordering of events:**

1. if a and b are events in the same process, and a occurred before b, then a → b
2. if a is the event of sending a message m in one process, and b is the event of receiving that message m in another process, then a → b
3. if a → b, and b → c, then a → c (i.e., the relation "→" is transitive

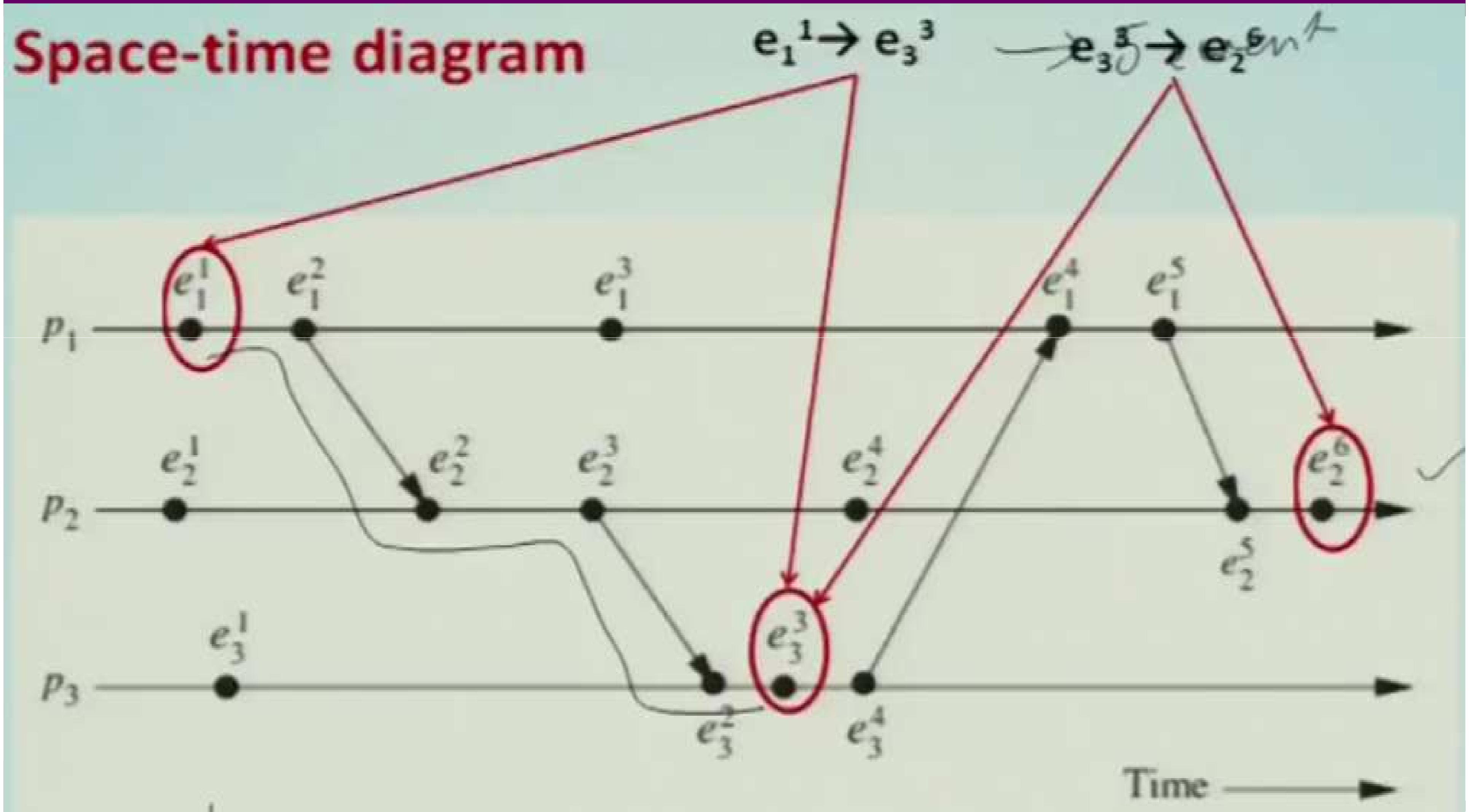
Causality

- Past events influence future events
- This influence among causally related events (those that can be ordered by "→") is referred to a **causally affects.**
- If a → b, event **a** causally affects event **b**

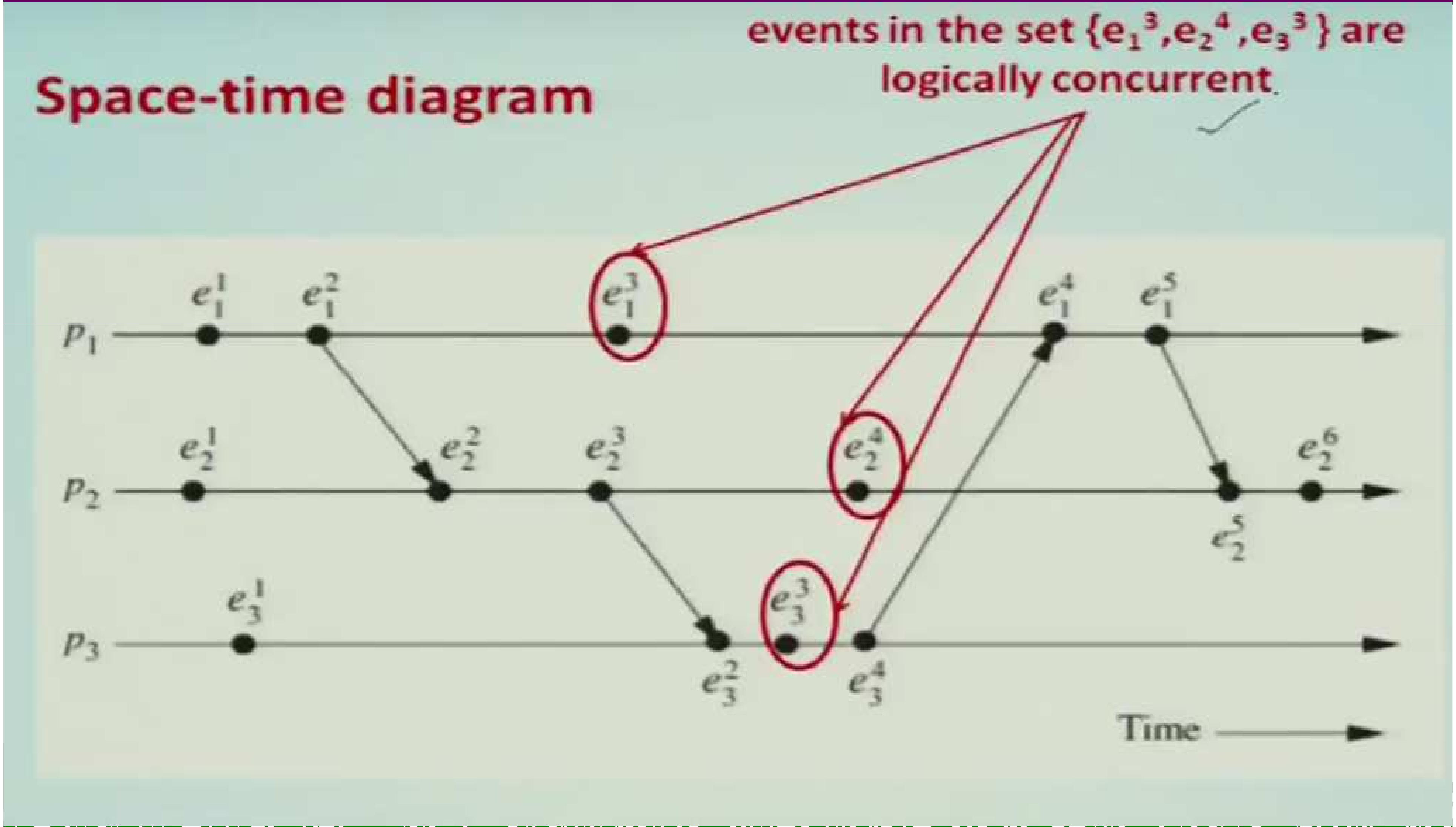
Concurrent events

- Two distinct events **a** and **b** are said to be concurrent (denoted "a || b"), if neither a→ b nor b → a
- In other words, concurrent events do not causally affect each other
- For any two events a and b in a system, either: a → b or b → a or a || b

Causal Events



Concurrent Events



Lamport's Logical Clock

- To implement " → " in a distributed system, Lamport (1978) introduced the concept of logical clocks, which captures " → " numerically
- Each process Pi has a logical clock Ci
- Clock Ci can assign a value Ci (a) to any event **a** in process Pi
- The value Ci (a) is called the timestamp of event **a** in process Pi
- The value C(a) is called the timestamp of event **a** in whatever process it occurred.
- The timestamps have no relation to physical time, which leads to the term logical clock.
- The logical clocks assign monotonically increasing timestamps, and can be implemented by simple counters

Lamport's Logical Clock

- **Clock condition: if a $\rightarrow$ b, then $C(a)<C(b)$**
- If event a happens before event b, then the clock value (timestamp) of a should be less than the clock value of b
- Note that we can **not say: if $C(a)<C(b)$, then a $\rightarrow$ b**
- **Correctness conditions (must be satisfied by the logical clocks to meet the clock condition above):**
- [C1] For any two events a and b in the same process Pi ,

  if a happens before b, then $C_i(a) < C_i(b)$
- [C2] If event a is the event of sending a message m in process Pi , and event b is the event of receiving that same message m in a different process Pk, then $C_i(a) < C_k(b)$

Lamport's Logical Clock

- **[IR1]** Clock Ci must be incremented between any two successive events in process Pi

  Ci := Ci + d , (d>0) (usually d=1)

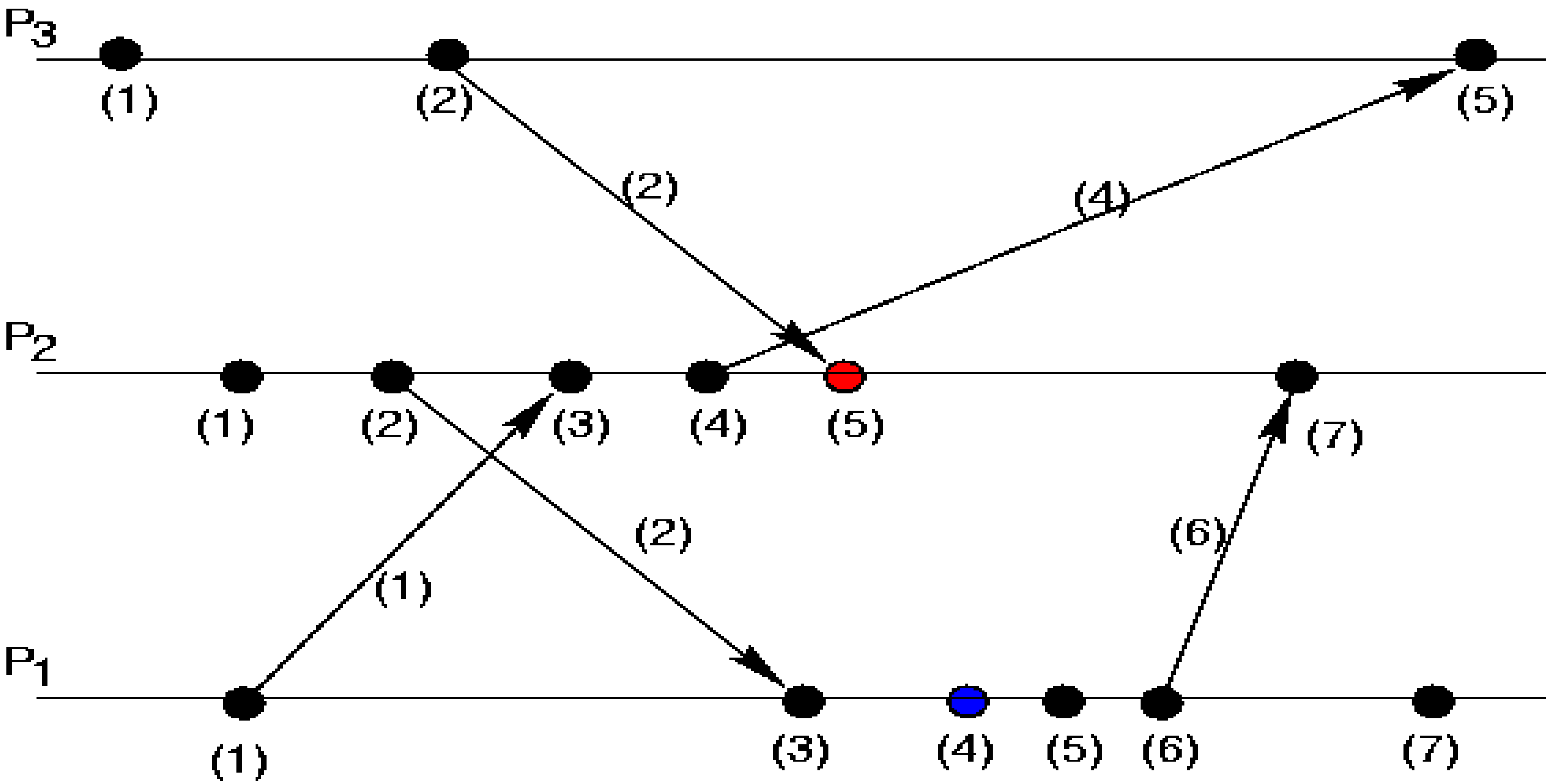
- **[IR2]** If event a is the event of sending a message m in process Pi , then message m is assigned a timestamp tm =Ci (a) When that same message m is received by a different process Pk, Ck is set to a value greater than or equal to its present value, and greater than tm

  Ck := max(Ck , tm + d) , (d>0) (usually d=1)

Lamport's Logical Clock

IR 1: Ci := Ci + d , (d>0), (usually d=1)

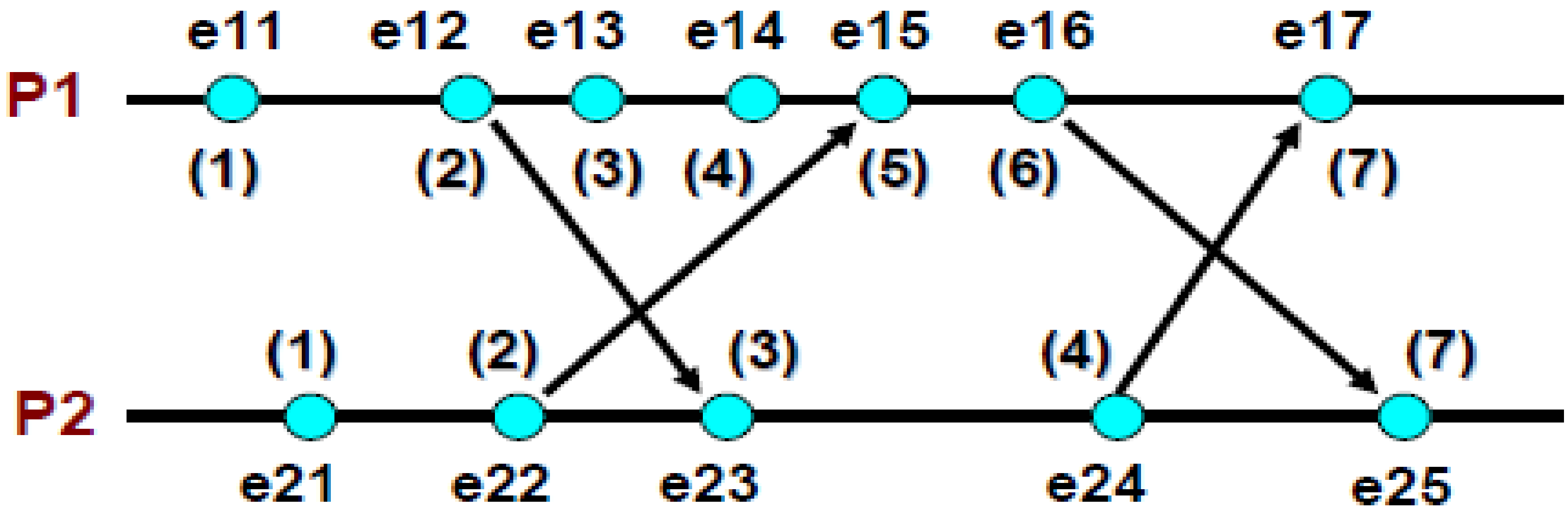
IR2: Ck := max(Ck , tm + d) , (d>0) (Usually d=1)



Lamport's Logical Clock

IR 1: Ci := Ci + d , (d>0) , (usually d=1)

IR2: Ck := max(Ck , tm + d) , (d>0) (Usually d=1)

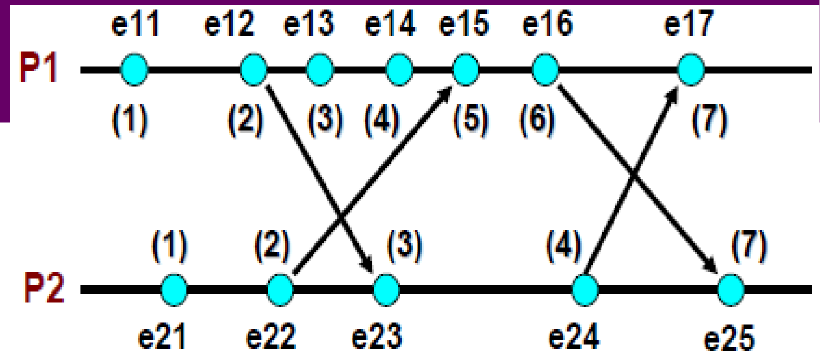


Lamport's Logical Clock

- A **total order of events** **(" => ") can be obtained as follows:**
- If a is any event in process Pi , and b is any event in process Pk , then **a => b** if and only if either:
- **Ci (a) < Ck (b) or**
- **Ci (a) = Ck (b) and Pi << Pk**

where "<<" denotes a relation that totally orders the processes to break ties

Limitations of Lamport's Logical Clock



- With Lamport's logical clocks,
- if a → b, then C(a) < C(b)
- The following is **not necessarily true if events a and b occur in** different processes:
- if C(a) < C(b), then a → b

  C(e12) < C(e23), and e12 → e23 is true

  C(e12) < C(e24), but e12 → e24 is false

  C(e15) < C(e25), but e15 → e25 is false

- Cannot determine whether two events are causally related from timestamps

Vector Clocks

Vector Clock

- Maintain a vector of values for every event that happens in all processes.
- Update happens for group of values in every event.

Vector Clock

- [IR1] Clock Ci must be incremented between any two successive events in process Pi :

  $C_i[i] := C_i[i] + d$, (d>0, usually d=1)

- [IR2] If event a is the event of sending a message m in process Pi , then message m is assigned a vector timestamp tm =Ci (a) When that same message m is received by a different process Pk , Ck is updated as follows:

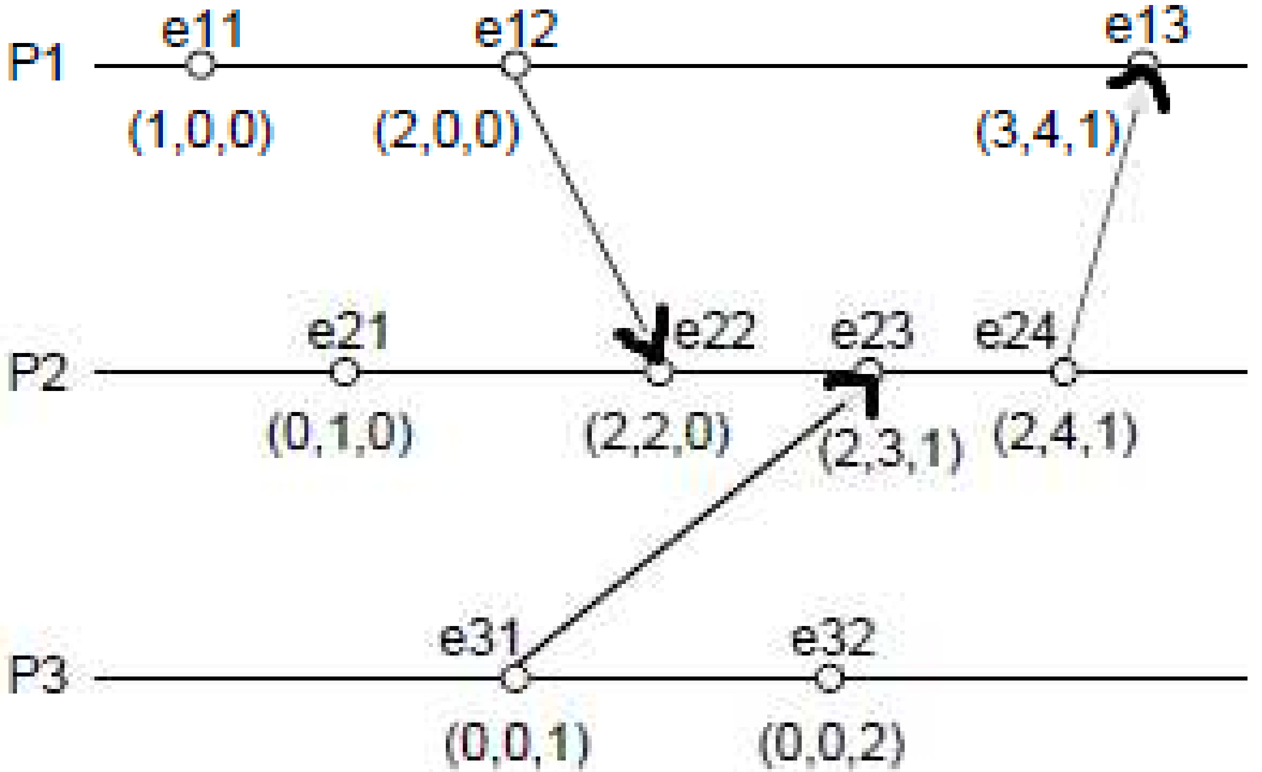
  $\forall p,\ C_k[p] := \max(C_k[p], t_m[p] + d)$, (usually d=0 unless needed to model network delay)

- It can be shown that **$\forall i, \forall k : C_i[i] >= C_k[i]$**
- Rules for comparing timestamps can also be established so that
- if ta < tb , then a → b. Solves the problem with Lamport's clocks

Vector Clock

IR1: Ci [i]:= Ci [i] + d . (d=1)

IR2: ∀p, Ck [p]:= max(Ck [p], tm [p] + d) . (d=0)



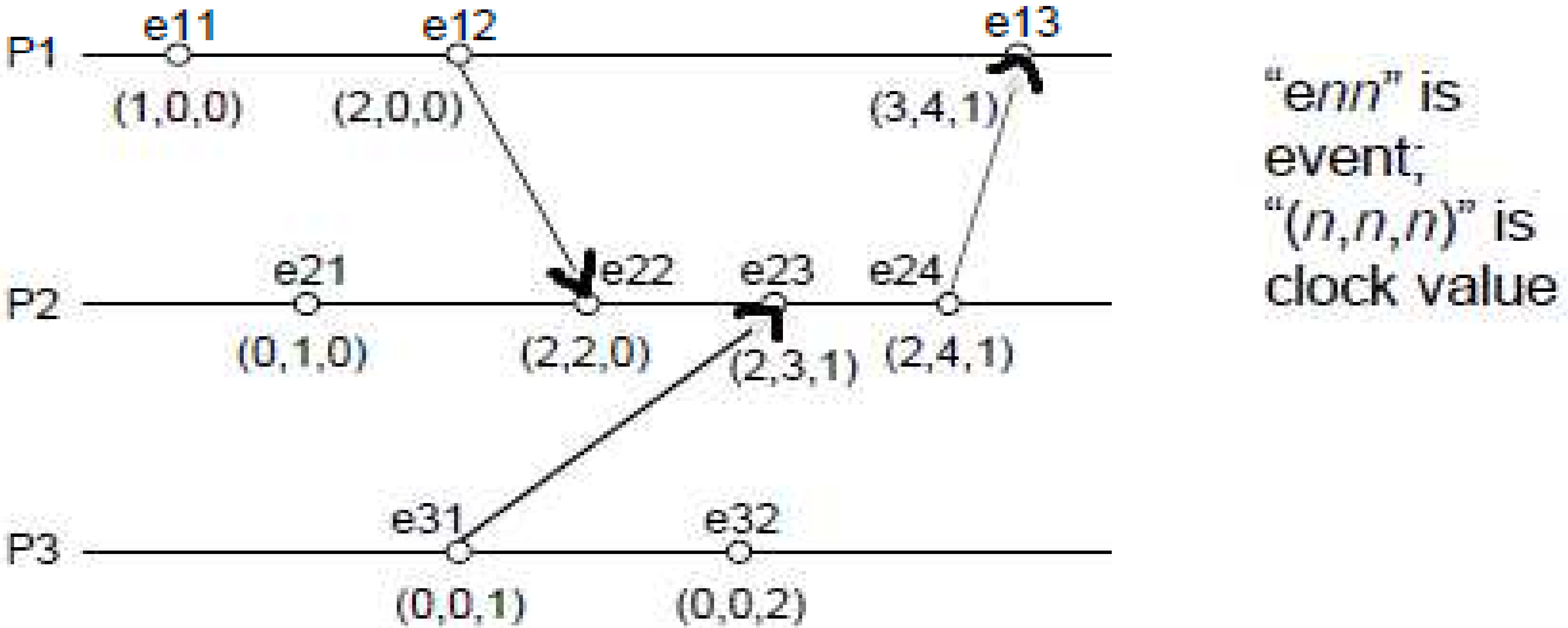
"e*nn*" is event; "(*n*,*n*,*n*)" is clock value

Vector Clock – Solving Logical Clock Problem

if t(e31) < t(e23) then e31 → e23 is true.

if t(e12) < t(e24) then e12 → e24 is also true.

Concurrent events e32 || e24; e32 $\not\rightarrow$ e24 and e24 $\not\rightarrow$ e32



Vector Clock

Example of Vector Clock

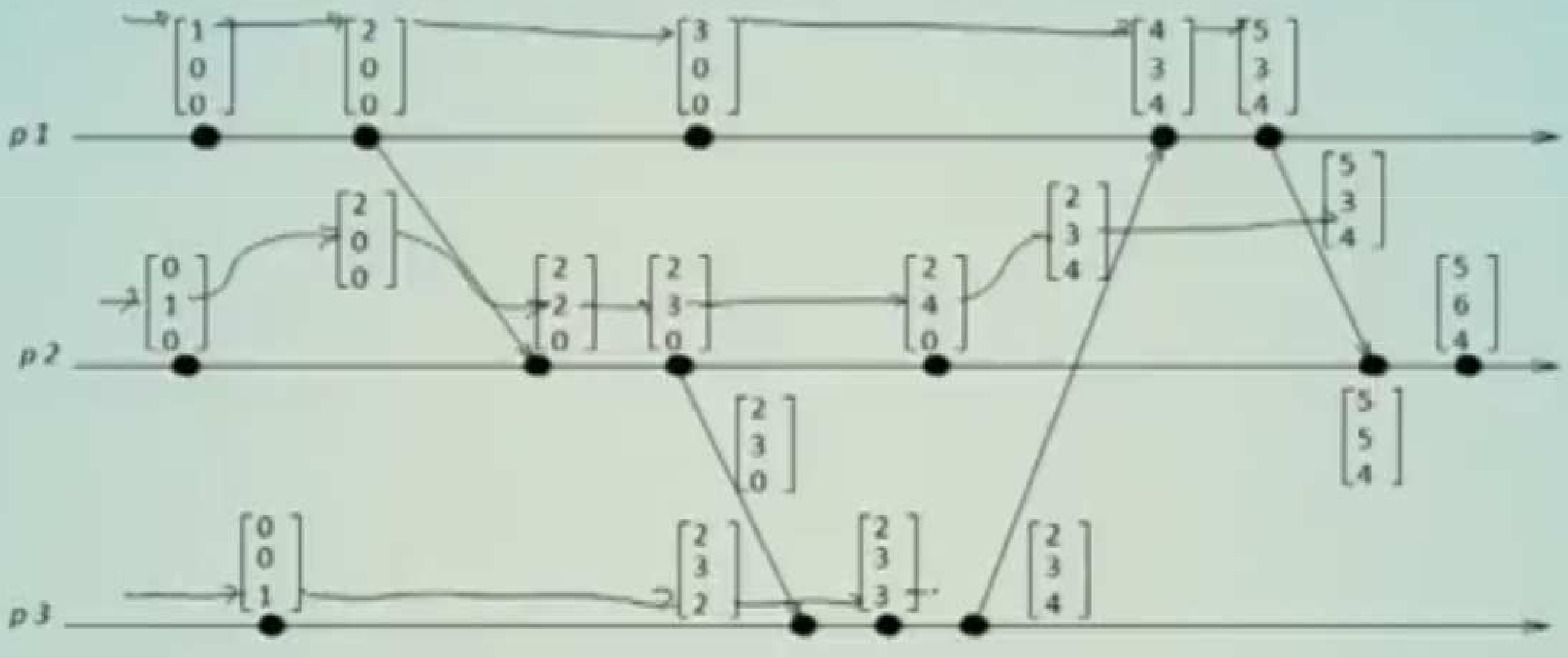


Figure 4.3: Evolution of vector time.

Summary

- Physical Clocks
- Synchronizing Physical Clock (Algorithms)
- Problems with Physical Clock
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Thank You