Real-Time Systems

Time and Order

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Overview

following Tanenbaum/Coulouris for Logical Time
and Kopetz for Physical Time

- Events, computer generated and environmental
- The order of events, temporal and causal
- Logical clocks
- Physical clocks and their properties
- Global time in distributed systems

Questions to Answer

- Can clocks (logical or physical) be used
  - to derive the order of events
  - to identify events
  - to generate events at certain points in time?

- Which precision can be achieved
  - to measure time?
  - to measure durations?

- How and how often should clocks be synchronized?

Time in Distributed Systems

- Actions / events in distributed real-time systems
  - concurrent
  - on different nodes
  - must have a consistent behavior / order.
- Consistent order
  - temporal order
  - causal order
- Global Time Base

Events in Computers

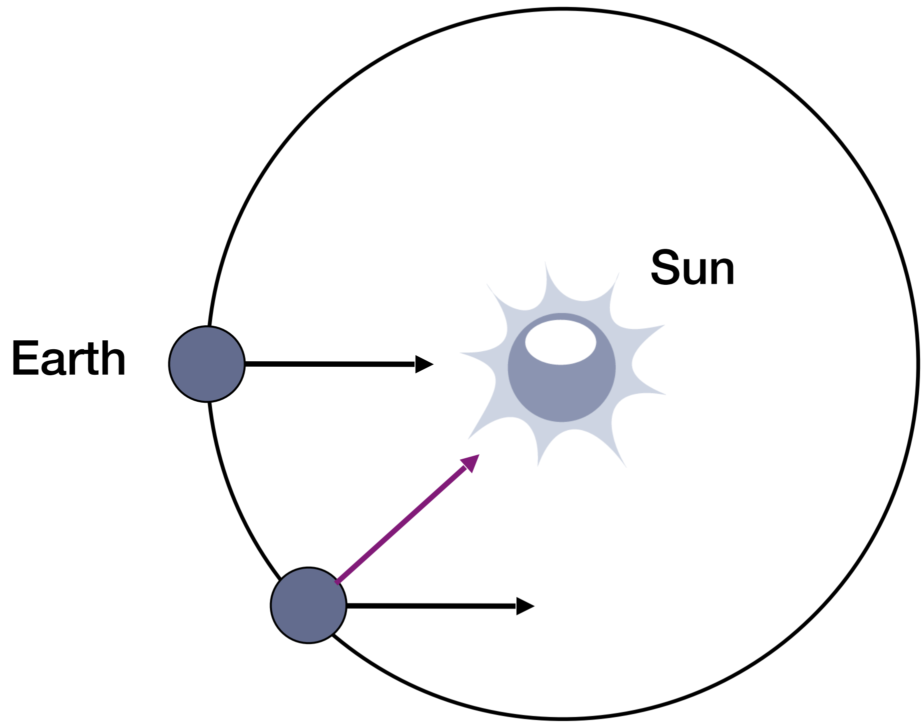
- Computer Generated Events:
  - execution of statement
  - sending / receiving a message
  - start and end of a compilation
  - creation / modification of a file
- Sequence of states is determined by
  - instructions, disk accesses
  - discrete steps

Events in the Real World

- Environmental Events:
  - Newtonian mechanics
  - pipe rupture
  - human interaction
- Sequence of states is determined by
  - laws of physics
  - physical time: “second”
  - continuous

Astronomical Time

- Solar Day: from noon to noon
- Solar Second: Solar Day / (24 * 60 * 60)



Atomic Time

TAI — International Atomic Time

- 1 second = “duration of 9192631770 (9 Gigahertz) periods of the radiation of a specified transition of the caesium atom 133”
- GPS Time is based on onboard atomic clock in the satellites

Time Standard

UTC — Coordinated Universal Time

- TAI adjusted with leap seconds to compensate for variations (slowing) of earth rotation
- Sources:
  - earth-bound radio
  - Geosynchronous satellites
  - GPS
  - NTP

Temporal vs. Causal Order of Events

Temporal Order

- induced by (perfect) timestamp

Causal Order

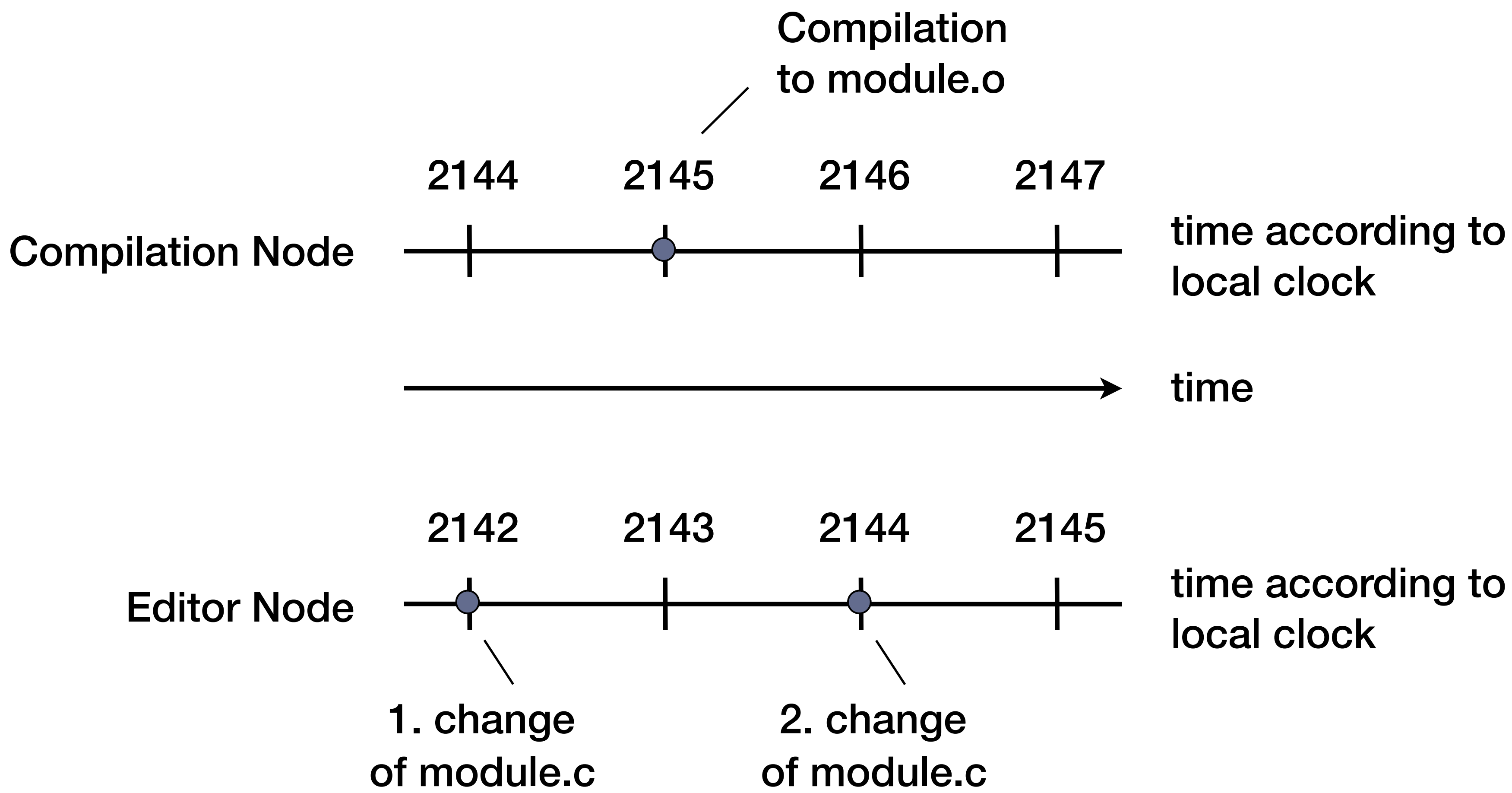
- induced by some causal dependency between events

Example

- e1: somebody enters a room
  e2: the telephone rings
- cases
  e1: occurs after e2 causal dependency possible
  e2: occurs after e1 causal dependency unlikely
- Temporal order is necessary but not sufficient to establish causal order

Example

Imperfect Timestamps can be misleading in establishing causal dependency (example by A.S. Tanenbaum)



Causal Order

Partial Order for Computer Generated Events

a → b "a causes b"
(happened before, causally dependent)

- If a, b events within a sequential process then a → b, if a is executed before b.
- If a is „sending of a message" by a process and b the „reception of that message" by another process,
  then a → b.
- → is transitive.

Temporal Order

Modeling the continuum of time:
infinite set of instants {T}

- {T} is ordered:
  if p, q any 2 instants, then either p,q simultaneous (i.e. the same instant), or (exclusive) p precedes q, or q precedes p
- {T} is dense:
  at least 1 instant q between p and r iff p and q are not simultaneous
- Instants are totally ordered

Timestamps, Duration, Clocks

Timestamp

- Events occur at an instant of the timeline

Duration

- Duration is a section of the timeline

Clock

- Clocks measure time imperfectly, create imperfect Timestamps

Clocks: Physical and Logical

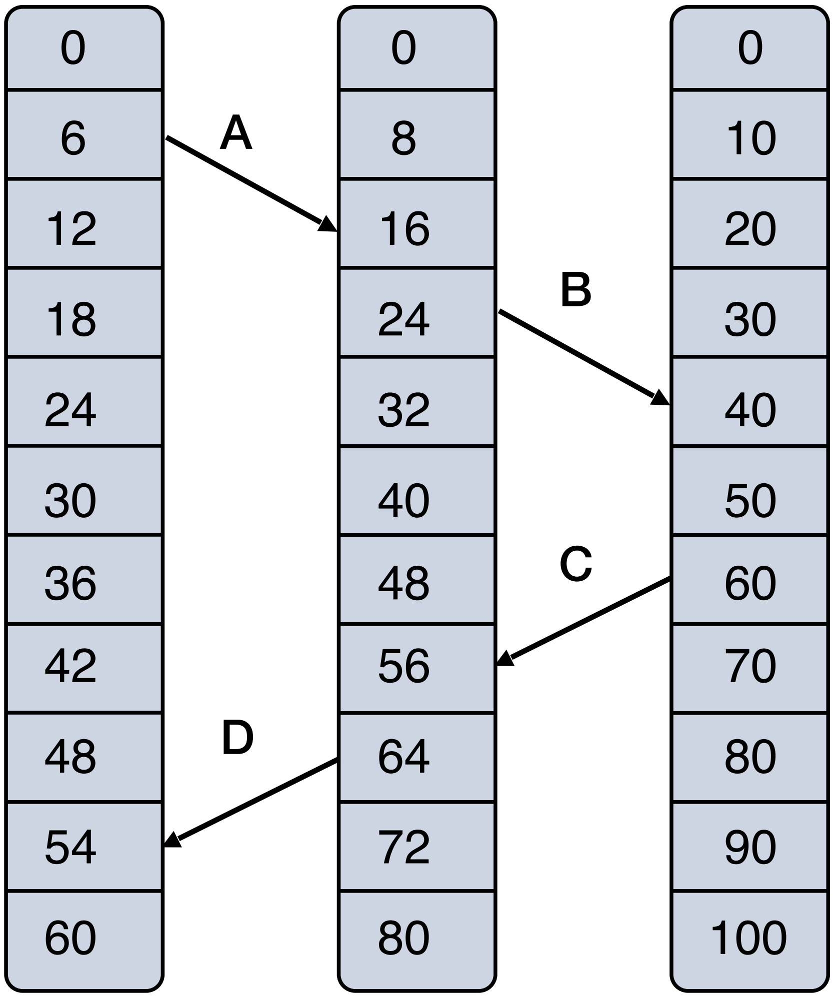
Physical Clocks

- devices to measure time
- necessarily imperfect (more later)
- Problems:
  - how to create knowledge about causal dependency of computer events without relying on physical clocks? → Logical Clocks
  - how to establish a ‘x certainly occurred after y relation’ (temporal order) for environmental events? → Global Time

Logical Clocks

- Definitions:
  - monotonically increasing SW counters (COULOURIS)
  - clocks on different computers that are somehow consistent (LAMPORT)
- Events: a,b: $a \rightarrow b$: a causes b (causally dependent)
- Timestamps: C(a), C(b)
- Potential Requirements for logical clocks:
  - $a \rightarrow b \quad \Rightarrow \quad C(a) < C(b)$
  - $a \rightarrow b \quad \Leftrightarrow \quad C(a) < C(b)$

Logical Clock Example



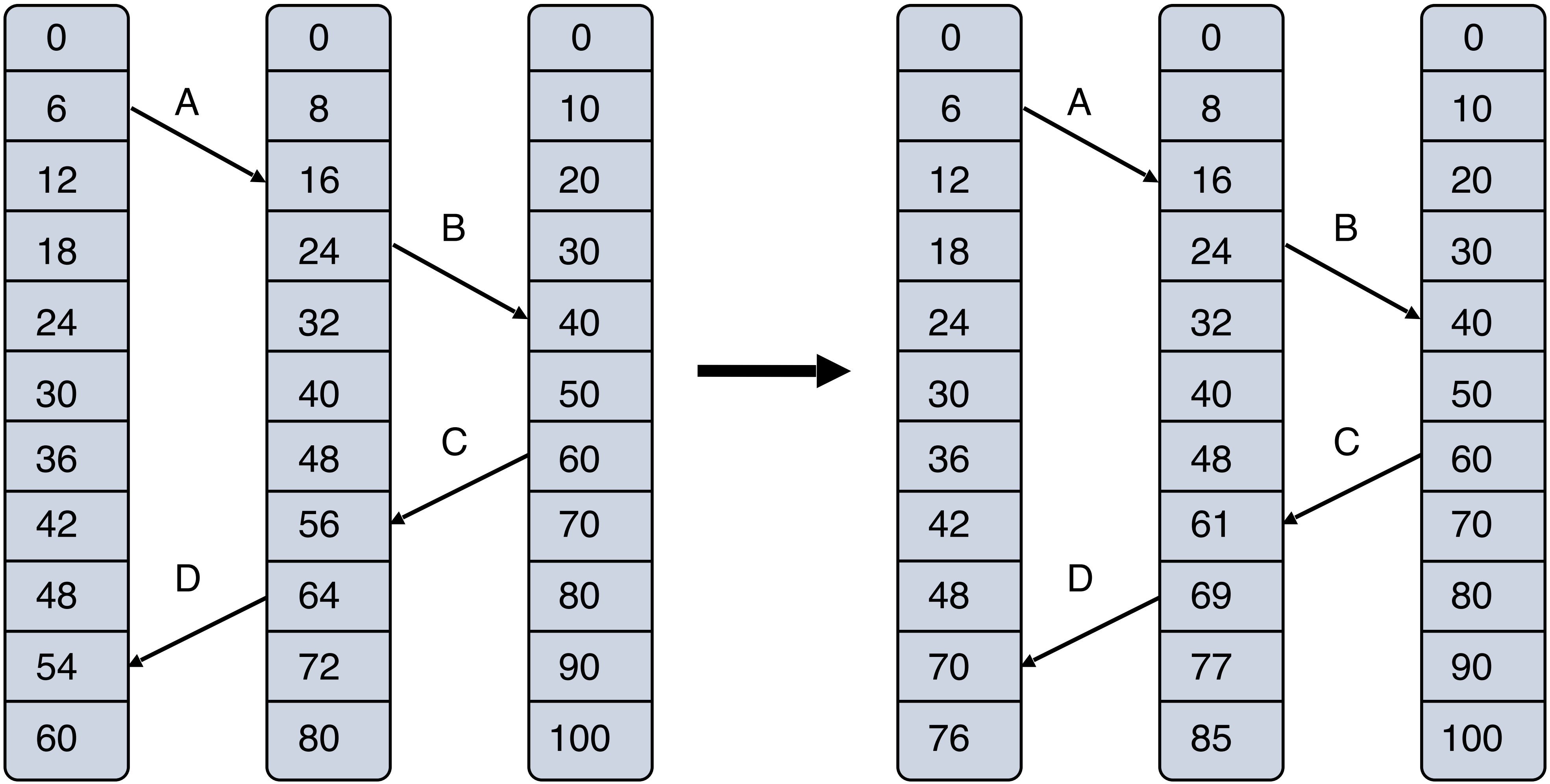
Lamport's Logical Clocks

each Process has local clock LC_i

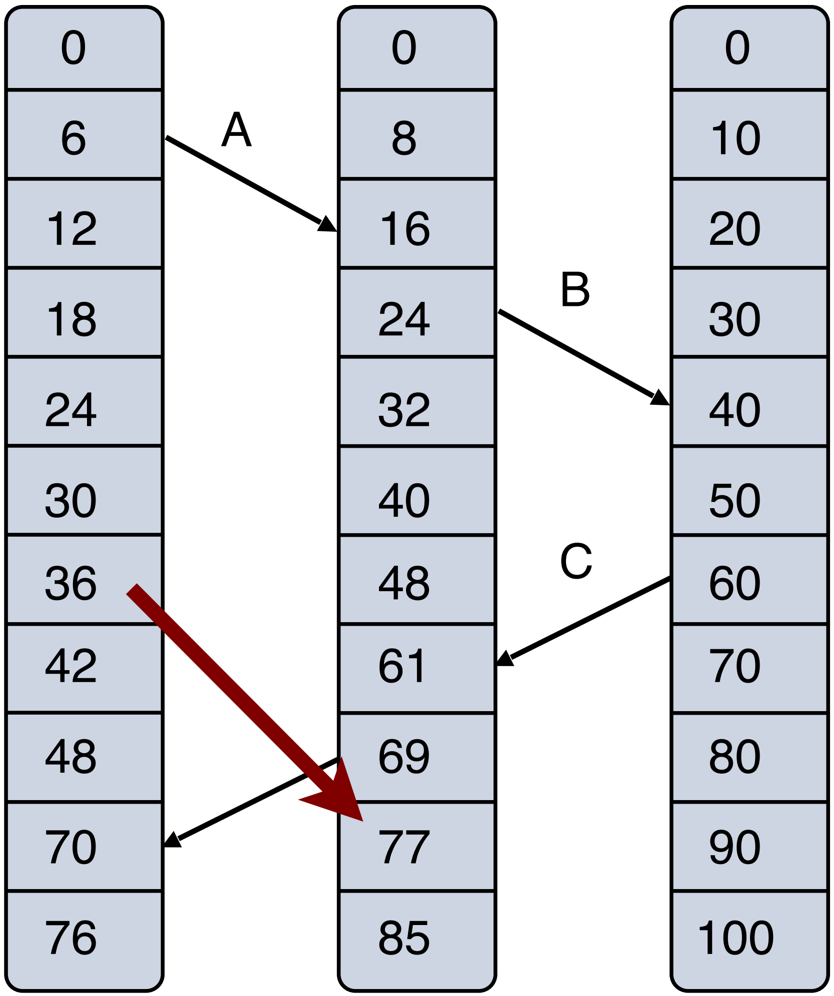
Tick

- with each local event e:
  $LC_i := LC_i + 1$; e
- with each sending of a message by process P_i:
  $LC_i := LC_i + 1$; send(m, LC_i)
- with each reception of a message (m, LC_m) by P_j:
  $LC_j := \max(LC_m, LC_j)$; $LC_j := LC_j + 1$

Lamport's Logical Clocks



Partial Timestamp Order



Lamport Clocks

Properties

- $a \rightarrow b \Rightarrow C(a) < C(b)$,
- but not:
  $C(a) < C(b) \Rightarrow a \rightarrow b$
- Lamport Clocks establish a partial order relation

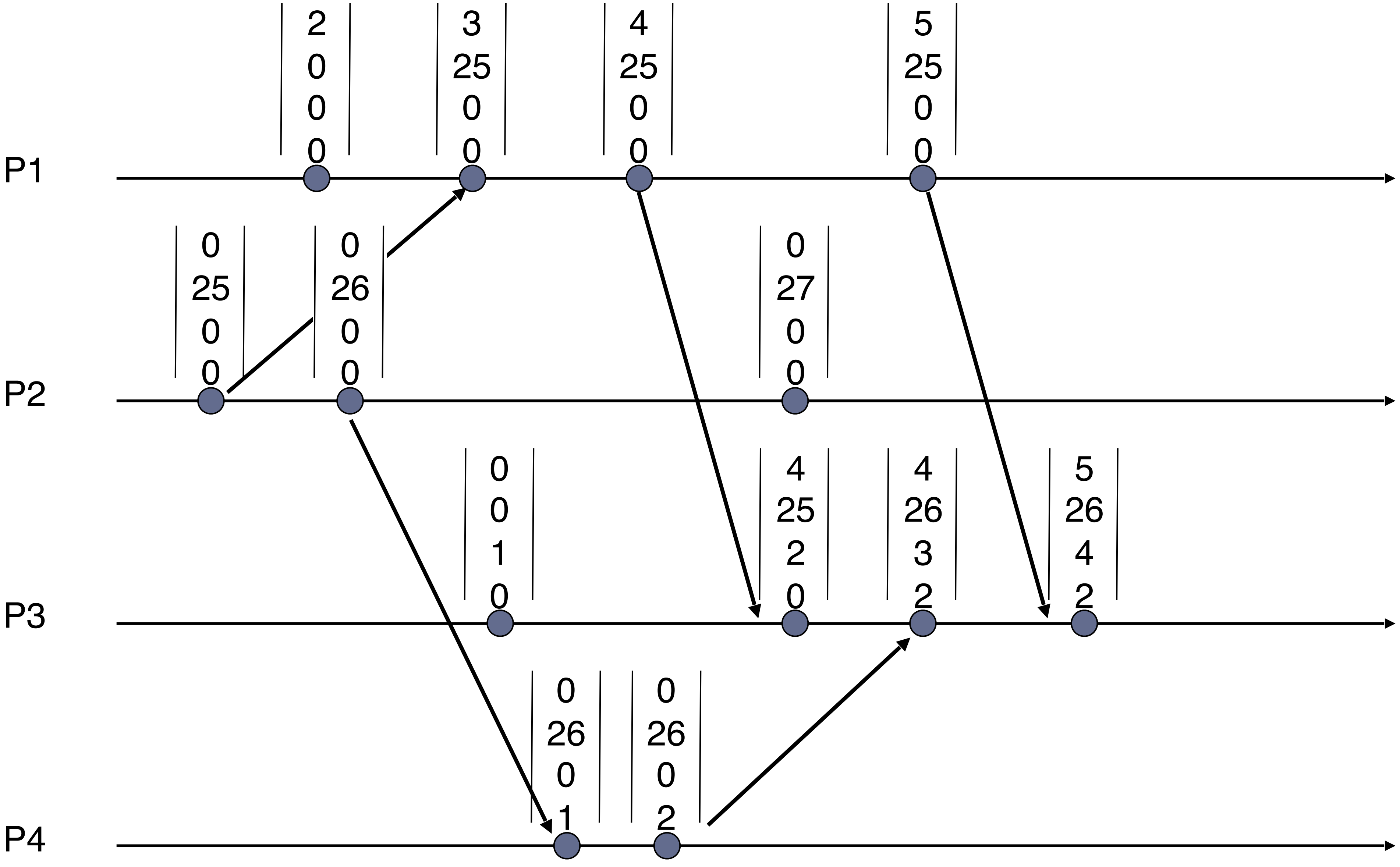
Vector Time (Mattern 1989)

- Each process P_i has its own vector clock C_i
- C_i: n-dimensional vector
- n: number of processes
- Intuition: $C_i[j]$ is the timestamp of the last event in P_j by which P_i has potentially been effected

Vector Time Ticks

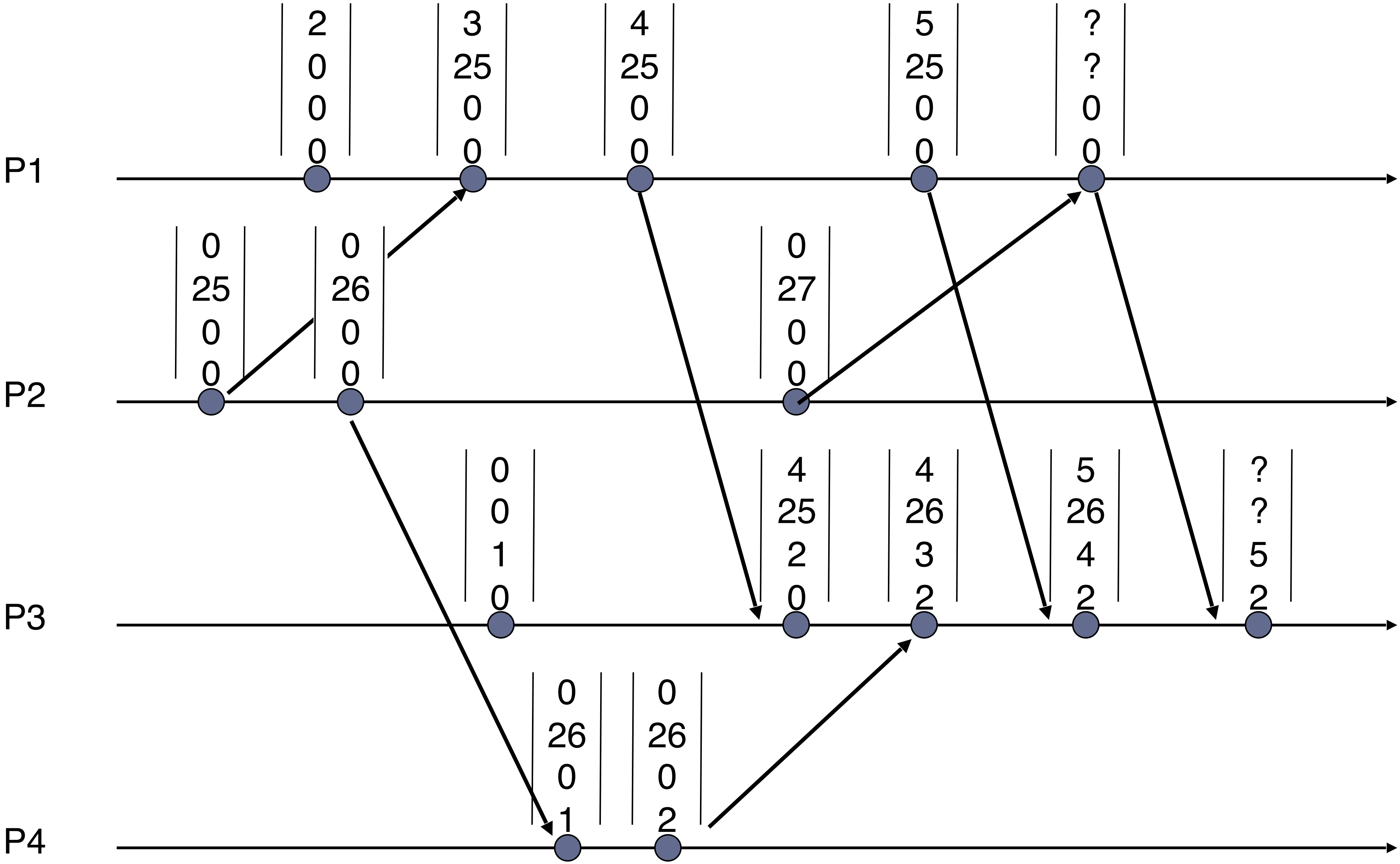
- Initial:
  C_i:= (0, ...,0)   for all i
- Local event in P_i:
  $C_i[i] := C_i[i] + 1;$
- Sending message m in P_i:
  $C_i[i] := C_i[i] + 1;$ send(m, C_i)
- Receiving a message (m, C_m) in P_j:
  $C_j[j] := C_j[j] + 1;$
  $C_j[k] := \max(C_m[k], C_j[k])$, for all k

Example



P1
P2
P3
P4
2 0 0 0
3 25 0 0
4 25 0 0
5 25 0 0
0 25 0 0
0 26 0 0
0 27 0 0
0 0 1 0
4 25 2 0
4 26 3 2
5 26 4 2
0 26 0 1
0 26 0 2

Example



P1
P2
P3
P4
2 0 0 0
3 25 0 0
4 25 0 0
5 25 0 0
? ? 0 0
0 25 0 0
0 26 0 0
0 27 0 0
0 0 1 0
4 25 2 0
4 26 3 2
5 26 4 2
? ? 5 2
0 26 0 1
0 26 0 2

Properties of Vector Time

Definitions

- $C_a \leq C_b :\Leftrightarrow \forall k: C_a[k] \leq C_b[k]$
- $C_a < C_b :\Leftrightarrow C_a \leq C_b \wedge C_a \neq C_b$
- $C_a \parallel C_b :\Leftrightarrow C_a \nless C_b \wedge C_b \nless C_a$

Property

- $C_a < C_b \Leftrightarrow a \rightarrow b$

Physical Clocks and Their Properties

Physical Clock

- device for measuring time
- counter + oscillator → microtick
- time between microticks:
  granularity leads to digitalization error

Notation

- g^{clock}, $microtick^{clock}_{number}$ of tick
- To discuss properties of physical clocks, we invent the perfect reference clock as purely theoretical construct

Reference Clock, Notation (Kopetz)

Reference Clock z

- perfect with regard to UTC
- very small granularity
  (to disregard digitalization error)
- Reference Ticks: Ticks of the perfect reference clock
- z(event): (Absolute) Timestamp from reference clock establishes temporal order
- g^k granularity of clock k in microticks of ref. clock

Reference Clock, Notations (Daum)

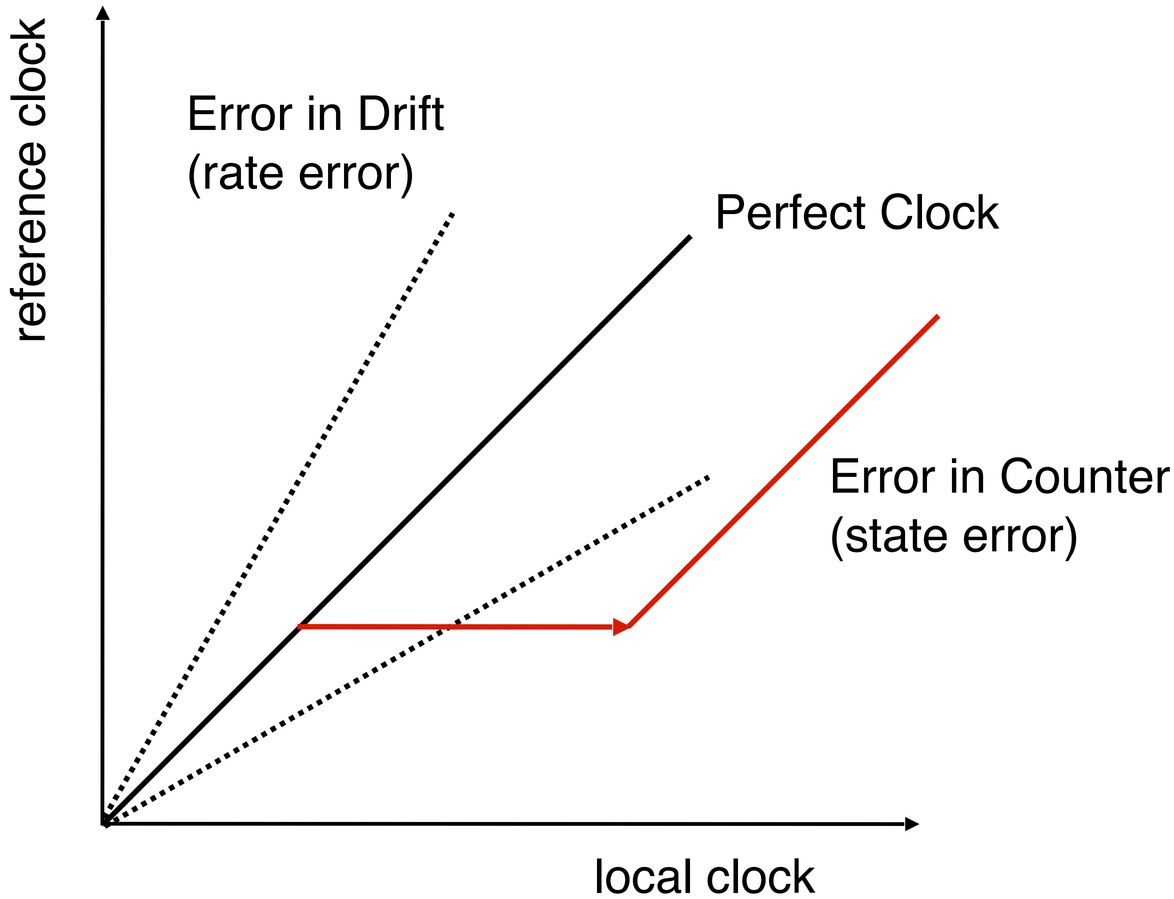
Reference Clock z

- perfect with regard to UTC
- dense (no ticks, to avoid digitalisation error)
- z(event): (Absolute) Timestamp from reference clock establishes temporal order
- g^k granularity of clock k in terms of z-duration

Tick Tack Terms

- Micro-Ticks — Ticks generated by the physical oscillator of a clock
- Macro-Ticks — Multiple of Micro Ticks chosen by designer of clock
- t^k(event) — Timestamp in number of microticks of clock k
- Granularity — distance between adjacent microticks

Failure Modes: Drift and Counter Errors



Maximum Drift Rate

Drift-Rate

- Varying
- Influenced by environmental conditions (temperature, …)
- clocks specify maximum drift rate (10^{-2} … 10^{-7})

$$\rho_i^k = \left| \frac{z(microtick_{i+1}^k) - z(microtick_i^k)}{g^k} \right|$$

Precision of an Ensemble of Clocks

Offset

- between two clocks j,k of same granularity at microtick i:

$$offset_i^{jk} = \left| z(microtick_i^j) - z(microtick_i^k) \right|$$

- in the period of interest: $offset^{jk} = \max_i (offset_i^{jk})$

Precision

- of an ensemble of clocks {1,2, … ,n} in the period of interest:

$$\Pi = \max_{1 \le j,k \le n} (offset^{jk})$$

- maximum offset for any two clocks

Accuracy

Accuracy

- of a given clock in the period of interest:

$$accuracy^k = \max_i \left| z(microtick_i^k) - i \cdot g^k \right|$$

- maximum offset to reference clock
- If all clocks of an ensemble have accuracy A, the precision of the ensemble is ?

Resynchronisation

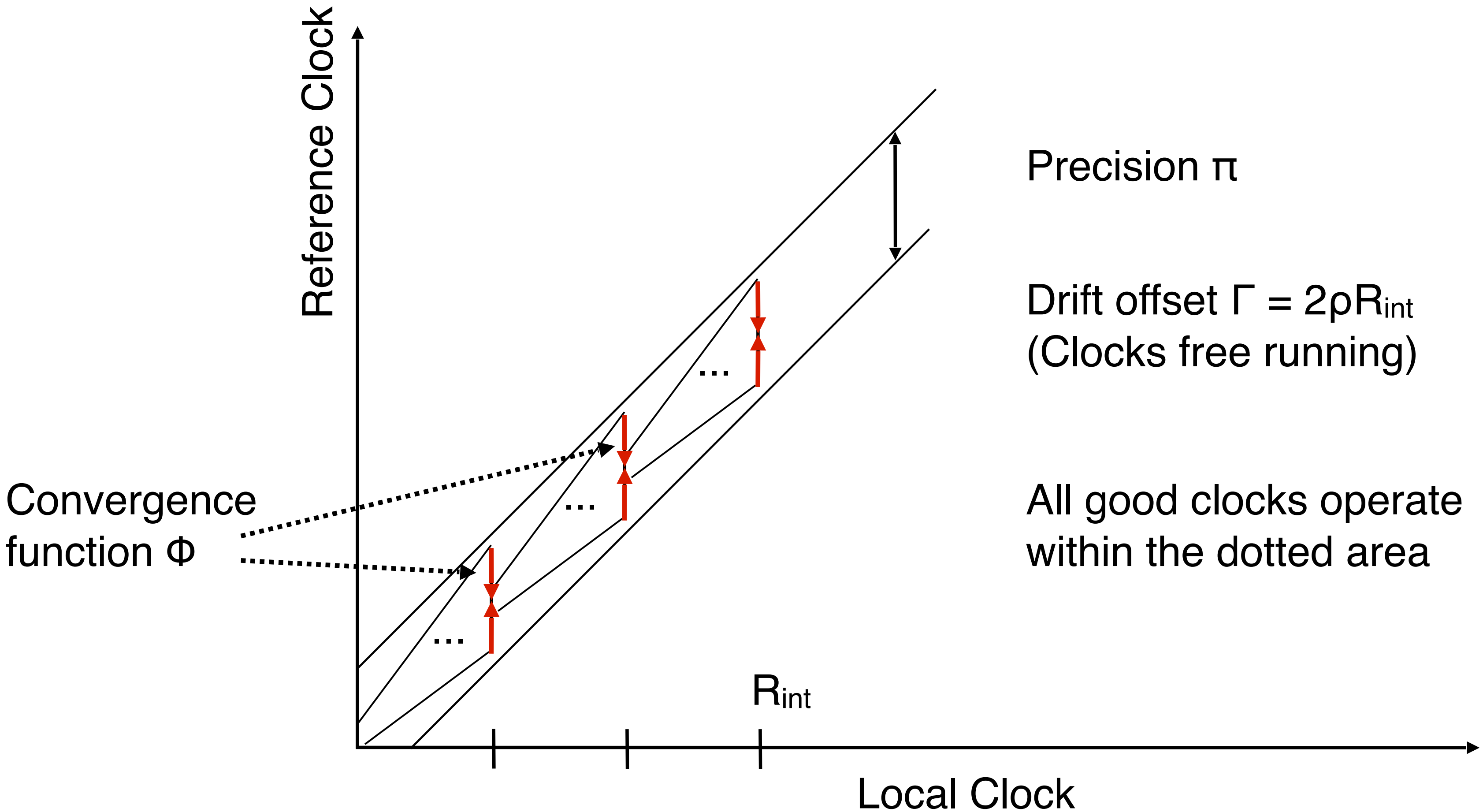
External Resynchronization

- resynchronization with reference clock
- to maintain bounded accuracy

Internal Resynchronization

- mutual resynchronization of an ensemble
- to maintain bounded precision

Internal Clock Synchronisation



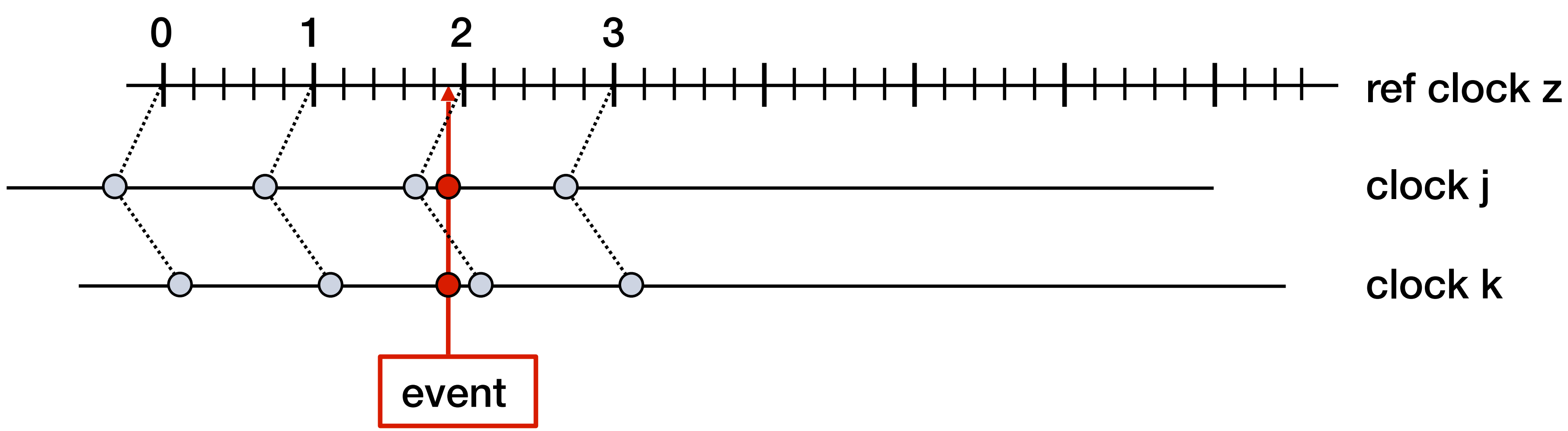
$$\Phi + \Gamma = \Pi$$

Synchronisation Condition

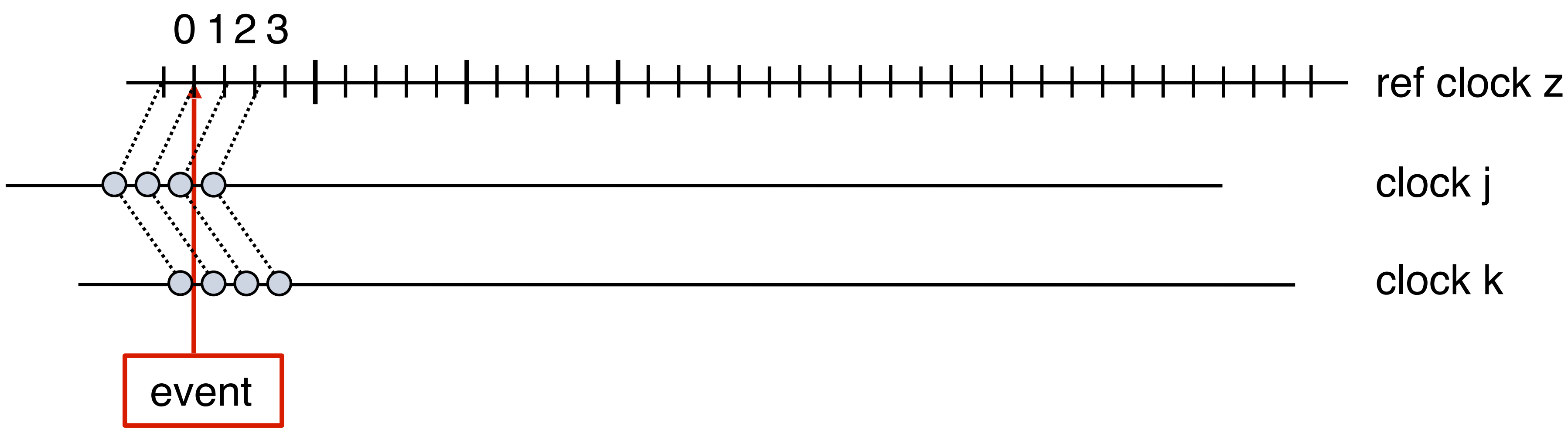
- resynchronization interval: R_{int}
- convergence function : Φ offset after resynch.
- drift offset: $\Gamma = 2\,\rho\,R_{int}$
- Required: $\Phi + \Gamma = \Pi$

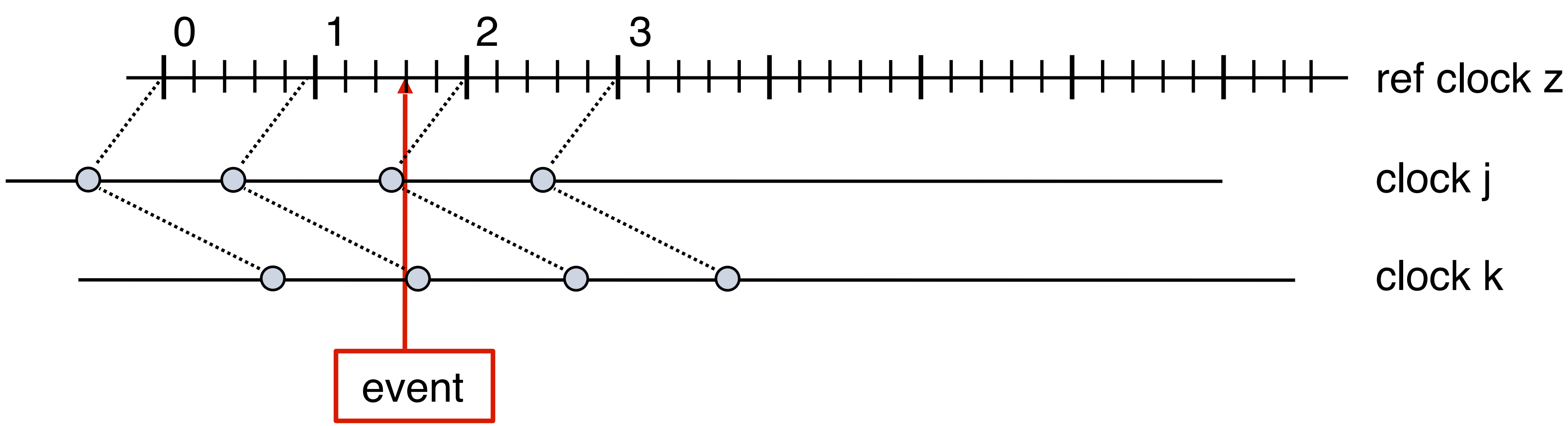
Global Time

- Given an ensemble of clocks (internally) synchronized with precision π
- For each clock select macrotick as local implementation of a global notion of time with granularity g^{global}
- We note ref clock time (real-time, UTC) in units of g^{global}



Examples for Bad Choice for Global Time

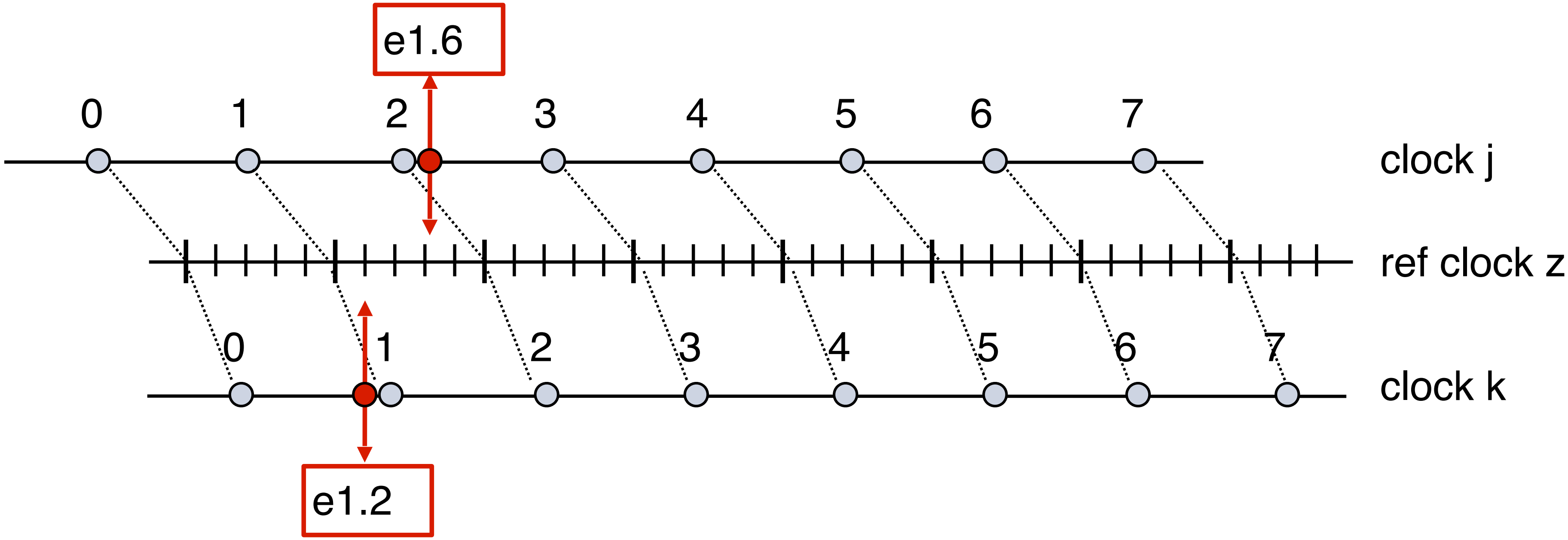




Reasonable: One Tick Difference

- Reasonableness Condition:
  - global time t is reasonable if
    $\mathbf{g^{global} > \pi}$ holds for all local implementations
- t^j(event): denotes global timestamp for event at clock j
- Then: For any single event e, holds: $$\left| t^j(e) - t^k(e) \right| \leq 1$$
- Global timestamps differ at most by one (macro-)tick.
- This is the best we can achieve!

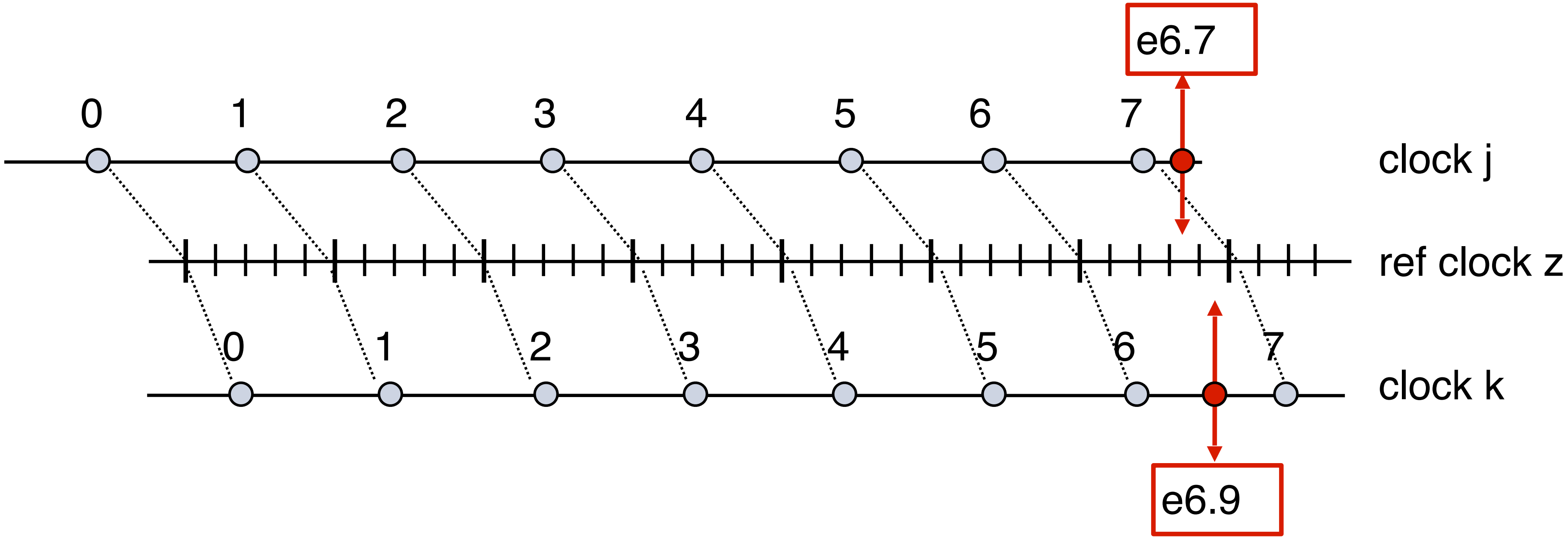
Necessary Distance to Establish Order



- $z(e1.6) - z(e1.2)$: 0.4 reference clock
- $t^j(e1.6) - t^k(e1.2)$: 2 global time ticks
- Temporal order can be established because $Tick^k_1$ must be before $Tick^j_2$ (Reasonabless Condition)

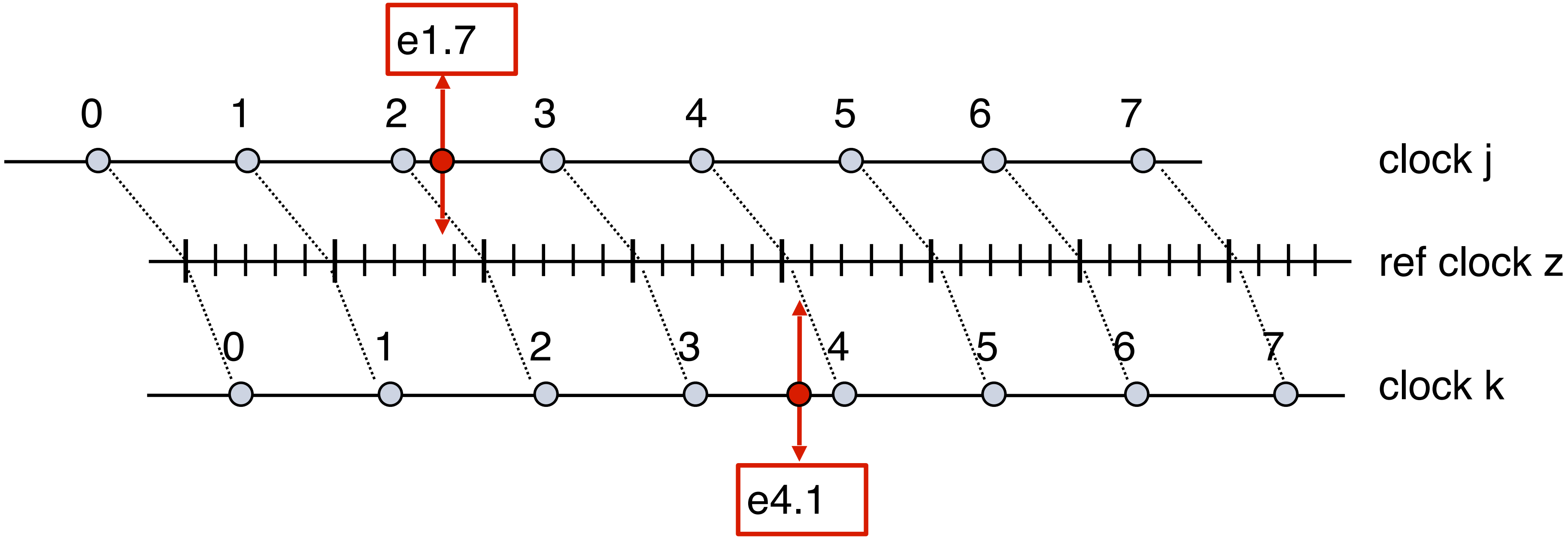
If timestamps differ by two ticks, temporal order can be established.

Example for Nearby Events



- $z(e6.9) > z(e6.7)$
- $t^k(e6.9) < t^j(e6.7)$

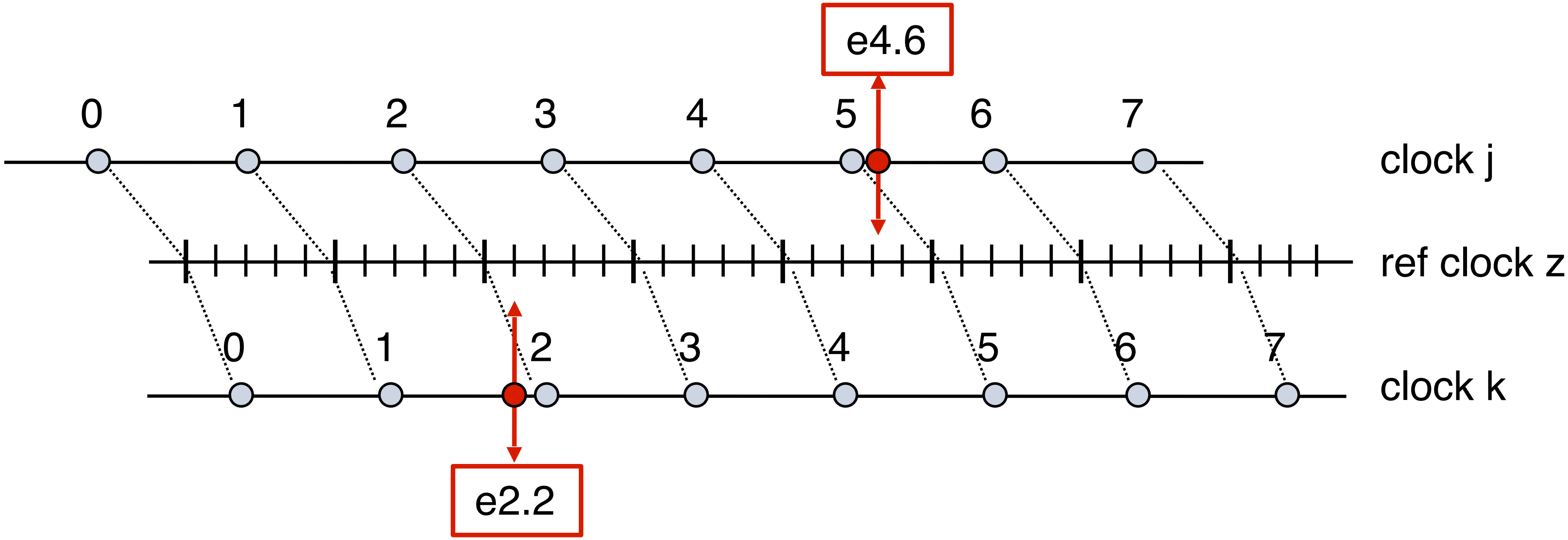
Sufficient Distance to Establish Order



- z(e4.1) – z(e1.7): 2.4 reference clock
- t^k(e4.1) - t^j(e1.7): 1 global time ticks

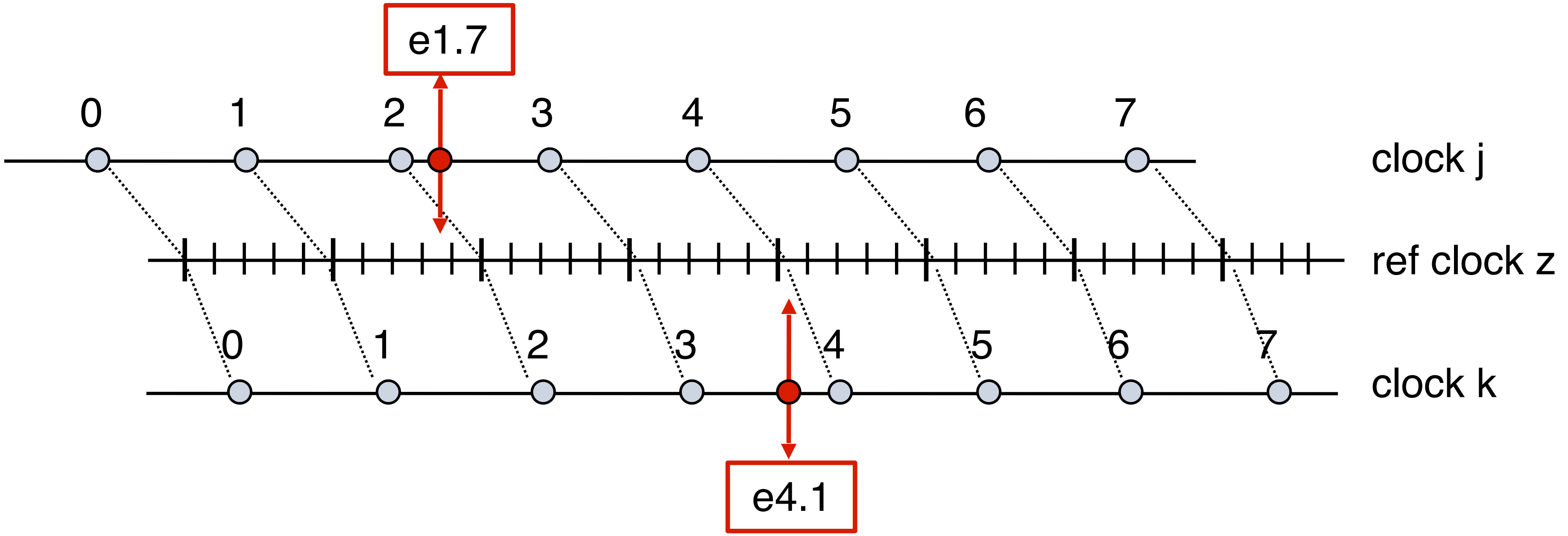
A distance of 2*g^{global} between two events does not suffice to reliably establish temporal order. A distance of 3*g^{global} is required.

Interpretation for Durations



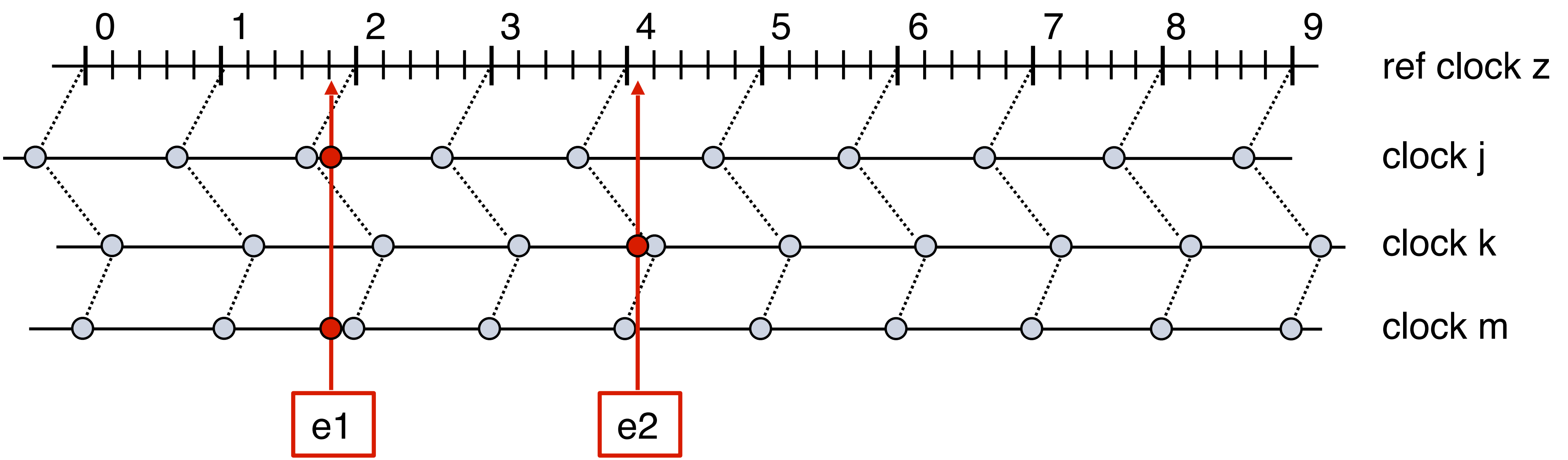
- True duration: 2.4
- Observed duration d: $t^j(e4.6) - t^k(e2.2) = 5-1 = 4$
- Extreme case: true duration can become 2+ε (for small ε), while observed duration remains 4
- $d^{obs} - 2 * g^{global} < d^z$

Interpretation for Durations



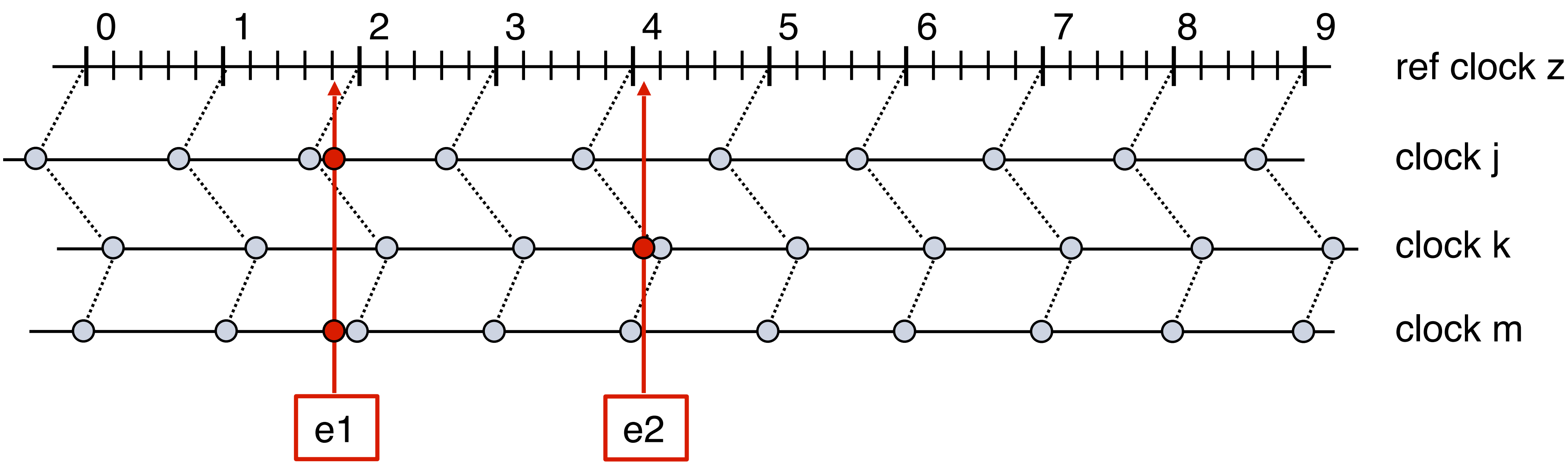
- True duration: 2.4
- Observed duration d: $t^k(e4.1) - t^j(e1.7) = 3\text{-}2 = 1$
- Extreme case: true duration can become 3-ε (for small ε), while observed duration remains 1
- $d^{obs} - 2{*}g^{global} < d^z < d^{obs} + 2{*}g^{global}$

Cooperation and Clocks



- (only) nodes j and m can observe e1
- (only) node k can observe e2
- Node k tells nodes j and m about e2
- Nodes j and m draw their conclusions …

Dense Time Requires Agreement



- j observes e1 at t=2, m observes e1 at t=1
- k observes e2 and reports to j and m: “e2 occurred at t=3”
- j calculates a time difference of 1, hence concludes: “events cannot be ordered”
- m calculates a time difference of 2, hence concludes: “events definitely ordered” → inconsistent view

Agreement Protocols

- information interchange:
  each node acquires local views from all other nodes
- deterministic algorithm that leads to same result on all nodes
- expensive

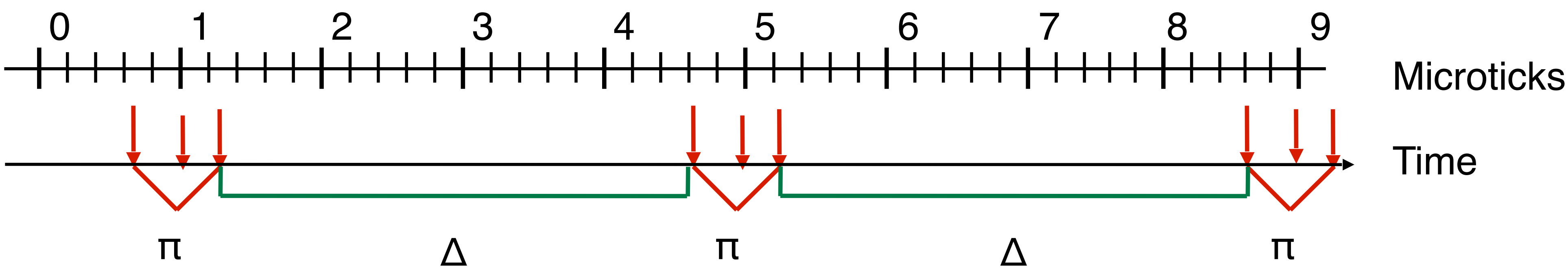
Sparse Time

- Two clusters A,B with synch clocks of granularity g each, no clock synch between A and B
- Cluster A generates events, cluster B observes

Goals

- If at cluster A events are generated at same cluster-wide tick never should temporal order be concluded at cluster B
- Always establish temporal order otherwise

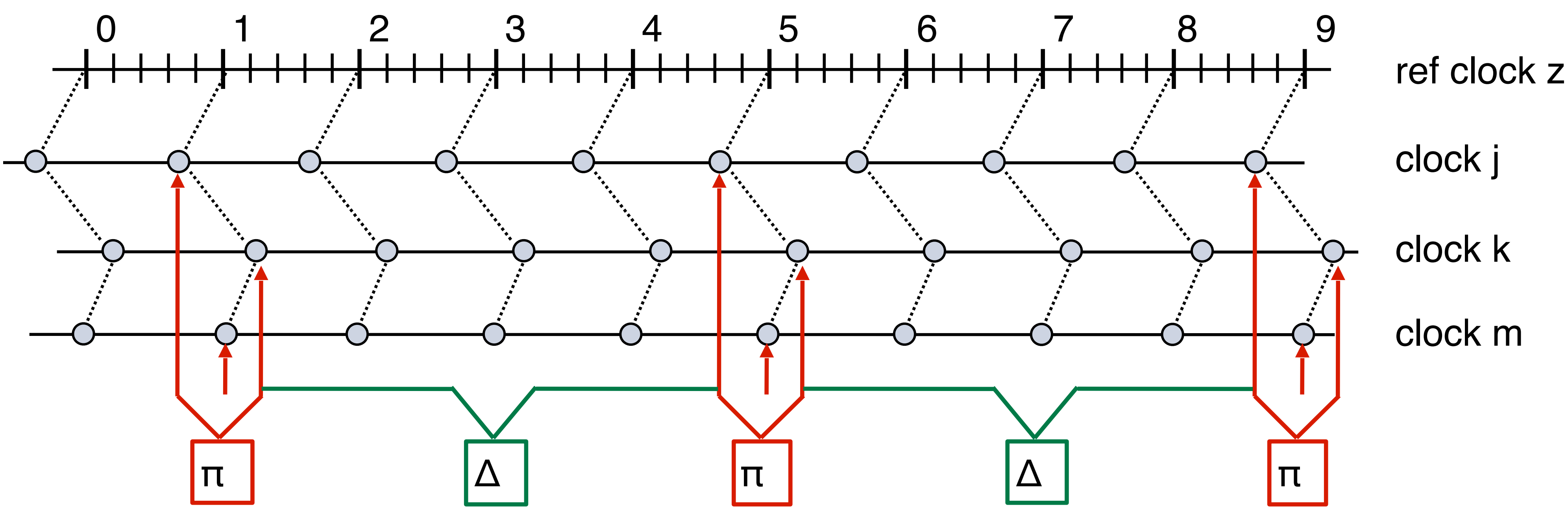
Dense Time vs. Sparse Time



- dense time: events are allowed at any time
- sparse time: events are only allowed within active time intervals π
- sparse time only possible for computer controlled events

Generated Events

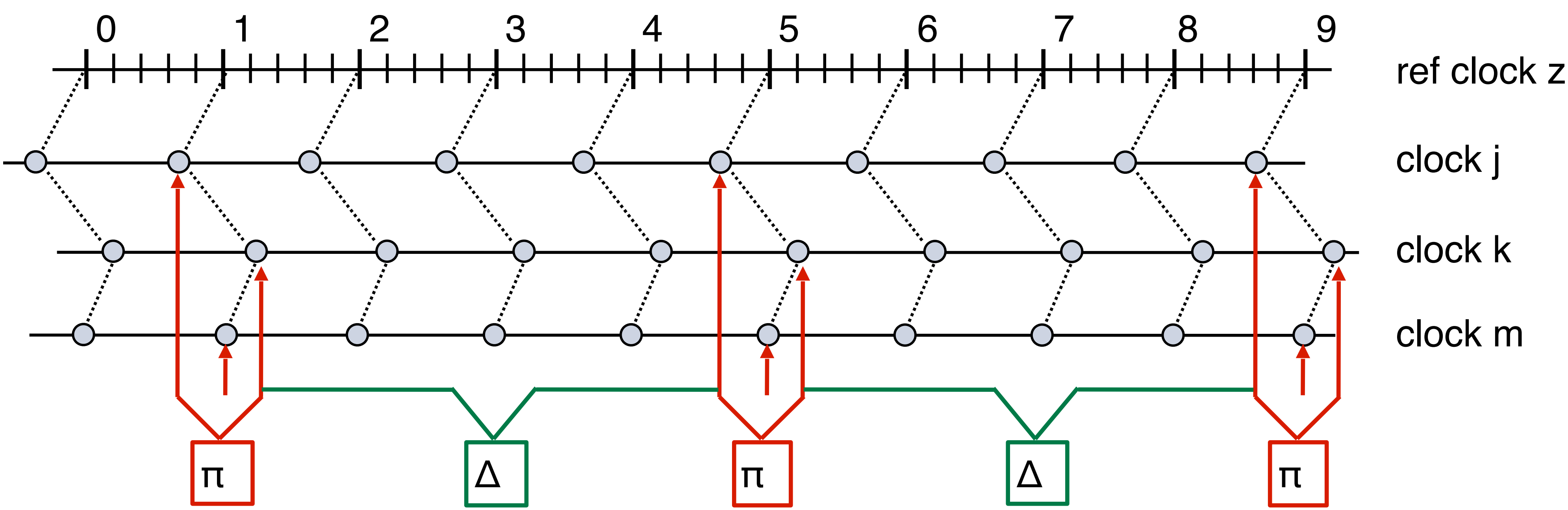
- Cluster of three nodes:
  - each generates event at the same global tick
  - t = 1, 5, 9
- observation:



π/Δ-Precedence of Sets of Events

- Properties of sets of events:
  - How far apart (number of ticks) must events be to enable reconstruction of order?
- A set of events is called π/Δ-precedent, if:

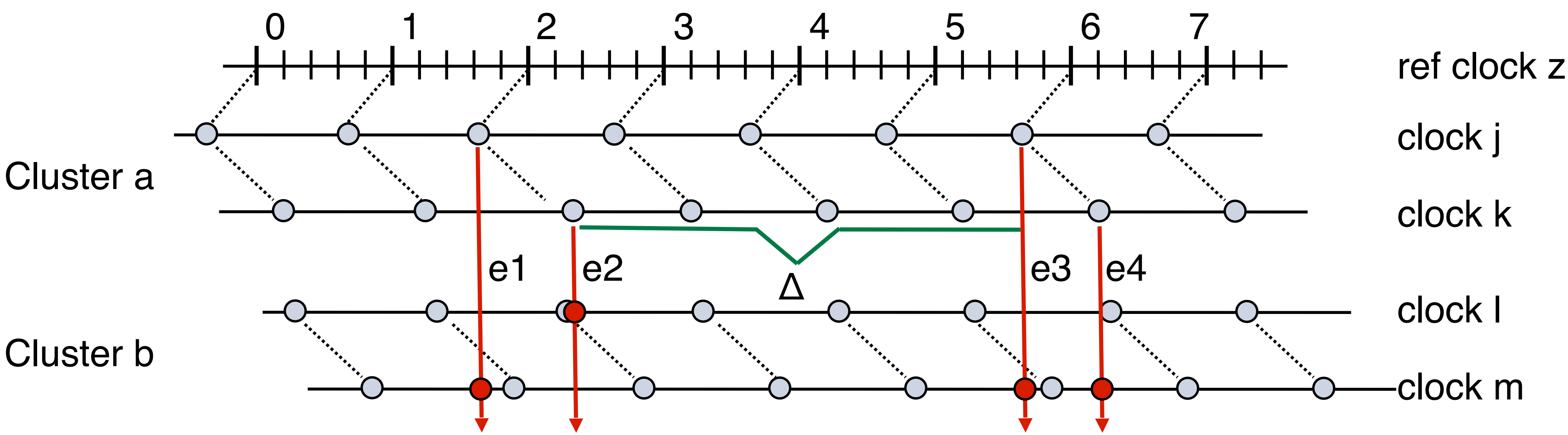
$$\left(\left|z(e_i) - z(e_j)\right| \leq \Pi\right) \vee \left(\left|z(e_i) - z(e_j)\right| > \Delta\right)$$



Temporal Order

Event Set	Observed timestamps of two nonsimultaneous events are always greater or equal to	Temporal order of the events can always be reestablished
0/1g precendent	$\left\| t^j(e_1) - t^k(e_2) \right\| \geq 0$	no
0/2g precendent	$\left\| t^j(e_1) - t^k(e_2) \right\| \geq 1$	no
0/3g precendent	$\left\| t^j(e_1) - t^k(e_2) \right\| \geq 2$	yes
0/4g precendent	$\left\| t^j(e_1) - t^k(e_2) \right\| \geq 3$	yes

Example for 1g/3g



- $t^l(e2) - t^m(e1) = 2$:
  - should not derive order because events were intended by cluster A for the same time
- $t^m(e4) - t^l(e2) > 2$ but: $t^m(e3) - t^l(e2) = 2$:
  - temporal order is intended ($\Delta > 3g$), but we cannot distinguish this case from the case above
- 1g/3g precedence not sufficient → 1g/4g required

Fundamental Results in Time Measurement

- A single event observed at different nodes may have timestamps differing by one; not sufficient to establish temporal order
- temporal order can be recovered from their timestamps if they differ by 2 global time ticks
- temporal order of events can always be recovered from timestamps if the event set is 0/3g precedent
- Duration: $d^{obs} - 2{*}g^{global} < d^{z} < d^{obs} + 2{*}g^{global}$